Summary of Thesis

Submitted by James B. Brown, Queen's College, in partial fulfilment of the requirements for the D. Phil. degree.

INVESTIGATION OF THE PHENOMENA OF FRICTIONLESS TRANSPORT AT LOW TEMPERATURES.

The work reported in this thesis divides naturally into two parts. The first concerns the development of a technique for isolating the supra-surface film of Helium II from the bulk liquid and the vapour pressure over it, and the study of properties of the film in equilibrium with the gas phase only. The second part of the thesis gives the results of a general investigation of high transport rates in the film.

A solution of the problem of isolating the film was seen to depend upon the devising of a practical form of super-fluid filter. Capillary leaks through metal tubes containing closely packed wires, such as those used by Allen and Misener [1] in their work on the viscosity of the bulk liquid were found to be suitable.

The construction and testing of such wire-tube filters is described. The performance data are tabulated for a typical one, consisting in this case of two tubes in parallel, each containing 900 wires of #47 Eureka in a 5 cm.

long cupronickel tube, initially .157" outside diameter, .072" inside diameter, drawn down finally to .104" outside diameter.

Representative values of the amounts of gas, N.T.P., passed by this filter into a vacuum from one atmosphere of helium were: .01 cc./min. at 290°K; .06 cc./min at 90°K; .45 cc./min. at 20°K; 7 cc./min. at 4.3°K. As the pressure is reduced in the helium temperature region, the amount of gas passed diminishes correspondingly, and at 4 cm. Hg., 2.2°K, it becomes .07 cc./min. N.T.P. Below the λ-point, the filters pass no measureable quantity of gas when they are not dipping into liquid. The total transport circumference provided by the above combination of two leaks in parallel is 30 cm., giving a maximum possible film flow corresponding to 110 cc. gas/min., N.T.P.

It is pointed out that the filters can be easily incorporated into metal apparatus, and an example is given of their application to the study of the vapour pressure over the film, and also the effect on the transport rate of lowering the vapour pressure over the film.

It is found that the vapour pressure in equilibrium with the isolated film is the same as that of the bulk liquid at the same temperature.

Above a critical rate of pumping, apparently

determined by the incidental film flow up an auxiliary tube, and the evaporation loss of the particular arrangement used, the pressure over the isolated film suddenly decreases, and transport stops. It is shown that at the same time there is a sudden fall of temperature at the transport surface, and apparently a thermomechanical effect in the film which prevents it from moving into the container being pumped. It seems possible that the film is still present but immobilized, and if this is the case, oppositely directed thermomechanical forces along the path do not cancel each other, but act independently.

A variety of geometrical arrangements have been investigated for the occurrence of high transfer rates. It has been found that the transport through a small hole in a surface can be several times larger than that calculated from the perimeter of the hole and the rate established by Daunt and Mendelssohn[2] for flow over cylindrical beakers. A number of such holes have been tested, and it has been found that there is sometimes a strong dependence of the transport rate on the height of the hole above the upper liquid level, and on the shape of the inside surface of the beaker.

Experiments have been made similar to those of K. R. Atkins[3], who reported high transfer rates in capill-

aries ending in bulbs, and under the influence of the temperature gradients. The results of Atkins have not been verified, and a probable explanation, based upon the interpretation of his geometrical arrangement, has been given for the apparently high rates observed in the second of his experiments. Some possible explanations for the other discrepancies are considered, and it is recognized that hitherto unexplored experimental factors may be involved. Experiments have been made to eliminate certain possibilities, one in particular being the formation of thick films under certain conditions. This has led incidentally to an observation of a striking example of the high conductivity of helium as a free liquid, apart from the presence of solids on which subsurface could be carried.

A summary of the experimental background of the field investigated, and some of the theoretical interpretations, is given in two chapters at the beginning of the thesis.

Ref. 1. J. F. Allen and A. D. Misener, Nature, 141, 75, (1938.
2. J. G. Daunt and K. Mendelssohn, Proc.Roy.Soc.A, (170, 423, 1939.
3. K. R. Atkins, Nature, 161, 925, 1948.

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A thesis submitted by

James B. Brown

Queen's College

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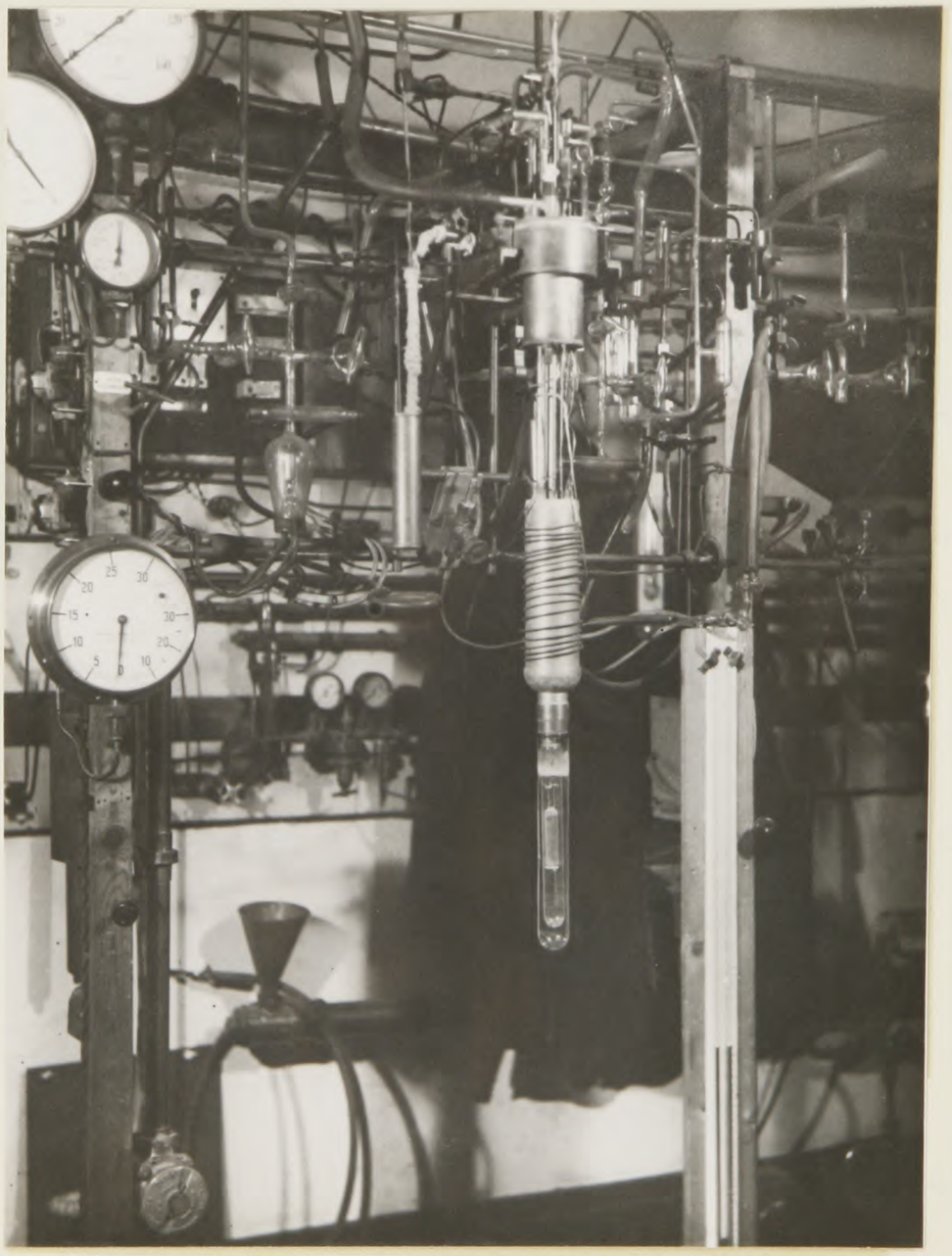


FIG. 1

INTRODUCTION

The work reported in this thesis divides naturally into two parts. The first, the development of a technique for studying the isolated supra-surface film of helium II, is described in Chapter III. Conclusions as to the development of the technique, and particular applications of it, are given on p. 33. The second part, a study of high transport rates in the helium film, is described in Chapter IV, a brief summary of the findings of the investigation being given under "Conclusions" on p. 335.

The above chapters are preceded by two giving the background of the field of research. The existing experimental facts are summarized in Chapter I. It has been found convenient to discuss the theoretical interpretations separately, and in Chapter II a brief account of these has been given, in so far as they relate to the phenomenon of frictionless transport.

The helium liquefactions connected with the investigations reported here were carried out in a modified form of the liquefier first described by Ruhemann.[38] A description of this type of liquefier has recently been given by Daunt and Mendelssohn.[14] A photograph of the apparatus is given in fig. I.

CHAPTER I

Summary of Existing Experimental Facts.

Possibly the most spectacular of the phenomena of He II, that of the creeping film, made a brief appearance under a different guise as early as 1922, well before determinations of the density, dielectric constant, specific heat, heat conductivity, and other properties had focussed attention on what later became known as the λ-point. Kamerlingh Onnes[19] pursuing still lower temperatures by refining his cryostat arrangements, had placed a small open Dewar vessel in the helium bath. He observed that the liquid level inside the vessel not only appeared to evaporate at the same rate as the surrounding bath, but also would return to the same level as the bath if the levels had been separated by splashing liquid out, or applying radiation strongly to the bath only. It was perhaps natural that he should ascribe this incidental phenomenon to some evaporation-condensation process, and so describe it in his account of the new record for low temperature that he had obtained.

Fourteen years later, Rollin[37], observing the way in which the evaporation of liquid helium from a closed container connected by a tube to the warmer part of the cryostat above, increased when the temperature was reduced below the λ-point,

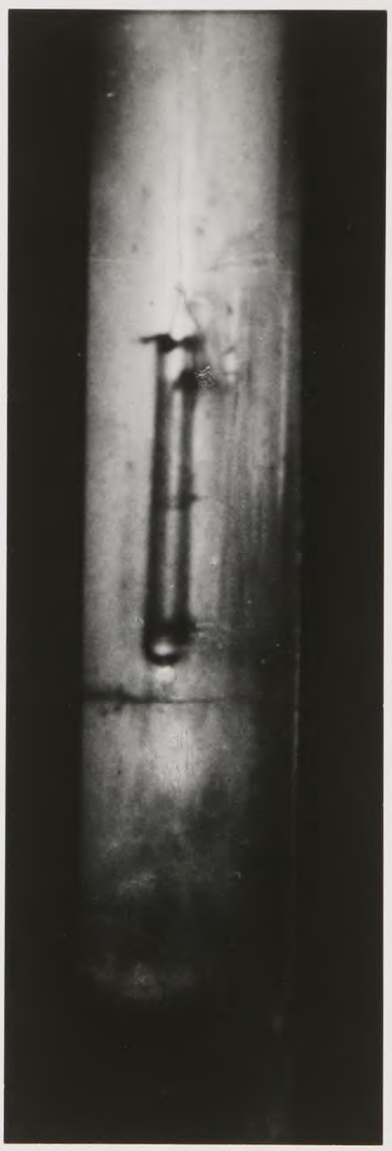


FIG. 2

was led to suggest the existence of a liquid film on the walls above the bulk liquid. By that time, the unusually high heat-conductivity of helium II had just been discovered[22K], and the supposition was that this film of liquid underwent a transition to a state of thermal supra-conductivity. Kikoin and Laserew[25] made further experiments to demonstrate the sudden appearance of this enormous heat conductivity at the λ -point, and further made an approximate determination of the film thickness, obtaining 2 to 3 x 10^{-6} cm.

The actual mechanism of the heat conductivity in this case, however, was disclosed soon after by a systematic investigation of the Kammerlingh Onnes effect by Daunt and Mendelssohn.[11,12,13] They demonstrated conclusively that it was not a heat conductivity of the film that was responsible, but rather a transport of the film itself. In fact, from extensive experiments with the film emptying and filling cylindrical beaker arrangements, it appeared that, up to a certain limiting rate, this transport was carried out without a difference in gravitational potential. The motion of the film over the rim of a beaker could not be described ~~as~~ simply as a syphon action, for the rate of transport was practically independent of the difference in liquid level, as was demonstrated not only in these experiments but in a rather striking later one[13] using concentric beakers. That is to say, as will be seen more clearly later, the film phenomenon encountered was not one of

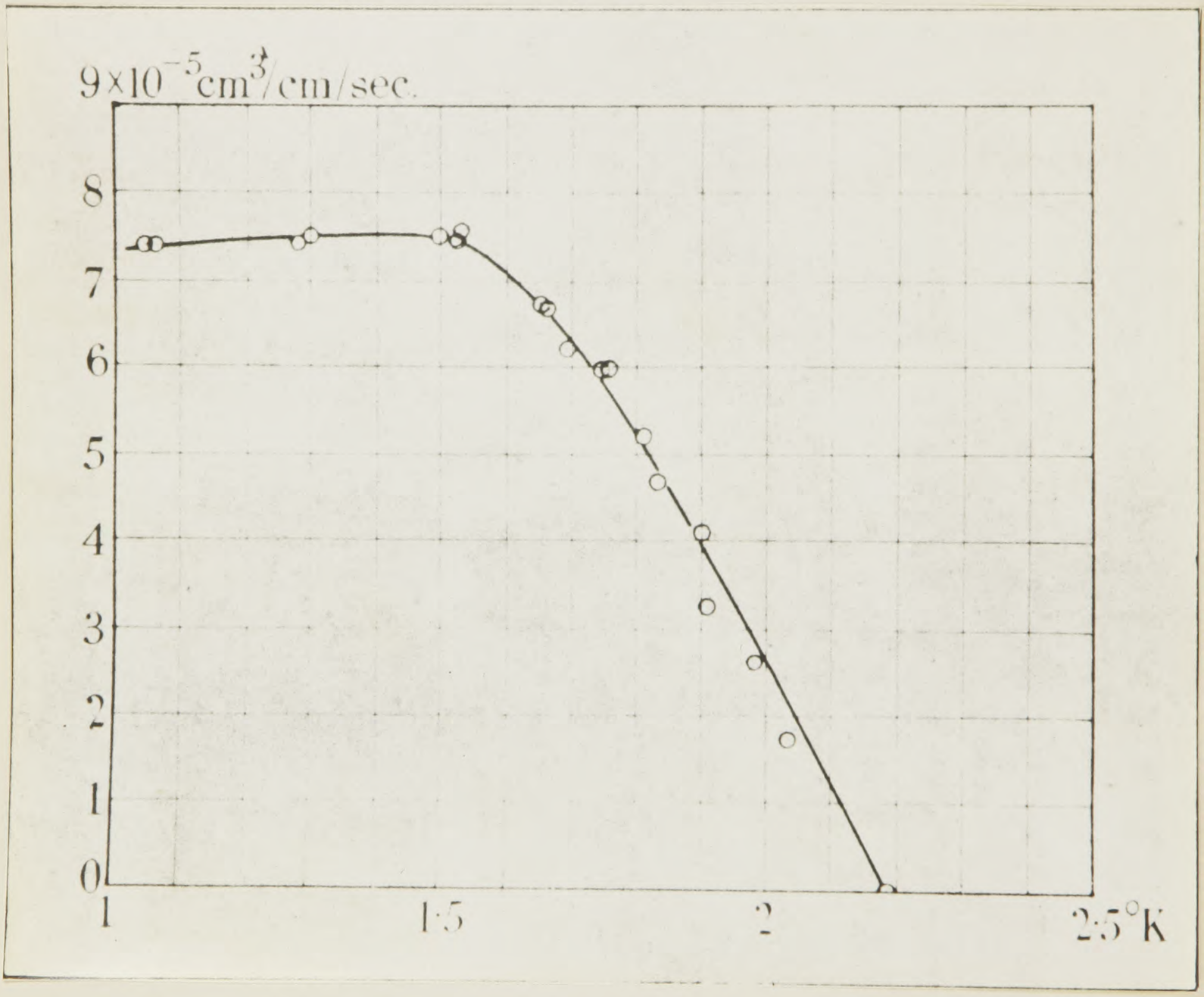


FIG. 3

thermal supra-conductivity, but rather one of supra-fluidity, or frictionless transport.

One of the most immediately convincing evidences that the emptying of a beaker to bath level was in fact by a surface film, and not by evaporation, as supposed by Kammerlingh Onnes, was that if the beaker were raised entirely clear of the bath, and if the radiation falling on it were kept sufficiently small, then the liquid could actually be seen to collect in drops on the bottom of the beaker before falling into the bath. The necessity for low radiation intensity was most important, and the use of suitable light sources, such as neon lamps, as well as the further small evaporation resulting from the particular cryostat techniques used in the Clarendon Laboratory, were essential to the success of the observations.

As it was suggested recently that there was no photograph in existence of this falling of a drop from a transport beaker, one was taken during an experiment to be described in thesis, and is shown in fig. 2 .

Daunt and Mendelssohn found that the rate at which film flowed between two liquid levels was accurately proportional to the narrowest width of the connecting surface above the upper liquid level. This rate varied with temperature in the manner shown in fig. 3 . Whether there is actually a significant drop in transport rate from 1.5° to 1° or not is still undecided, but it is clear that the maximum value is

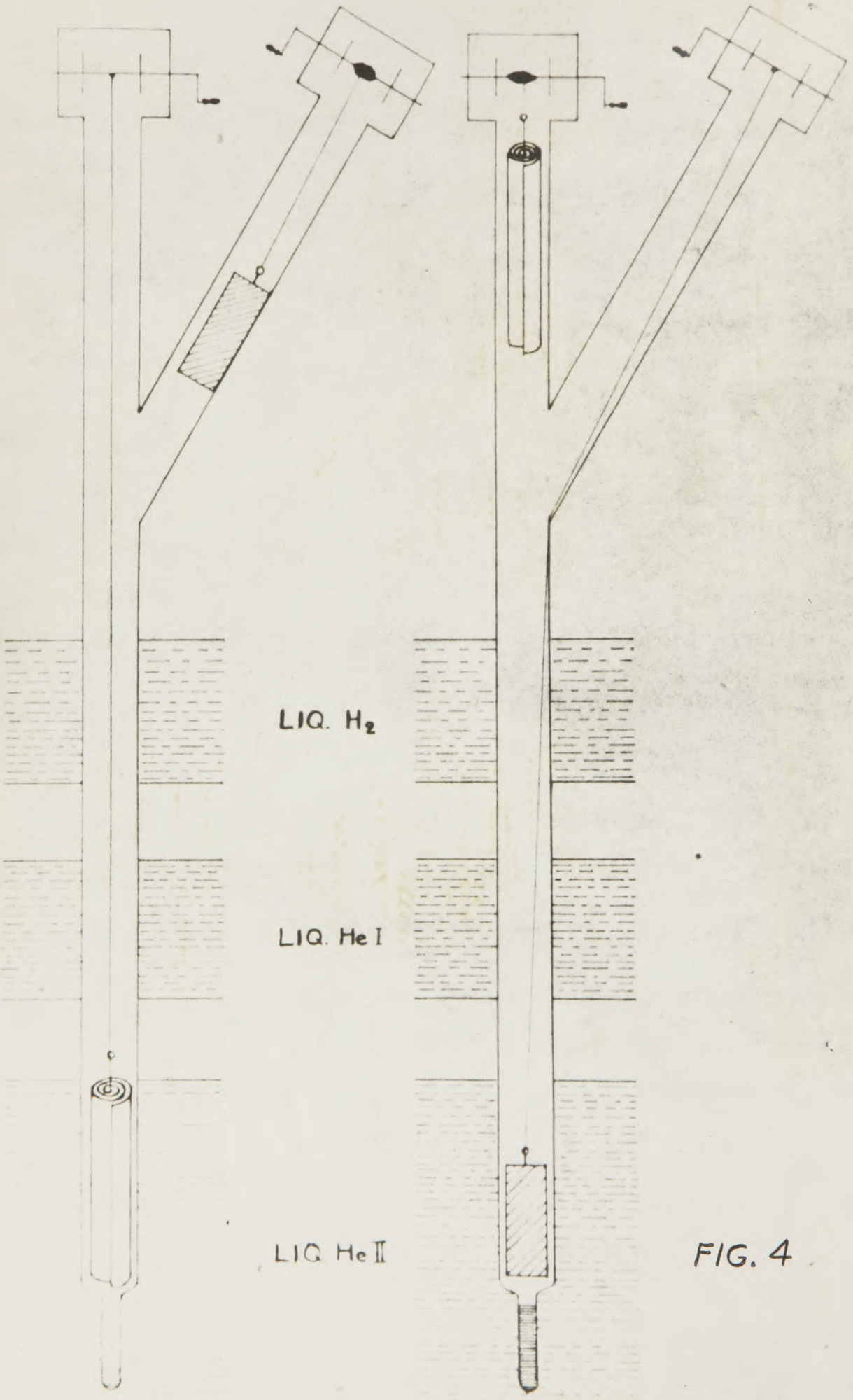


FIG. 4

close to 7.5×10^{-5} cc./sec./cm.

From this rate at which liquid was carried into and out of the vessels, it was possible to deduce the average velocity of the film once its thickness was known. Daunt and Mendelssohn's determination of the thickness was carried out by means of the apparatus shown in fig. 4 . A special roll of polished copper sheet was allowed to be covered with film at the bottom of the closed tube shown. When this roll was raised to room temperature, the evaporating film was forced, by the surrounding constant temperature baths, to condense as liquid in the calibrated capillary at the bottom. To avoid corrections for displaced gas, a small copper cylinder of the same volume as the sheet was lowered from a side tube as shown.

The average value obtained in this way was 3.5×10^{-6} cm., with no change in order of magnitude between 2.1 and 1.5° K. By combining this value with the transport rate of 7.5×10^{-5} cc./sec./cm., the maximum transport velocity is seen to be about 20 cm./sec.

Further evidence that a frictionless flow existed in helium II was also emerging from direct experiments on the viscosity of the bulk liquid. The earlier work such as that by Wilhelm, Misener and Clark[44] with an oscillating cylinder, and more refined experiments on an oscillating disk by Keesom and MacWood[22] indicated a drop in viscosity by one or two orders of magnitude below the λ -point. The application of

other classical methods of measuring the viscosity, however, notably by Allen and Misener[2], who used long capillaries of 1mm. and less diameter, and by Kapitza[20K], who measured the flow between optically flat plates separated by less than a micron, showed not merely a far greater reduction in coefficient of viscosity below the λ-point, to the order of 10^{-9} c.g.s. units, but also a difference in character of the flow, which appeared to be almost independent of the pressure head. The discrepancies between the various results were finally largely reconciled by a systematic investigation by Allen and Misener[3] on capillaries of widely differing diameters, ranging from 4.38×10^{-2} cm. to about 10^{-5} cm., and in one case of differing lengths. It appeared that all the viscosity measurements might be explained in terms of a superposition of two types of flow. The first of these, associated with helium below or above the λ-point, is of the order of 20 micropoise, and therefore measureable, but has a temperature dependence which resembles the viscosity of gases more than that of liquids, even above the λ-point. The second was thought by Allen and Misener to be probably that of a sub-surface film of helium similar to the supra-surface film of Daunt and Mendelssohn. Whether this second flow actually takes place in a film on the walls was not established by Allen and Misener, but it would seem to be probably of a frictionless, or nearly frictionless, nature. The further evidence for this picture comes from

consideration of other properties to be mentioned below.

Further direct experiments on the heat conductivity of liquid helium, in addition to those briefly referred to above, were made by Allen, Peierls and Uddin[4], Keesom, Saris, and Meyer[23], and others in the usual helium II temperature range, and by Kurti and Simon[26] between 0.2 and 0.5° K. These experiments showed a heat conductivity having a maximum just below 2° K. which is several orders of magnitude greater than that usually associated with metals at room temperature. Strictly speaking, however, a heat conductivity in the ordinary sense could not be defined. Rather, it was found that from 1.6 to 1.0° K. the quantity of heat transported was proportional to the cube root of the temperature gradient, and varied as the fifth power of the temperature. When the region investigated by Simon and Kurti had been reached, however, the measured conductivity had fallen back to the order of 10^{-3} cal./deg. cm.sec., and varied as the cube of the absolute temperature.

Kapitza[20] performed a number of experiments to demonstrate directly the presence of a stream of liquid in a heat conducting capillary, accompanied by the flow apparently of a film in the opposite direction. He also showed that the two flows must differ in their heat content at the same temperature. It appeared that the velocity of the film in his experiments must be at least five times that of the supra-surface film of Daunt and Mendelssohn, and possibly very much thicker, but it

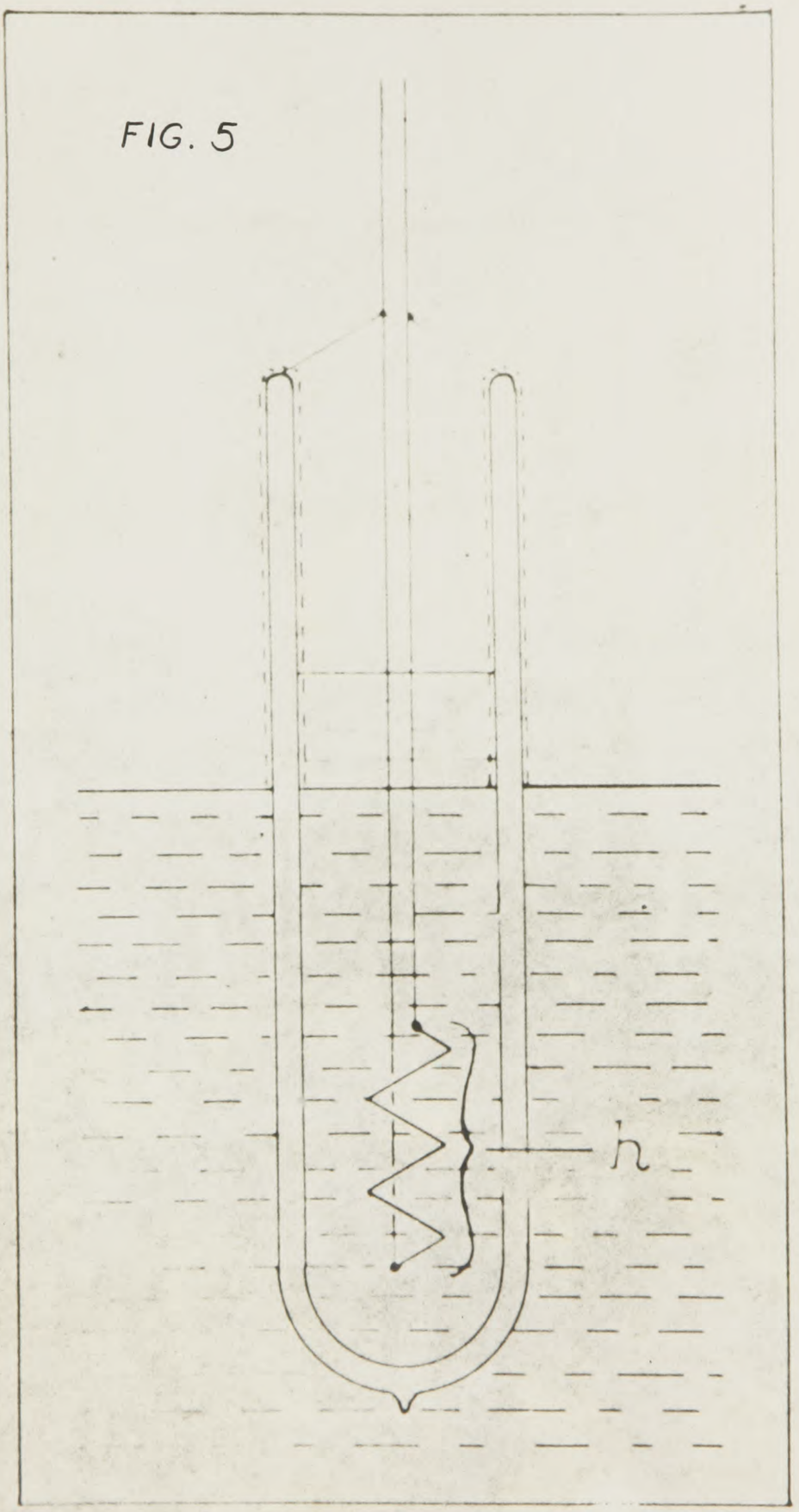
is clear that his heat flows were so great that the process was largely irreversible. Experiments of his to prove that the conduction through the free liquid apart from any film flow is relatively small have been questioned by Meyer and Mellink.[34]

Later experiments by Kapitaz[21] on slits between glass discs appear to have been carried out in the region of reversible flow processes, and it is interesting that the velocities involved appeared still to be greater than those of the supra-surface film.

Kapitza has pointed out that a general objection to most of the former experiments designed to measure viscosity, as distinct from heat conductivity, is that proper allowance has not been made for possible thermomechanical pressures set up by temperature gradients.

The recent experiments by Meyer and Mellink[34] on the heat conductivity through slits reduced to the order of a micron and less have shown that the heat transported in this case becomes proportional to the temperature gradient directly, rather than the cube root of it, this being true even for somewhat larger slits if the gradient is small. They also found evidence of a critical velocity of liquid flow in the slits above which irreversible heating effects occurred. This velocity was approximately the same as that observed by Daunt and Mendelssohn for films, but of course the transport rate

FIG. 5



expressed as fluid flow per circumference of their slits was then larger in the same proportion as the width of their slits to the thickness of the film, i.e., several orders of magnitude.

These last investigations were carried out in connection with another set of phenomena of importance here; the thermomechanical effects. In the course of experiments on thermal conductivity, Allen and his collaborators[1] came upon the "fountain effect". It was observed that if the liquid in an open container connected to a helium bath by a constriction, such as a capillary, were heated, then liquid would flow into it with sufficient pressure that it could emerge from the top end as a jet. It was shown that the pressure varied with temperature, in a very similar way to the heat conductivity, having a maximum below 2° K. The work of Mellink and Meyer, referred to above[34], showed that for sufficiently small slits the fountain effect and heat transport at any given temperature depended in the same way on the temperature gradient.

Daunt and Mendelssohn[11,12] had previously shown that an effect, now seen to be analogous to that of the fountain, existed in the case of the transport film. The arrangement is shown in fig.5, the film flowing into a beaker containing liquid electrically heated above the temperature of the bath. These authors later showed that the fountain is a reversible phenomenon, its converse being termed the mechano-caloric effect. Here, the draining of liquid helium under the action

of a gravity through a porous plug produces a rise in the temperature of the liquid left in a beaker.

Another phenomenon closely related to the fountain effect is that of second sound. It is a propagation of temperature waves through the bulk liquid, and while it was first predicted by Tisza,[42] its discovery by Peshkov[36] was based on parallel theoretical work by Landau.[27] While it is of incidental importance here in helping to establish the two fluid picture emerging, experimental work[27k] on it has so far been confined to velocity measurements from which the entropy differences between the two fluids may be measured. Attenuation measurements may later give information on the reversibility of the mechanisms involved.

Returning to films above the liquid surface, there have been recent attempts to measure the thickness as a function of height. Several indirect methods have been used by Atkins,[6] but the results have not been conclusive. The tentative results appeared to indicate that the thickness varied inversely as the height above the free liquid. A direct interferometric measurement has been begun by Jackson.[18] Preliminary results have indicated that the thickness is approximately independent of height, but have shown a possibility of unusually thick films being formed under certain conditions at the surface of the evaporating liquid.

A last item, of relevance to the theory of the

phenomena concerned here, it has been found[15] that the He^3 isotope either does not show the properties of frictionless transport, or else has a λ-point considerably lower than that of the He^4. Experiments with the rare isotope in visible quantities are yet to be reported.

CHAPTER II

Summary of Theoretical Interpretations.

The theory of frictionless transport in Helium II is in a somewhat similar state to the theory of supra-conductivity, with which in fact it appears to be connected. That is, there are a number of partial descriptions and useful concepts which may be mentioned here, but anything like an adequate whole is yet to be assembled, and the impression is that key experimental facts have yet to be supplied. In particular, the nature of the supra-surface film is still largely obscure.

Simon[40] pointed out that below the λ-point liquid helium tends to some highly ordered state, even though remaining in the liquid condition, probably to absolute zero. Assuming an approach to some lattice arrangement similar to that in crystals, F. London[28] calculated the potential energy of a number of possible structures, and found the diamond lattice to have the lowest. Fröhlich[16] showed that this lattice could be considered as two interlocking lattices, one a cubic body-centred lattice of which only one half the sites were occupied, the other a diamond lattice formed by the unoccupied sites. In analogy with the λ-point phenomenon of β-brass, Fröhlich explained the helium transition as an ordering of this alloy of atoms and holes. It was shown by F. London[29] that when

second neighbors were considered the occupied sites would be less preferred than the holes, however, and moreover the results of X-ray analyses by Keesom and Taconis[24] did not confirm the diamond structure anyway. Other spatial lattices have been proposed, but development in this direction does not seem promising, especially for the bulk liquid.

F. London[29] then proposed the Boss-Einstein condensation of an ideal gas as approximating the λ-point transformation. The gas-like character of the coefficient of viscosity, even for helium I, supports the view that the weak interatomic forces of helium would permit this picture to be approximately correct. Born and Green[10] have since deduced from their theory of quantum liquids that the actual statistics obeyed are not important, but this first attempt focussed attention on the idea of a condensed phase separated from the excited atoms by an energy gap, i.e., a two-fluid model.

Once this two-fluid model has been granted, the hydro-dynamics of helium II may be developed in some detail. H. London[32] deduced the equation for the fountain effect pressure by considering a thermodynamic cycle, developing an analogy with the thermoelectric equations.

Tisza[43] derived the same equation by analogy with osmosis, but of course the mechanism is immaterial if the process be reversible. Tisza also predicted the temperature waves which Landau[27] obtained independently, and named "second sound".

Landau bases his hydrodynamics on an abstruse introduction of quantum operators. There seems to be disagreement as to the validity of his methods, (e.g. F. London,[30] Max Born[9]) but his macroscopic equations agree with those of Tisza, except that Landau assigns a rigorously vanishing entropy to the condensed phase where Tisza endows it with Debye waves.

The Born-Green theory referred to above appears to be an impressive frontal attack on the theory of liquids. Nevertheless, it is felt that one does not have to have verified the difficult mathematical development to doubt that the theory as yet "explains rather nicely all the phenomena of heat transport in He II."[17] The theory does attempt to throw definite light on the transport phenomena, however, the equation derived for the effective thermal conduction becoming

$$\underline{q} = -\lambda \frac{\partial T_1}{\partial x} - K \underline{u}_1 \cdot \frac{\partial \underline{u}_1}{\partial x}$$

where the first term is the small, true conductivity of the liquid itself, K is a factor, small in magnitude, calculated directly from the wave function for a helium atom, and called the "coefficient of thermal mobility", and the last factor is a symmetrised non-divergent velocity gradient tensor of the type defined in standard treatments on hydrodynamics. For the laminar flow of a film in the x- direction with a velocity u_x, $\frac{\partial u_x}{\partial y}$ being the only other non-vanishing quantity, the heat flow becomes, neglecting the first

term, $g_x = 0$. $g_y = -K u_x \frac{\partial u_x}{\partial y}$. $g_z = 0$.

The authors then postulate a flow of heat across the film, such as might be caused by evaporation, and to maintain this value of g_y when K is very small it follows that the film velocity, u_x must be appreciable. Thus a qualitative suggestion is made as to the mechanism driving the film, i.e., an evaporation process accompanied by a flow of heat normal to the motion of the film.

It is suggested that the λ -point corresponds to the point where the wave function begins to contain states of angular momentum l = 2, 4, --- in addition to l = o. Kahn is reported to have calculated that the appearance of the state l = 2 occurs at 2.28° K.

Schiff[39] calculated the thickness of the helium film on the assumption that surface forces were balanced by gravity, and obtained an inverse dependence of the thickness on the cube root of the height above the free liquid.

Bijl, de Boer and Michels[8] calculated the film thickness on the assumption that the zero point energy resulting from the confinement of the molecules in the film was balanced by the gravitational potential, and obtained a thickness varying inversely as the square root of the height. They also used the idea of zero point energy, as determined by the thickness of the film, to suggest a connection between the critical film velocity and the uncertainty velocity.

A recent paper by F. London and P. R. Zilsel[31] has developed the theory of heat transport by internal connection in helium in a straight-forward manner based on the usual two-fluid hydrodynamic assumptions. The self-viscosity of the normal component was included but the two fluids were considered uncoupled, as would seem largely justified. While it had been hoped that Meyer and Mellink's[34] work on narrow slits, where they obtained a heat transport directly proportioned to the temperature gradient, would now allow the theory to be verified, it was found that the theory gives values very much smaller than those obtained experimentally. Critical velocities obtained from the theory agree roughly with the larger values of Kapitza, and are therefore in disagreement with those of Meyer and Mellink, which appear to be connected with Daunt and Mendelssohn's supra-surface film, rather than the mechanism considered here.

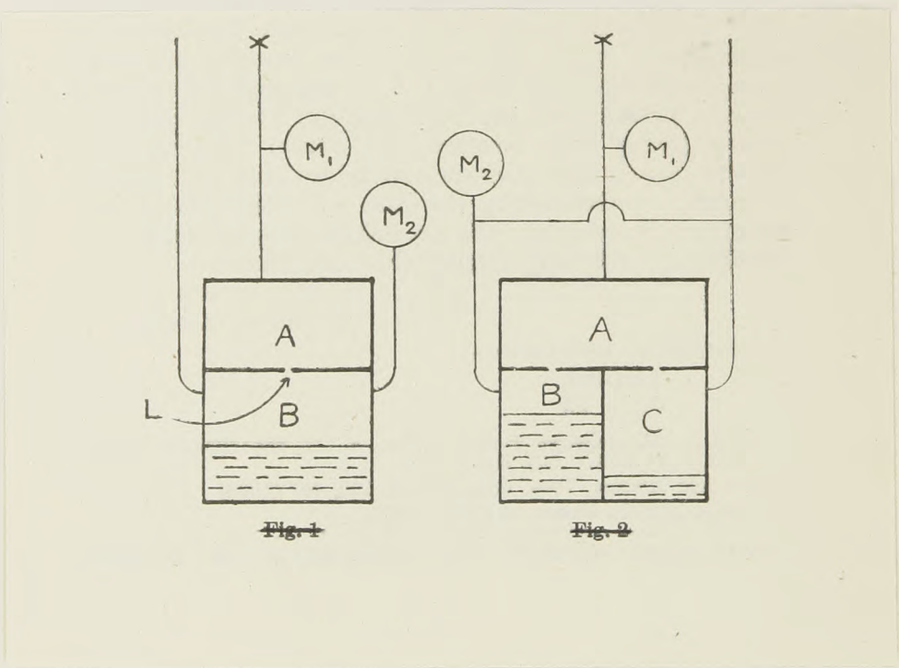


FIG. 6

CHAPTER III.

Isolation of the Helium Film.

In this chapter the nature of the problem to be investigated is stated, followed by a description of the technique developed for its solution, and finally results are given of applications of the technique to particular experiments.

The Problem.

In the past, experiments on the properties of the supra-surface film of helium II have generally been carried out with the bulk liquid present. The film has thus necessarily been under the vapour pressure of the liquid at the temperature prevailing. It seemed desirable, therefore, to develop some method whereby the film could be isolated and the simpler case studied, that of the properties of the film when in equilibrium with its own vapour pressure only.

The procedure proposed is illustrated schematically in fig. 6 (a). Here two containers, A and B, the latter containing liquid helium I, are connected by a small leak L. If A is evacuated and then closed off, helium gas will leak from B into A, the rise of pressure in A being measured by the gauge M1. When the liquid helium in B is cooled below the λ-point, however, a

new process makes its appearance. Helium in the form of the transfer film now runs up the sides of B and passes over the perimeter of L into A, thereby constituting an additional leakage. If, by using progressively smaller leaks, the stage can be reached where the gas leakage becomes insignificant compared with the film leakage, it is then possible to study the film in A under varying gas pressures independently of the vapour pressure of the liquid.

It is apparent that there is a variety of problems to which the technique outlined above could be applied. For instance, the question as to the influence of the vapour pressure over the film on the transport rate can be decided by extending the arrangement as in fig. 6 (b). Here, by introducing a second suitable leak, or filter, leading into a third container C, which is also filled with liquid helium II, but at a lower liquid level than that in B, the transfer of liquid by means of the film from B through A into C can be studied.

Thus it is seen that a solution of the problem of studying the isolated film depended on the devising of some practical form of super-fluid filter, which would allow the film to pass, but neither the bulk liquid nor the vapour associated with it.

Among the methods considered for providing this filter was the use of slits between ground glass joints, or those between optically polished glass surfaces separated by thin spacers. Devices of this sort have been sometimes used for viscosity measurements and fountain effect studies.[34,21] There are obvious difficulties inherent in these methods, however, both in making suitable surfaces and in arranging that they should have appropriate spacings over any appreciable length of path.

A more rugged construction, having advantages in the ease with which it could be incorporated into various experimental arrangements, as well as in the fact that its construction would require the techniques of the machine shop rather than the precision optical bench, was apparently offered by the use of capillary leaks through metal tubes containing closely packed wires, such as used by Allen and Misener[3] in their work on the viscosity of the bulk liquid. It was therefore decided to undertake the construction and testing of capillary leaks based on this design.

Construction of Filters.

A number of available materials were tried for the wires and the outer metal tube. The method of reducing the size of the capillary leaks required the tube

containing the wires to be drawn through successively smaller die-plates, and it was soon clear that very hard materials such as steel could not be used for the outer tube. Also, it was found that steel wires in a softer jacket could not easily be made sufficiently tight.

It was found that copper wires did not seem to become tight as the drawing was continued to smaller die-plates holes, the wire simply stretching with the tube, and the whole unit becoming longer. There was a further practical reason for avoiding copper. Dr. J. F. Allen kindly furnished details of his experiments, where, of course, the requirements as to tightness against gas flow were as stringent as here. He had found copper wires in nickel silver tubes to be most satisfactory for his purposes, but nevertheless with the finest tubes it had been found that any heat applied after the drawing resulted in the copper wires fusing together under their surface tension. Thus it was not possible to make soldered connections to the tubes after drawing.

A very satisfactory combination was found to be provided by using 900 wires of #47 Eureka (.0020" diam.) in a cupronickel tube, initially .157" outside diameter, .118" inside diameter, drawn down finally to .104" outside diameter. The method for determining at what stage to stop

FIG. 7

drawing is described below.

The first step in making up the filter consisted in winding the wire back and forth between two pegs mounted about 40 cm. apart. Care was taken to keep the wire as straight and tight as possible. Some breakages in this operation with such fine wire seemed unavoidable, but the joins could be placed at the ends near the pegs. When the required number of wires had been wound, a thin steel wire was passed through the loop so formed, which was then removed from the pegs, and slid quite easily by hand into the cupronickel tube.

As it was found difficult to do the drawing smoothly by hand, even with a specially made tool, the pulley and steel cable attachment shown in the upper left of fig. 7 was devised so that a power milling machine could be used for the purpose. Also shown in this figure are a cupronickel tube before drawing, one immediately after (with ends trimmed back), and another with a copper connector slid part way over it for testing, to be described below. It was found that soft solder could be applied directly as shown without the heat fusing the wires together. Further, the outer tube could readily be filed round and peeled off, leaving any desired section of the wires bare, with very few broken, as seen on the bottom tube projecting from the

small piece of apparatus in the lower right of fig. 7.

Testing the Filter.

Generally, the wire-filled tubes were drawn down through about five holes in succession on a die-plate before it was necessary to test their condition. It was then required that their resistance to gas flow be measured in order that they might be made just sufficiently tight that the gas leakage would be negligible and yet the tube would be able to pass film.

The difficulty in making the tests arose from the combination of the great increase in viscosity and decrease in density of helium gas between about 1.3 ^{o}K, where the filter would have to be used, and any convenient testing temperature. A considerable amount of trouble was encountered in attempting to use high pressure hydrogen for the test at room temperature. A number of tubes were tested in this way and then placed in the cryostat for experiments below the λ -point. In each case the tube appeared to be satisfactory during the drawing operations, but gave low transport rates when used in liquid helium II. Tests finally showed that in fact these tubes were completely blocked, but that each time the hydrogen had been applied the outer tube had apparently stretched elastically, sometimes under only an atmosphere or so pressure, and had then

contracted again when the hydrogen was removed. The additional complication of an apparent transport rate was finally proved to be due to a hitherto unknown high transport effect through a very small hole into the measuring beaker which had been provided for another purpose. This effect is dealt with separately in the chapter on Transport Rates.

It was thus found that the only satisfactory way to test the tubes during drawing was to connect them temporarily to a chamber which could be evacuated, and then measure on a manometer the rate at which gas leaked through into this chamber. The first test was usually made simply with atmospheric air, helium at liquid oxygen temperature being used for the final test before doing a helium experiment.

As an illustration of the performance of the filters, the following table gives the rate at which the pressure rose from a vacuum in a volume connected to the helium bath container by two of these wire-tube filters in parallel. Each of the filters in this case consisted of a 5 cm. length of cupronickel tube, the outside diameter drawn down from .157" to .104", inside diameter initially .072", containing 900 wires of the #47 Eureka. The volume in which the pressure was measured was made up of two parts; one of 47 cc. at room temperature, consisting of discharge

tubes and other dead volume, and the other, connected to the first by a capillary, a 1.5 cc. chamber immediately above the wire-tube filters at the temperature stated. The arrangement was essentially that of fig. 6 (b). For further comparison of flows at different temperatures, the total gas collected in the combined volume has also been expressed in cc./min., N.T.P.

(Next page)

TABLE I

Temperature	Pressure	Conditions	Pressure Rise	Equivalent Gas
290° K	760 mm.		.2 mm/min.	.01 cc/min. N.T.P.
90	760		.9 "	.06
20	760		4.8 "	.45
4.31	836	(liquefying)	40. "	7.6
3.29	270	wires immersed in liquid	6. "	1.4
2.34	55		.4 "	.12
2.20	40		.22 mm/min.	.07
1.88	16	wires immersed	3.9 mm/10 sec. 5.0 mm/20 sec. 6.4 mm/40 sec. 10.5 mm/90 sec.	~8
1.88	~~12~~ 16	radiation shield only in liquid	3 mm/min.	1.1
1.88	16	wires and container out of liquid	rose to .5 mm. in 1 min. and stopped	-
1.65° K	6.8 mm.	wires immersed	4.4 mm./10 sec. 6.2 mm./30 sec. 6.8 mm./2 min.	~10 cc./min.

It will be noted that as the temperature was lowered on the first four readings the rate of gas leaking in to the test volume steadily increased, owing to the fall in viscosity of the gas and its greater density. When helium temperatures had been reached and the pump turned on over the liquid bath, the rate of gas entry fell as the vapour pressure, and hence the pressure on the wire-tubes, was reduced, reaching quite small values again before the λ-point was attained. As soon as the λ-point was passed there was a sharp increase in the pressure in the volume, which rose to the vapour pressure of the bath in a few minutes. Repeating the test here with the wire wicks withdrawn, but the metal radiation shield around the apparatus still immersed, reduced the rate of film flow greatly, as would be expected. After raising the entire apparatus clear, the pressure in the space rose to about .5 mm., but no further, when the test was made. Immersing the wires without repumping immediately restored the flow. A further test at even lower temperature showed a similar greater inflow rate, the vapour pressure of the bath being reached again in two minutes.

It may be noted that the total transport circumference provided by the two 900-wire tubes in parallel was approximately 30 cm., both as calculated from the diameter of the wires before drawing, and as verified by subsequent

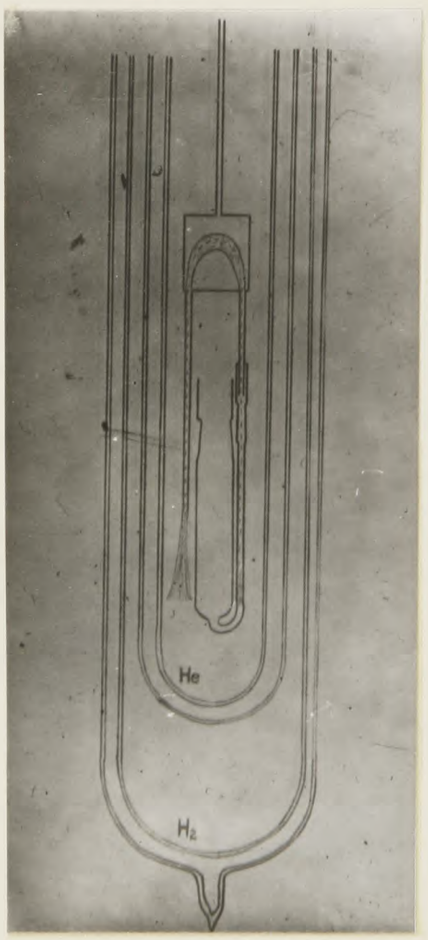


FIG. 8

transport rate measurements on this particular apparatus. The maximum quantity of film which could be carried into the measuring volume by transport can thus be calculated as (cf. fig. 3) 0.135 cc. liquid/min., which is equivalent to 110 cc. gas N.T.P./min.

It was possible to draw the wires somewhat tighter than for the case illustrated here, but difficulty was then encountered in not carrying the operation so far that the transport rate was greatly reduced. One pair of tubes, which was useful in studying the vapour pressure, was drawn which had a rate of pressure rise under test approximately the same as that illustrated above, but a gas leakage of only a quarter as much as this one above the λ-point.

It was found eventually possible to draw tubes to within one or two die-holes of the required size by micrometering the decrease in outside diameter. The final size was then approached carefully by tests at liquid air temperatures alternating with several more drawings on die-plates of small steps.

Application of the Method Developed.

The schematic arrangement of fig. 6 (b) was first given the practical form shown in fig. 8. The helium bath itself served as the container B, while A was a

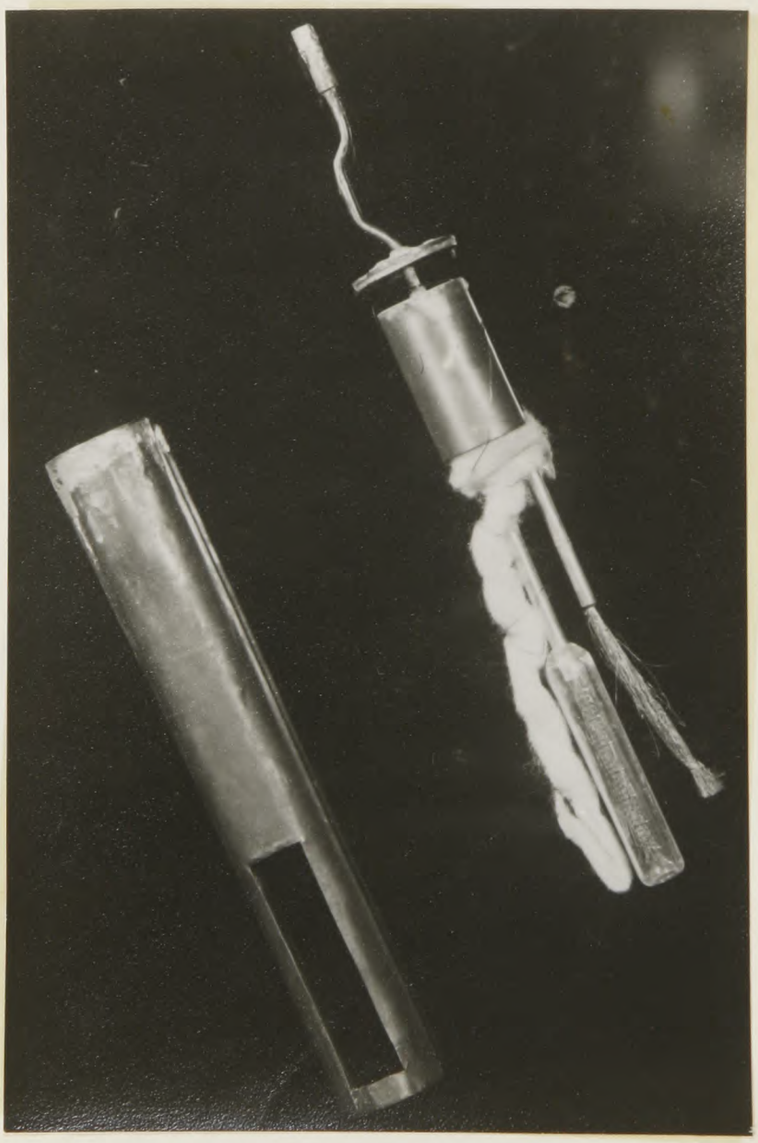


FIG. 9

small brass cylinder, as in the lower right of fig. 7. For C a small glass beaker with etched millimeter divisions and a copper glass seal, similar to that in fig. 13 A, was used. The two filters were provided by a single wire-filled tube from which a portion of the outer case had been removed, leaving the wires in space A (fig. 6) quite free. No difficulty was experienced through wires breaking when being bent after the drawing operation.

The original container C, of fig. 8, having an open top, was replaced first by that of fig. 13 A, and eventually by that in the final arrangement of fig. 9. Here the wire-tube comes directly through a seal into the top of the measuring beaker, being Wood's-metalled to the platinum tube of the seal. A thin blister was blown in the bottom of the beaker to assist in keeping temperature equilibrium. A small hole in the side of the beaker to equalize the pressures inside and out gave rise to an unexpected complication by exhibiting unexpectedly high transfer rates itself. The investigation of this effect is described separately in Chapter IV.

It was found necessary to provide a copper radiation shield as shown in fig. 9, and the cotton wick was added to ensure a covering of film directly on the brass container. The kink in the line running through the top to

the pump prevented radiation coming directly down from higher temperatures at the top of the cryostat.

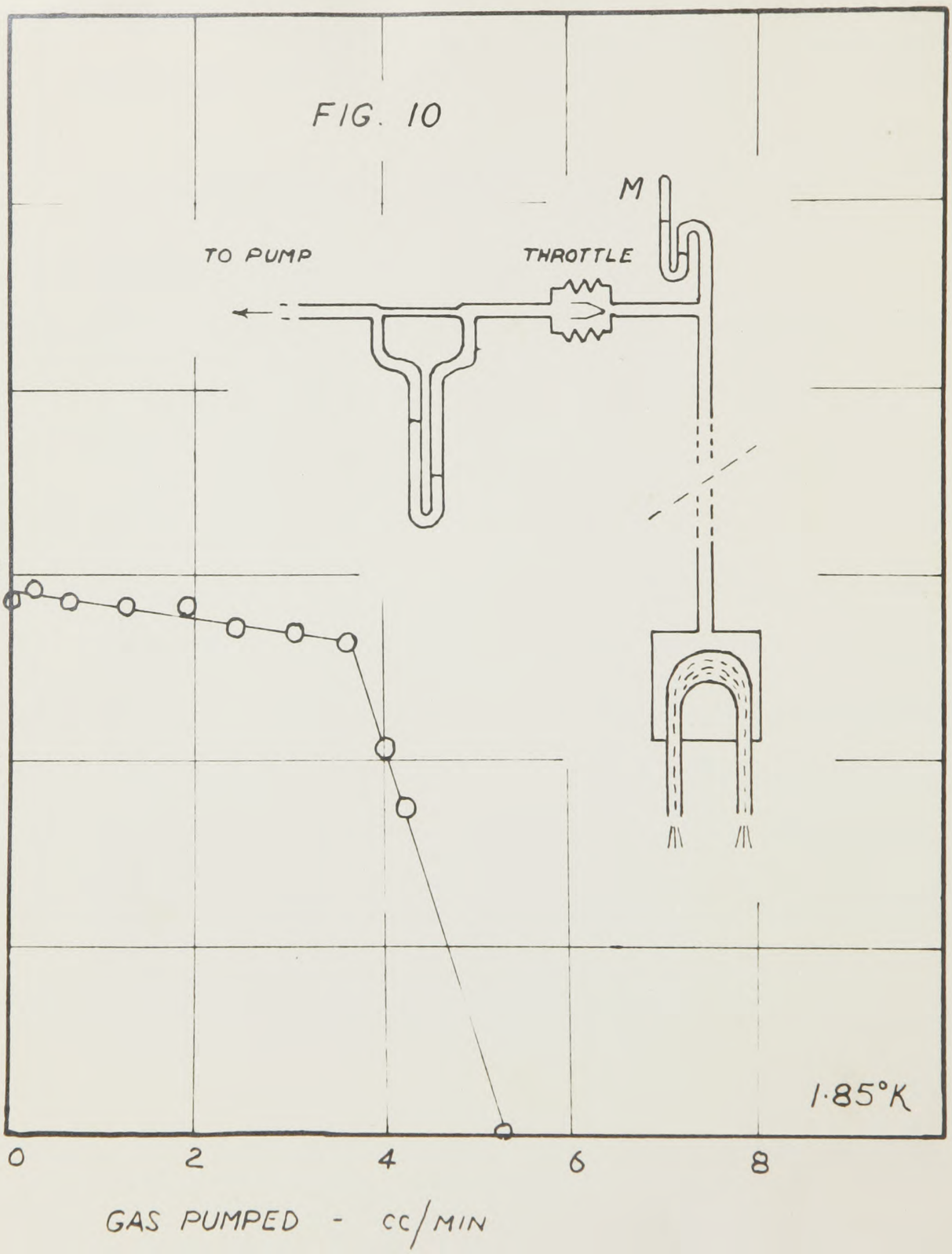
The Vapour Pressure Over the Film.

In the original form of the apparatus without the radiation shield it was found that the pressure in the space over the wires (fig. 8) rose to values sometimes as much as twice that of the vapour pressure of the bath. Tests with temporary radiation shields and lights shone in from the outside verified that the cause of this unexpected behaviour was a slight increase in the temperature of the container over the bath. Ensuring uniformity of temperature as described in the last paragraph of the preceding section resulted in the pressure in the container always coming to equilibrium with the vapour pressure of the bath. The rate at which this equilibrium was established clearly identified it as being brought about by the action of the film itself.

Effect of Vapour Pressure On Transport Rate.

The experiments on the effect on the transport rate of altering the vapour pressure over the isolated film were undertaken as part of a general program to study the latter's properties. While the investigation was in progress, however, a special interest was given to the problem by the

FIG. 10


M
TO PUMP
THROTTLE
1.5
1.0
.5
0
0
2
4
6
8
PRESSURE AT M - CM. HG
GAS PUMPED - CC/MIN
1.85°K

attempt of Born and Green to account for the high mobility of helium films, as outlined in Chapter II. Since in these authors' theory the velocity of the film was directly related to the heat current transverse to its motion, it was clear that experiments in which the vapour pressure, and thereby the evaporation and heat transport, were varied, would be most desirable.

Initial experiments on the transport rate, using the apparatus of fig. 9 in the manner outlined on page 18, with reference to fig. 2, showed that when the pressure in the space A was left undisturbed the transport rate followed closely that earlier determined by Daunt and Mendelssohn for films on amooth surfaces, (fig. 3). It appeared that the entire 14 cm. circumference of the wires was active. Thus it can be seen that a relatively large surface area can be provided in quite a small space, a feature which might be of advantage in connection with a number of problems, as,for example, the separation of the He^3 isotope by super-fluid transfer.

When a pump was connected to A rather unexpected results were obtained. As the pumping rate was increased considerable amounts of gas were removed with little or no observable effect on the transport rate. Suddenly, however, a rate of pumping was reached at which the

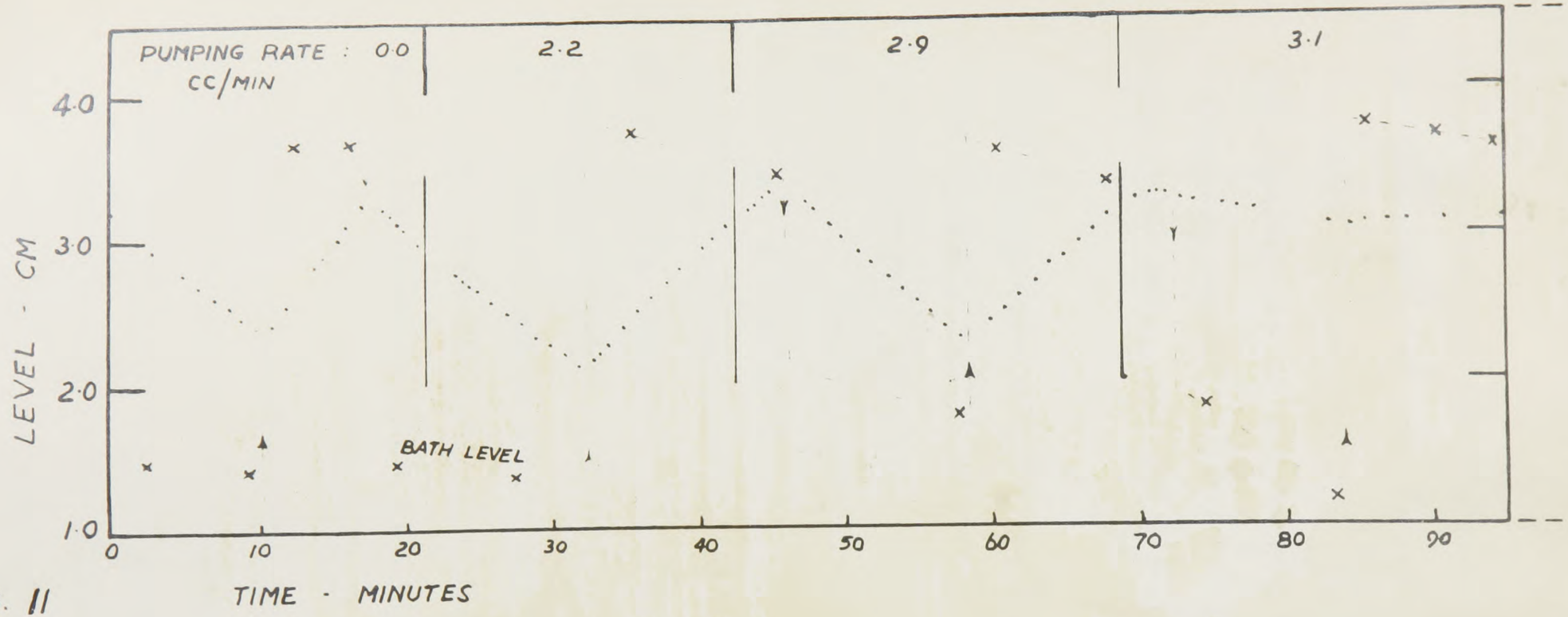
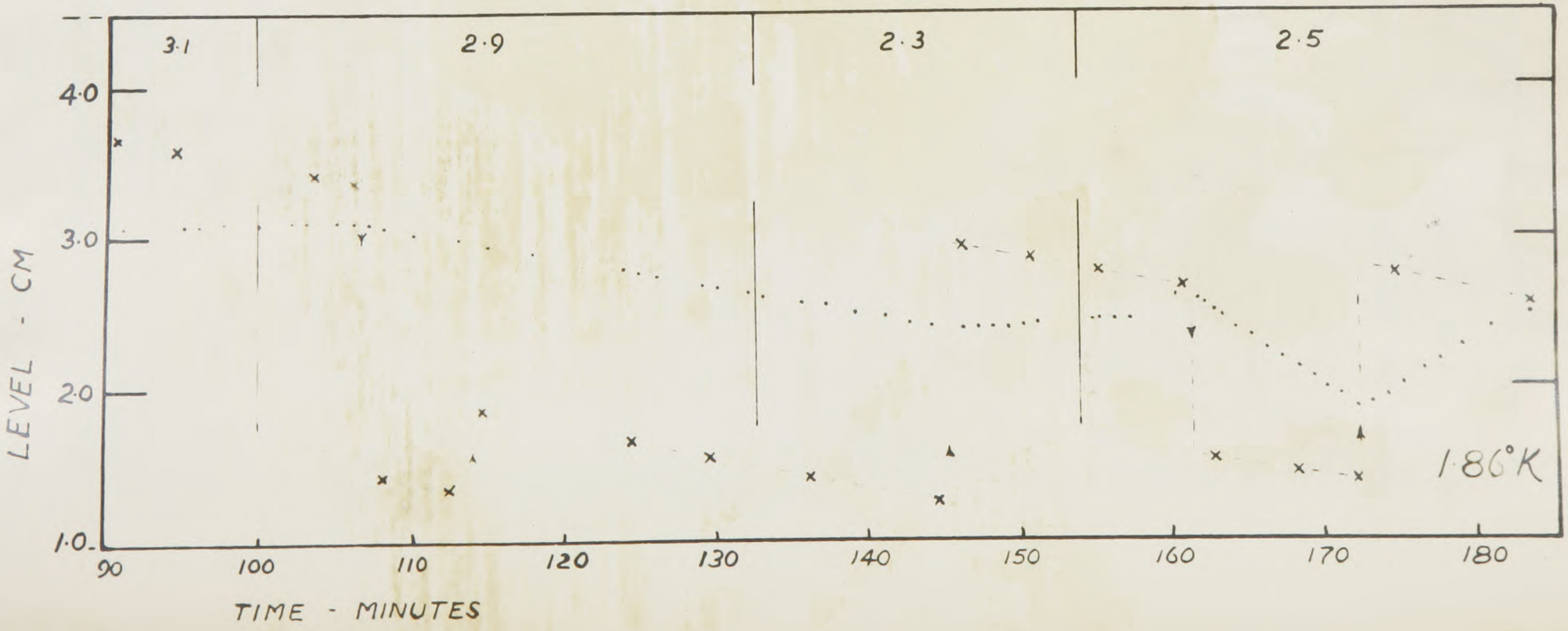

PUMPING RATE : 0·0 CC/MIN
2·2
2·9
3·1
BATH LEVEL
LEVEL - CM
4·0
3·0
2·0
1·0
0
10
20
30
40
50
60
70
80
90
TIME - MINUTES

FIG. 11


3·1
2·9
2·3
2·5
1·86°K
LEVEL - CM
4·0
3·0
2·0
1·0
90
100
110
120
130
140
150
160
170
180
TIME - MINUTES

pressure in A, as measured on M , fell abruptly, and transport ceased. There was no motion of the film, as measured by the rise or fall of liquid in C, in either direction, no matter where the bath level was placed with respect to the liquid level in C.

A flow rate meter and needle valve control were installed as shown in fig. 10, and the relation between the pressure at M, and the rate of pumping determined. The cessation of transport was always seen to coincide with the sudden drop on M, though on different occasions the pumping rate at which this occurred varied slightly.

A typical run showing the rise and fall of level in the measuring beaker while the pumping rate is altered is shown in fig. 11. It will be seen that on this occasion very little alteration in transport rate was encountered until the gas was being pumped at 3.1 cc./min. The small rise and fall then is largely accounted for by the film creep through the pressure equalizing hole, (mentioned above, and later in Chapter IV). It appeared that after the pumping had been again relaxed some time was required for the flow to be resumed.

The probable explanation for the observed results would seem to be as follows. A transport is constantly creeping up the inside walls of the central German silver

capillary tube (2 mm. diameter) from which the transport apparatus is suspended. So long as the pumping rate at the top of this tube is smaller than the rate at which gas is being supplied by the evaporation of this film, and any other evaporation in A caused by stray heat influx, there will be a cushion of gas preventing any appreciable fall of the pressure in A. As soon, however, as this rate is exceeded and the pressure in A begins to fall, transport ceases. The small slope in the first part of the curve of fig. 10, about 1 mm. fall in pressure for a pumping rate of 3 cc./min., is of the order estimated for the drop in pressure across the 70 cm. of 2 mm. tubing, (the temperature distribution is uncertain).

It thus seemed likely that the drop in pressure was associated with a fall in temperature and a resulting thermomechanical effect preventing the film from ascending the wires. As a direct test of this explanation, a phosphor bronze thermometer was mounted between the wires in A. It was found that there was no change in temperature as the pumping was increased until the fall of pressure occurred upon which the temperature recorded fell from 1.85 to 1.56 ^{o}K. It was noted that the amount which had to be pumped off to effect the fall in pressure had now increased several times, due presumably to the fact that more film could be evaporated

directly in A by the extra heat influx down the four thermometer wires, which were of #47 copper.

Conclusions.

A technique has been developed whereby the helium film can be isolated and studied independently of the bulk liquid and associated vapour. The filter developed for this purpose is mechanically strong and relatively easy to construct and combine with other pieces of apparatus. It is small in bulk and yet provides large transport surfaces.

By the use of this filter it has been established that the vapour pressure in equilibrium with the isolated film is the same as that of the bulk liquid at that temperature.

It has been found that altering the vapour pressure over the isolated film appears to set up the thermomechanical effects similar to those already observed in the supra-surface film by Daunt and Mendelssohn. Under these conditions the film appears to be immobilized; in this case opposing thermomechanical pressures developed around the path of the flow do not cancel each other. It seems likely that the film is not pumped away and broken, but rather remains at rest, evaporation being limited by the supply of heat.

CHAPTER IV

Transfer Rates.

1. Introduction.

One of the most striking results reported by Daunt and Mendelssohn[11] in their systematic investigation referred to in Chapter I was the existence of a critical maximum rate of transfer of the helium film. The value established was 7.5×10^{-5} cc./sec./cm., for temperatures below 1.5°K. It constitutes a definite characteristic of the transport phenomenon which must be accounted for by any adequate theory of the helium film. It is important, therefore, that any experimental evidence that would seem to indicate that this critical transfer rate could be exceeded should be carefully investigated.

Daunt and Mendelssohn had noticed in the course of their experiments with cylindrical beakers that while the transfer rate was practically independent of the difference in levels of the liquid inside and outside the beaker, it increased by the order of 20% when the inner liquid level was within about one cm. of the rim of the vessel, (see fig.15b). It had seemed possible that this effect might be an aspect of the approach to thermal equilibrium following the initiation of the flow, particularly as Tisza's[41] considerations had

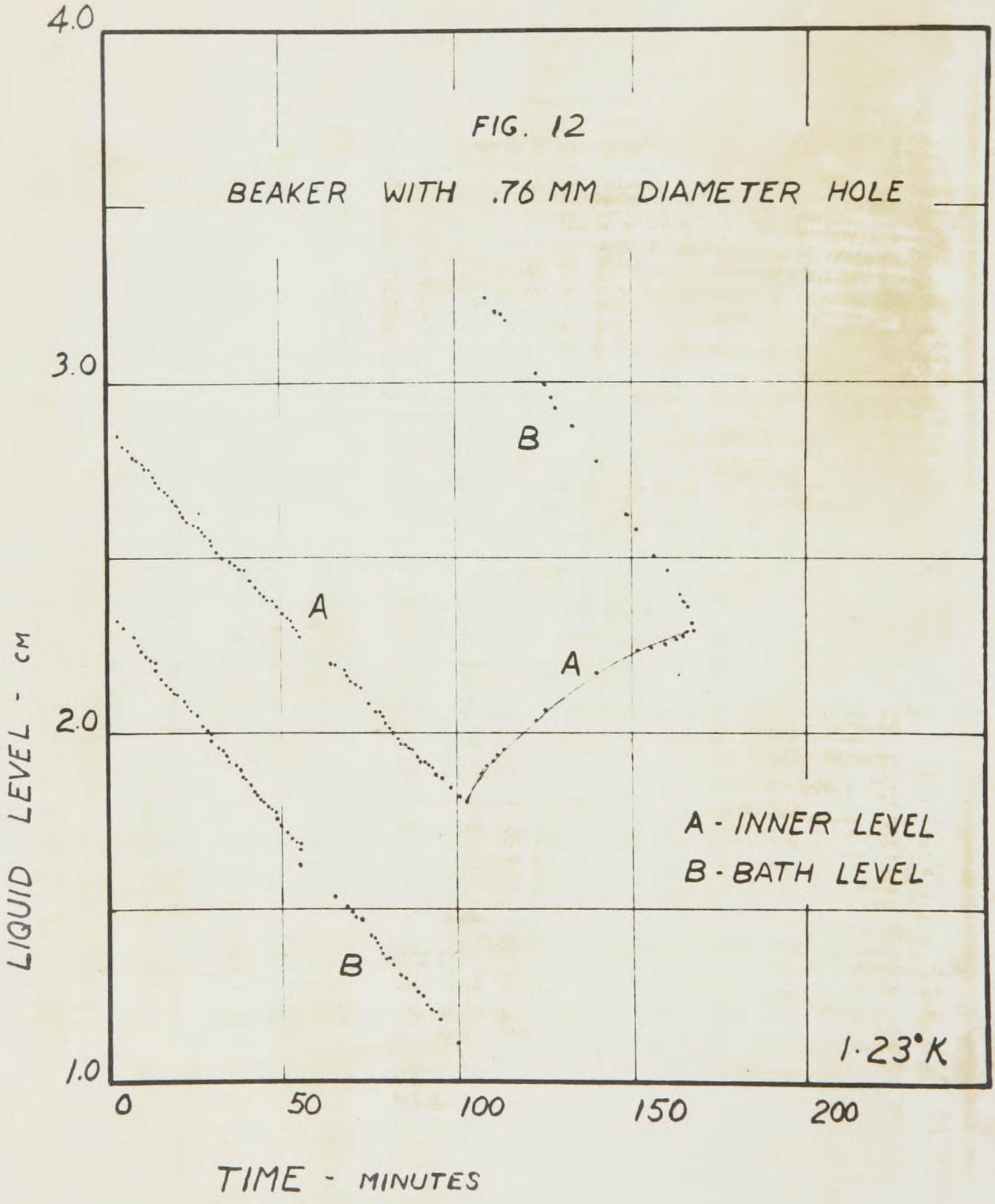


FIG. 12
BEAKER WITH .76 MM DIAMETER HOLE
4.0
3.0
2.0
1.0
LIQUID LEVEL - CM
A
A
B
B
A - INNER LEVEL
B - BATH LEVEL
1.23°K
0
50
100
150
200
TIME - MINUTES

suggested that the critical transfer might be set by the rate at which heat could be supplied to the beaker. It was demonstrated that this was not the case, however, for stopping and starting the flow when the liquid levels were over a cm. from the rim did not give an initial higher rate.

In the case of film transfer under the influence of a temperature gradient, i.e., under conditions analogous to those of the fountain effect of Allen and Jones,[1] Daunt and Mendelssohn[12] found the same critical transfer rate to obtain. The experimental arrangement was as shown in fig. 5, heat being supplied electrically to the liquid in the beaker.

2. <u>High Transfer Rates Through Holes</u>.

In the course of the experiments of Chapter III, abnormally high transfer rates were encountered in the case of a closed cylindrical vessel, the side of which was pierced by a hole of 1.17 mm. diameter. The vessel in question happened to be the small glass beaker of fig. 13A designed to collect the helium coming through the wire-filled tubes. It appeared that even when the tubes were completely blocked there remained a residual flow in and out of the beaker which was of the order of ten times that calculated for the small hole drilled through the copper above the upper glass seal in order to equalize the pressure inside and out.

As the copper glass seals and the soldered joints at

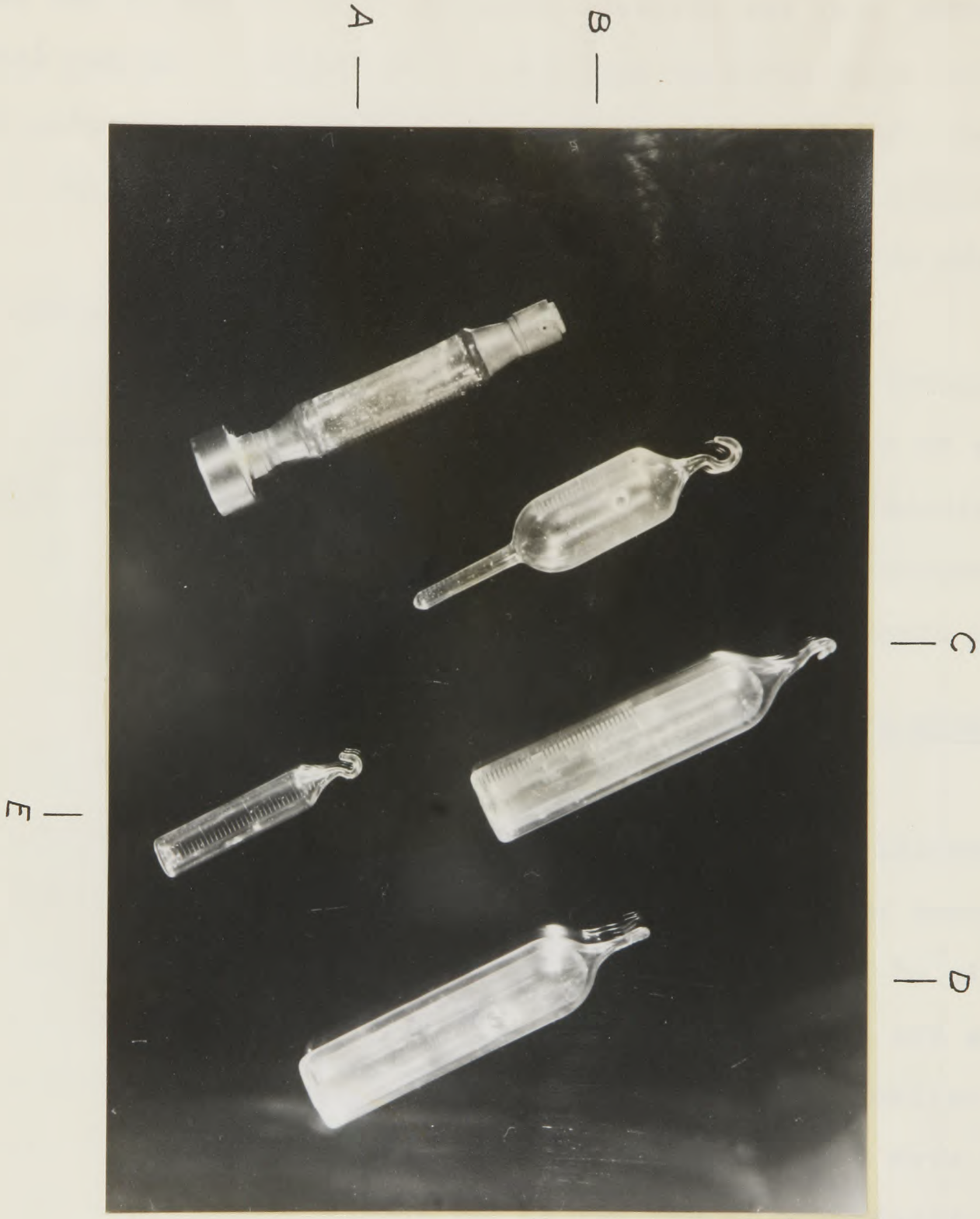


FIG. 13

the bottom of this beaker were suspected as possible "λ-leaks", the vessel was replaced by one having only a single platinum-glass seal, with the pressure equalizing hole of diameter .76 mm. pierced through the glass itself, (fig. 9). The copper bottom was dispensed with entirely, but a thin glass blister was blown and retracted, as shown in the figure, in order to give good thermal contact with the bath. Again, with the wire tubes inactive, a high flow rate through the hole was encountered, this time having a value of approximately 3.6 times the Daunt and Mendelssohn value. A run with this beaker, exhibiting an unexpected inflow curve departing from the usual linear results of Daunt and Mendelssohn, is shown in fig. 12 . It will be seen later how this varying rate of inflow is probably related to the height of the hole above the liquid level.

Following up these observations, tests were made on beakers with holes of approximately .5, 1, 2 and 3 mm. diameter. the results with these will now be described in turn.

The first beaker made especially for this purpose was similar in form to the last one mentioned above in connection with the wire-filled tube experiments, except that the sealed-in tube was omitted entirely. The thin-blown glass bottom was retained, as shown in fig. 13E.

In fig. 14 the transport rates for this beaker are plotted as a function of the height of the hole above the upper

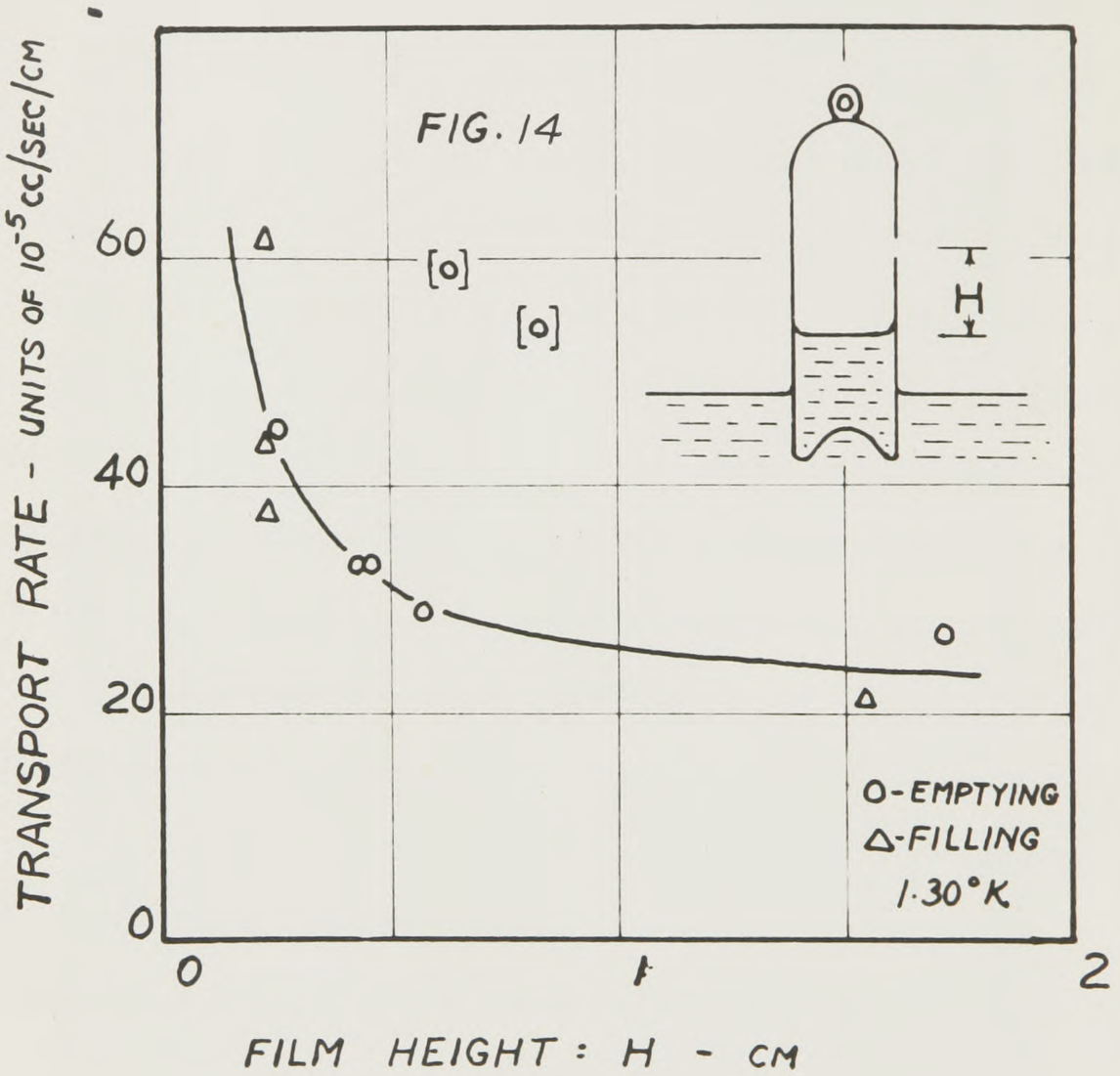


FIG. 14
TRANSPORT RATE - UNITS OF 10^{-5} CC/SEC/CM
60
40
20
0
0
1
2
H
O-EMPTYING
Δ-FILLING
1.30°K
FILM HEIGHT : H - CM

liquid level. It will be seen that if the two points in brackets are excluded there seems to be a decided decrease in transport rate as the height of the film is increased. It is, of course, difficult to measure such small transports accurately, and the curve drawn should be considered tentative in this case, but the exclusion of the two points off the curve is not considered unduly forced in that on this one occasion the hydrogen bath in the cryostat was necessarily unusually low, having come actually down into the open glass tail of the Dewar vessel.

In order to facilitate measurement of the liquid level change, from which the flow rate is determined, while at the same time maintaining a large surface in the vicinity of the transport hole, a second beaker was constructed with a small tail appended, as shown in fig.13B. The hole in this case was 1.07 mm. in diameter. The results obtained were unsatisfactory, however, because during the liquefaction of the helium the beaker was incidentally filled above the narrow tail, and when this had been done the time required to drain it to the tail would have been a full 10 hours. Flow rates determined from the rise and fall of the liquid in the large cross-section were difficult to measure, but appeared to agree approximately with the value 7.5×10^{-5} cc./sec./cm., rather than with the larger rates encountered with the previous holes.

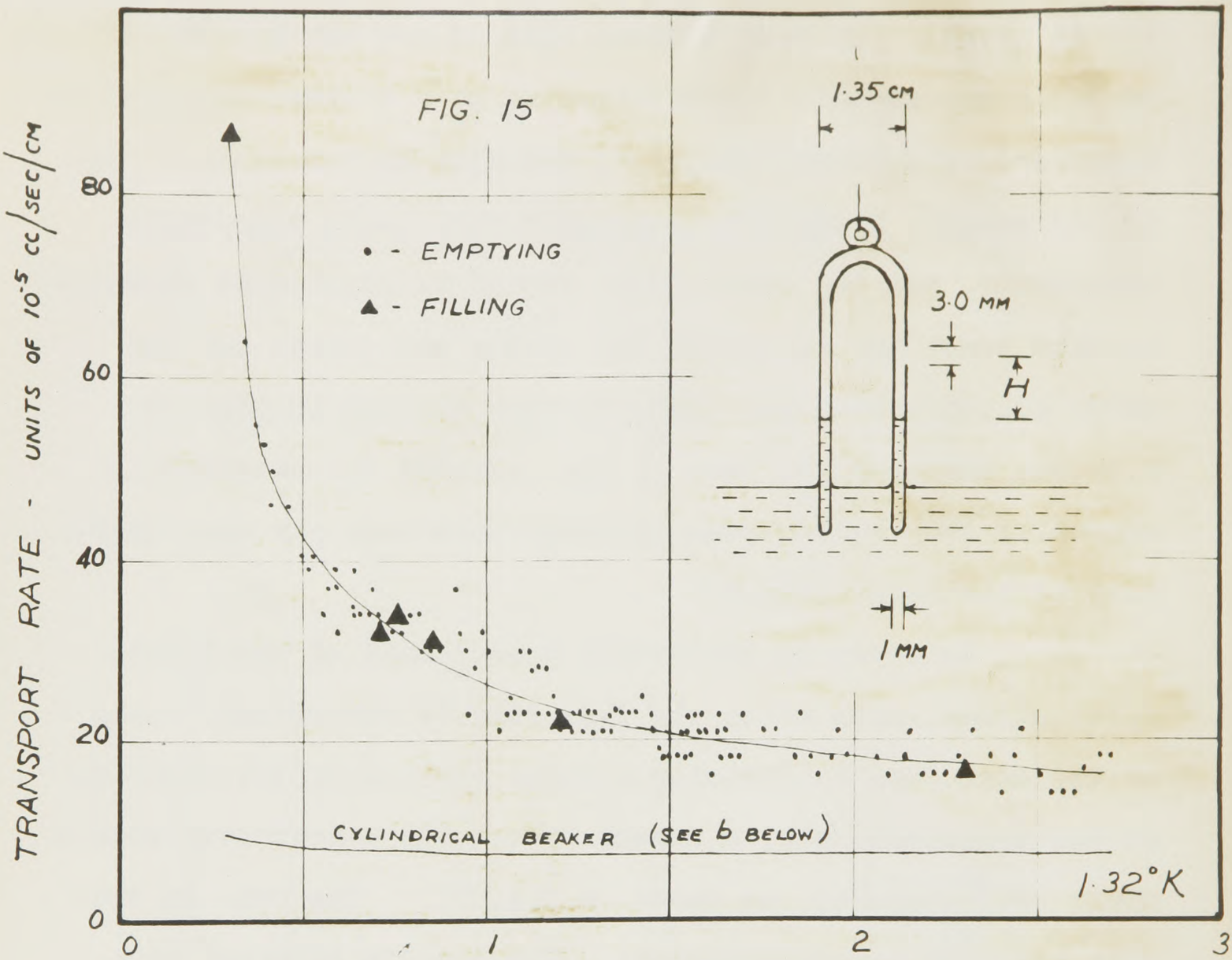


FIG. 15
TRANSPORT RATE - UNITS OF 10^{-5} CC/SEC/CM
• - EMPTYING
▲ - FILLING
1·35 CM
3·0 MM
H
1 MM
CYLINDRICAL BEAKER (SEE b BELOW)
1·32°K
0
20
40
60
80
0
1
2
3
FILM HEIGHT : H - CM

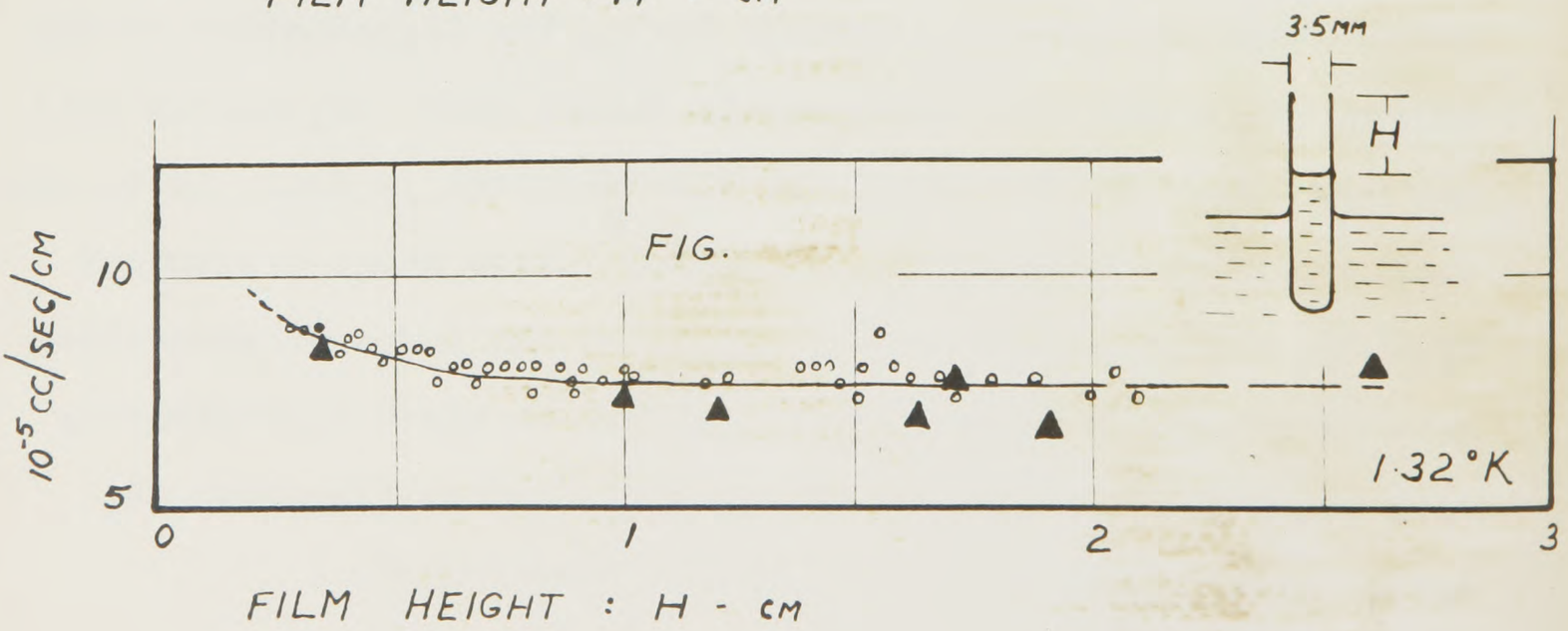


FIG.
10^{-5} CC/SEC/CM
3·5MM
H
1·32°K
5
10
0
1
2
3
FILM HEIGHT : H - CM

To overcome these difficulties in measurement, two beakers were then constructed with considerably reduced but uniform cross-section by sealing in a co-axial inner tube, as shown in fig.13C,D. It was decided to make an extensive investigation of the larger one, having a hole of 3.02 mm. diameter, since the flow rates could be measured most accurately with it. The smaller one, having a hole of 1.07 mm. diameter, was found to give a transport rate of 16.6×10^{-5} cc./sec./cm. when the hole was about 2 cm. above the upper liquid level, or about 2.2 times the standard rate of 7.5×10^{-5} cc./sec./cm. This result agrees approximately with that found for the larger beaker, for which the detailed results are given in fig.15 .

While the beaker was emptying, the height H was steadily decreasing. The outflow rates were therefore taken over 3 minute intervals, the H for each interval being taken as the average during the 3 minutes. While the beaker was filling, however, H was decreasing only very slowly, being set by the outside bath level. The inflow rates were thus determined over somewhat longer intervals, usually of the order of 10 minutes, although readings were actually taken every minute and the results plotted.

It can be seen from fig.15 , that when the height of the hole above the upper level is greater than about 1.5 cm., the observed rate of transfer is again almost constant. Its

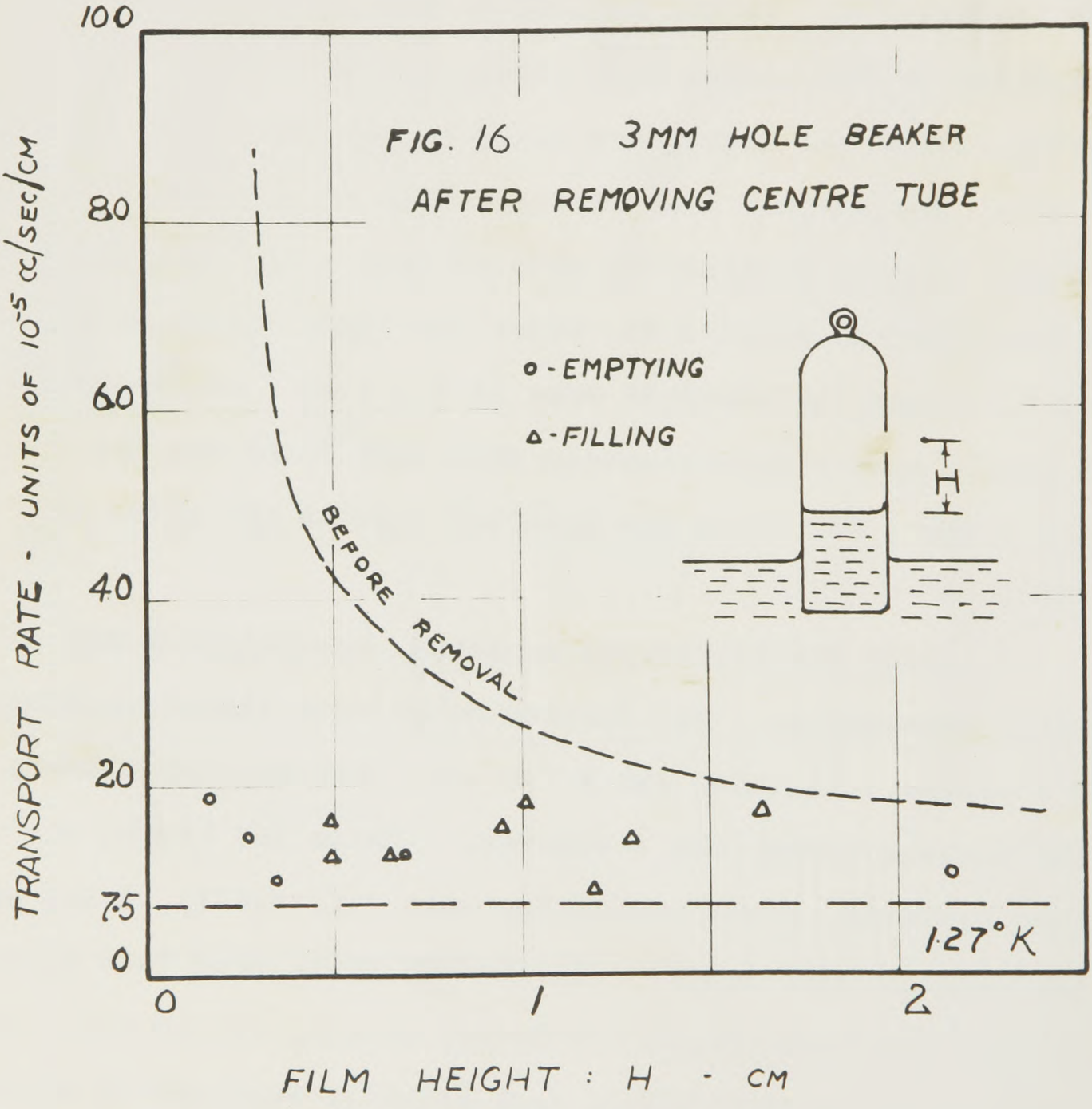


FIG. 16 3MM HOLE BEAKER
AFTER REMOVING CENTRE TUBE
o - EMPTYING
Δ - FILLING
BEFORE REMOVAL
H
1·27°K
TRANSPORT RATE - UNITS OF 10^{-5} CC/SEC/CM
100
80
60
40
20
7·5
0
0
1
2
FILM HEIGHT : H - CM

value, however, taking the circumference of the hole as the limiting perimeter, is about 2.4 times larger than the rate of transfer in a cylindrical beaker. As the height of the hole above the liquid is reduced below 1.5 cm. the transfer rate increases steadily until eventually the liquid seems to pour directly through the hole. The rates were substantially the same whether the liquid was flowing into the beaker or out of it.

For purposes of comparison, the transfer rate dependence on height was measured for a cylindrical beaker under identical conditions. The results, given in the lower curve, are in full agreement with the previous results of Daunt and Mendelssohn.

Because of the unusual nature of the results obtained with the last two beakers with holes in the sides, it was decided to test the 3.02 mm. one with the central tube removed, in case this particular type of construction had introduced any new factor. The removal of this tube meant returning to the former difficulties of measuring very slow level changes, but sufficient results were obtained to enable plotting the graph of fig.16 . Here the full line is taken from the previous results before removal of the tube, as shown in fig.15 .

As expected, the scatter of the experimental points is now seen to be greatly increased. While removal of the tube has entailed slightly shortening the beaker, preventing

measurements with the largest values of H, it is quite clear that the sharp rise in transport rate at small values of H is not now present. The average value of the transport rate, however, is still approximately double that for a cylindrical beaker.

Neither for these results nor for the previous ones with the central tube in place did there appear to be any correlation of the transport rate with the difference in liquid levels, or the position of the lower one, as distinct from the height of the hole above the upper liquid level.

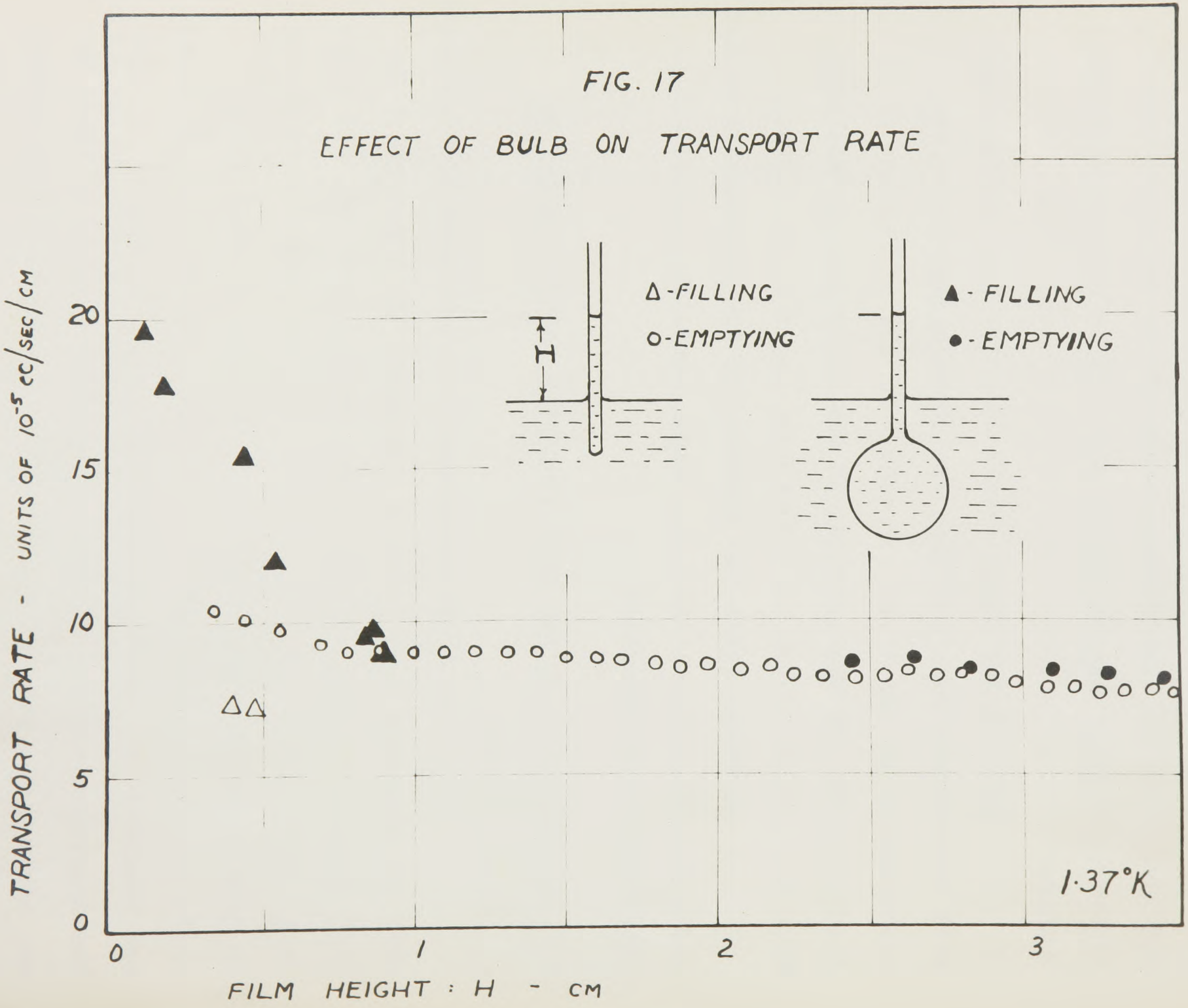
We shall leave the question of the explanation of the above phenomena until the other experiments on high transport rates have been described.

3. Investigation of the high transport rates reported by K. R. Atkins.

While the above experiments on transport through holes were in progress, K. R. Atkins reported the observation of high transport rates in capillaries ending in bulbs, and under temperature gradients. The first of these experiments seemed to have a possible connection with the flow through holes, while the second appeared to be in conflict with that of Daunt and Mendelssohn mentioned above and shown in fig. 5 . It was therefore decided to make experiments similar to those of Mr. Atkins, who very kindly furnished unpublished experimental

FIG. 17

EFFECT OF BULB ON TRANSPORT RATE



details.

For the first type of experiment, using capillaries ending in bulbs, we selected a 1.08 mm. inside diameter capillary whose transport rate we had recently measured very carefully. A bulb of 1.6 cm. diameter was blown on the end of it, and the transport rates again measured. Both sets of results are plotted in fig. 17 against height of the rim above the upper liquid level.

It will first be noted that before addition of the bulb the transport rates, with the beaker filling or emptying, do not increase appreciably as the film height H is reduced. (The slightly larger value of the emptying rate at .4 cm. is possibly due to evaporation, and will be discussed later.) This result is in agreement with that for the larger cylindrical beaker mentioned above, (fig. 15b), and the previous work of Daunt and Mendelssohn.

After the bulb had been added, the transport rate did appear to be larger as the rim was approached, but not until within 1 cm. The large increase observed by Atkins is not present. For a .54 mm. diameter capillary ending in a 3 cm. diameter bulb, Atkins obtained a transport rate of approximately 28×10^{-5} cc./sec./cm. at 3 cm. from the rim, rising to 40×10^{-5} cc./sec./cm. at 1 cm. from the rim.

It was learned that Atkins' capillary was of the thick walled type supplied commerically, with the outer

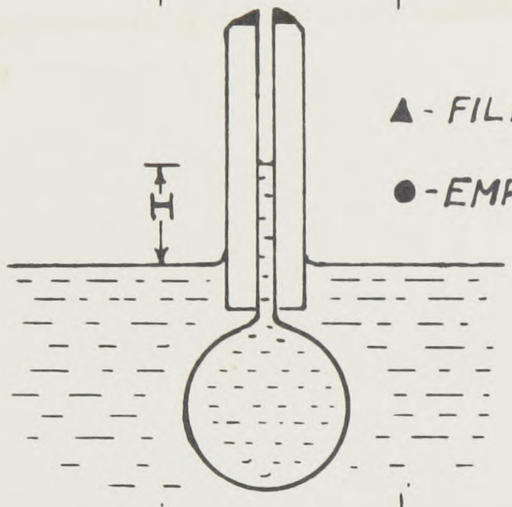
FIG. 18

diameter approximately ten times the inner, rather than drawn to a thin wall, as was the one used above. Since the previous experiments with the holes had suggested that the presence of a large surface covered with film, and immediately connected with the limiting perimeter, might be important, it was decided to repeat the experiment under these conditions. The calibrated capillary was retained, but a larger piece of glass tubing which would just slip over it was cemented in place at the upper end, as shown in fig. 18 . The outside diameter of this sleeve was 7.2 mm.

The results are shown in fig. 19 . In order to effect good contact between the sleeve and the capillary, the cement had been allowed to come part way down their adjacent surfaces, and consequently the liquid level could not be seen at the top end. Emptying rates therefore could not be determined as close to the rim as before, but of course filling ones could still be. It is clear from the points obtained that no significant increase in flow rates has been obtained. In fact, the effect would seem to be merely that of a slightly increased emptying rate and slightly decreased filling rate. Such an effect might be caused by an increase in evaporation from the capillary due to the larger amount of radiation intercepted by the sleeve.

The second type of arrangement employed by Atkins was similar to that of fig. 5 , except that the beaker was in the

FIG. 19 EFFECT OF ADDING SLEEVE TO CAPILLARY WITH BULB



▲ - FILLING

● - EMPTYING

TRANSPORT RATE - UNITS OF 10^{-5} CC/SEC/CM

20
15
10
7.5
5
0

0 1 2 3

FILM HEIGHT : H - CM

form of a small glass Dewar flask having a ground lip against which was pressed a glass cap with a ground flange. The only communication between the helium bath and the inside of the Dewar flask was via this ground joint, but the width of the gap was much greater than the thickness of the film.

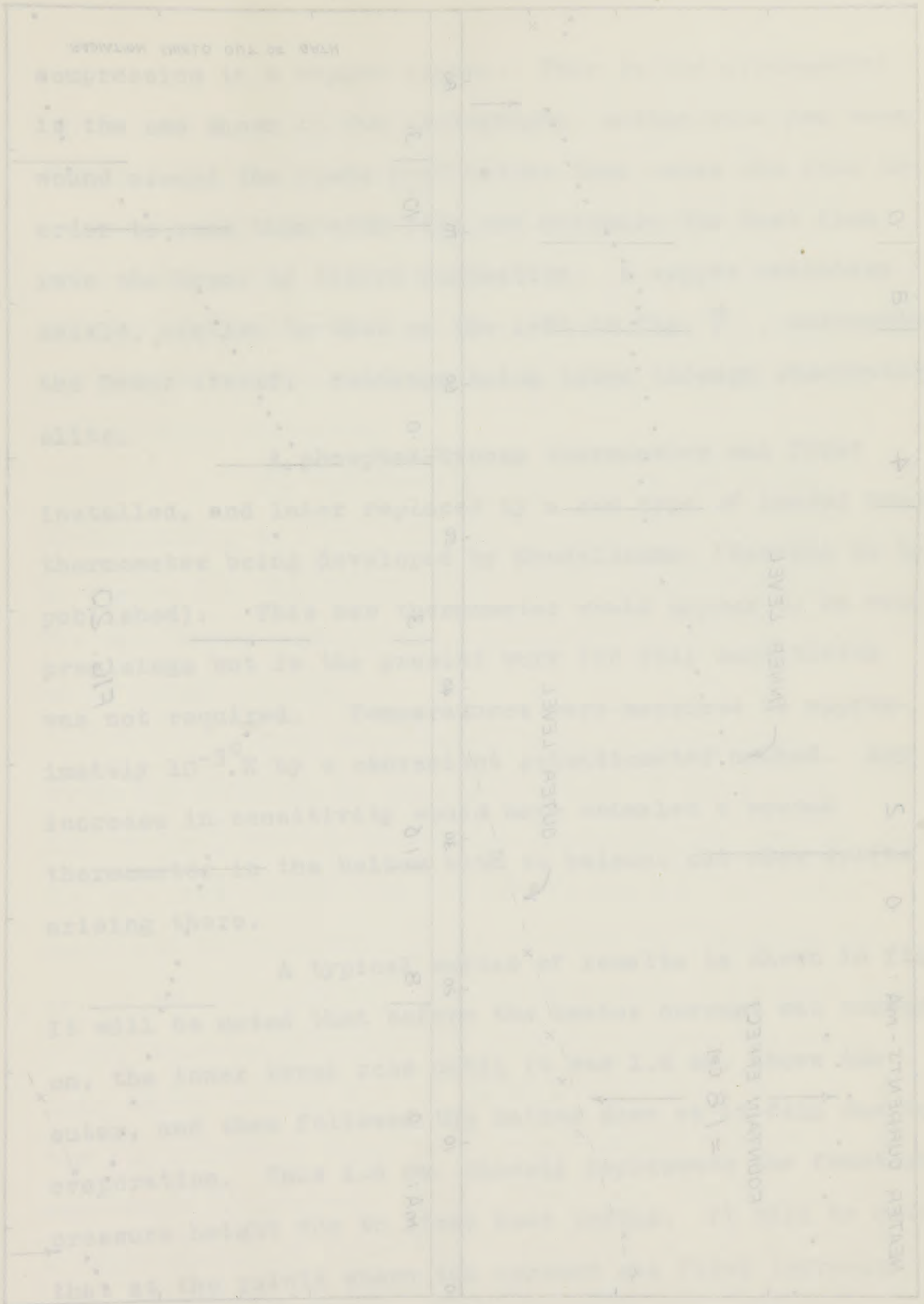
Since with this arrangement evaporation was greatly reduced by the ground joint, somewhat greater temperature differences between the inside and outside liquids, than were possible with the arrangement of fig. 5 , could be maintained. Atkins found that the transport rate increased with increasing temperature difference up to about 10^{-3}°K, at which point saturation occurred at a velue of 38×10^{-5} cc./sec./cm., or about five times the value of 7.5×10^{-5} cc./sec./cm.

There was one particular objection to Atkins' experiment in that the Dewar arrangement introduced doubt as to which circumference to take as the limiting perimeter. The outside circumference was necessarily several times larger than that on the inside end of the ground joint on Atkins' Dewar vessel, but right through the ground joint to this inside rim there were of course two walls on which transport could take place. Thus it would seem that the limiting perimeter would occur just at the inside, where the film emerged from the joint and crept down into the vessel.

If for any reason, however, the film flow were not limited at this point, one might obtain transports several times larger, limited only by the rate at which film could creep up the outside wall of the Dewar.

To avoid ambiguities suggested by the above considerations, the cap of the Dewar vessel in our arrangement was joined to an extra tube down which the film could flow from the upper side of the ground glass joint. In this way the combined inner surfaces could be made equal to that of the outer. The apparatus is shown on the right in fig. 18 A small hole has been made in the upper end of the central tube just below the ground joint to prevent any difference in pressure inside and outside it. An experiment to be described later in this chapter (p. 49-50) has shown this precaution was unnecessary.

Leads for the constantan heater (approx. 50 ohms) and the thermometer were of number 47 copper wire brought directly down the liquefier through a moveable German silver tube from which the apparatus was suspended. In the first series of tests this tube itself entered the top of the transport Dewar vessel through a copper-glass seal. In the later runs, however, the Dewar was isolated from the tube, and the leads were brought in through a small multiple seal of platinum in lead glass, the lead glass being sealed by



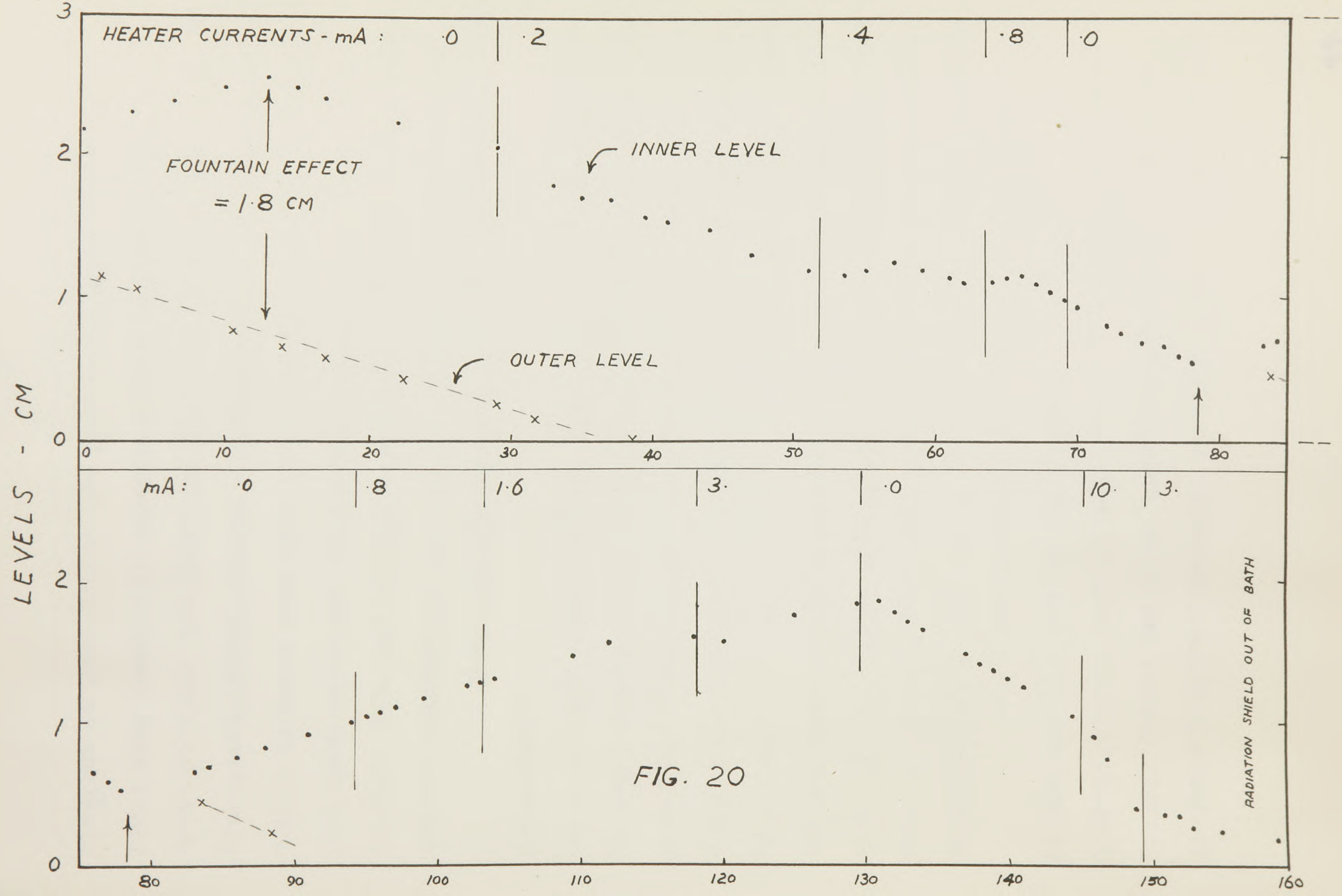

HEATER CURRENTS - mA : ·0 ·2 ·4 ·8 ·0
FOUNTAIN EFFECT
= 1·8 CM
INNER LEVEL
OUTER LEVEL
LEVELS - CM
TIME - MINUTES
mA : ·0 ·8 1·6 3· ·0 10· 3·
RADIATION SHIELD OUT OF BATH
1·37° K

FIG. 20

compression in a copper sleeve. This latter arrangement is the one shown in the photograph; cotton wool has been wound around the leads just before they enter the seal in order to soak them with film and minimize the heat flow into the Dewar by direct conduction. A copper radiation shield, similar to that on the left in fig. 9 , surrounded the Dewar itself, readings being taken through observation slits.

A phosphor-bronze thermometer was first installed, and later replaced by a new type of leaded brass thermometer being developed by Mendelssohn, (details to be published). This new thermometer would appear to be very promising, but in the present work its full sensitivity was not required. Temperatures were measured to approximately $10^{-3}{}^{\circ}$K by a convenient potentiometer method. Any increase in sensitivity would have entailed a second thermometer in the helium bath to balance out slow drifts arising there.

A typical series of results is shown in fig. 20 It will be noted that before the heater current was turned on, the inner level rose until it was 1.8 cm. above the outer, and then followed the latter down as it fell due to evaporation. This 1.8 cm. clearly represents the fountain pressure height due to stray heat influx. It will be noted that at the points where the current was first increased to

.4, .8 and 3 mA., the rise in fountain height reversed the direction of flow from out to in. The rate of flow, however, is seen to have been practically unaltered by any heater current up to the last one applied, 10 mA., upon which a rapid evaporation set in. That this effect was an evaporation and not an increased flow was established by later runs in the opposite direction.

The temperature rise inside the Dewar corresponding to even 3 mA. is far greater than that required by Atkins for saturation flow, being approximately 35×10^{-3} K. The saturation temperature, approximately 10^{-3} K, corresponded to .5 mA. current.

From the dimensions of our apparatus, for which the diameter of the outside edge of the ground joint was .98 cm., and the net inside cross section .382 sq. cm., the expected rate of rise in the beaker calculated from Daunt and Mendelssohn's value of 7.5×10^{-5} cc./sec./cm., is .36 mm. per minute. The average values obtained in most of the experiments described here agreed satisfactorily with this value, except that on several days there was a tendency for the transport rates to be considerably reduced as the experiment progressed. This effect was probably caused by a small amount of impurities condensing on the surfaces of the ground glass joint. Applying large heat inputs on these

occasions caused temporary rapid decreases in level, but were otherwise without effect.

The general result of all the experiments conducted was that, except for the apparent evaporation of liquid at excessive heat inputs, the transport rate was completely independent of the temperature difference between the liquid inside the Dewar vessel and out. This result directly confirms the experiment of Daunt and Mendellssohn mentioned previously, (p. 9). A possible explanation for the discrepancy between this result and that of Atkins will be discussed later.

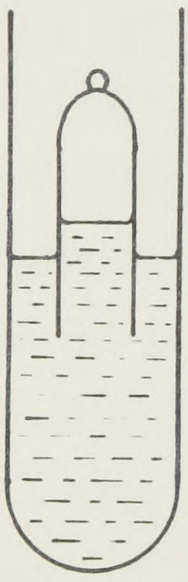
Other Experiments on the Transport Rate.

A number of individual experiments were performed in order to gain some insight into possible reasons for the observed high transport rates, and to eliminate some suggested causes for the discrepancies with Atkins' measurements in particular.

One experiment was performed to discover whether or not roughening the glasss surface over which the transport took place in a cylindrical beaker would affect the rate. It was considered possible not only that the transport might increase due to an increase in effective surface, such as that observed by Daunt and Mendelssohn[11] for drawn

copper wires, but that rather a reduction might be produced by the interruption of specular reflection of helium "atoms" from the glass wall. For this purpose, the outer and inner surfaces of the 3.5 mm. diameter beaker previously calibrated (fig.15b) were ground to a matte finish with carborundum powder for a distance of approximately one cm. from the rim. The transport rate with the roughened beaker was found to be identical, to within 3%, with that originally obtained.

Another experiment was performed with one of the small umbrella-like beakers shown on the left of fig.18. Here a thin-walled capillary of .74 mm. inside diameter had sealed around its lip a skirt of one cm. maximum diameter, so that a large surface carrying film was directly connected with it. The effect would therefore be similar to that of adding the outer sleeve to the capillary with the bulb, shown next to the umbrella-like beakers in fig. 18. The emptying rate with this beaker, whether the outer level were above or below the bottom of the skirt, was about 20% greater than the filling rate, which, when the skirt was immersed, corresponded approximately to the usual transport rate of 7.5×10^{-5} cc./sec./cm. With the skirt just clear of the bath, however, the beaker would sometimes not fill at all. It would thus seem likely that the main effect of adding the skirt had been simply to increase the evaporation rate of the film.

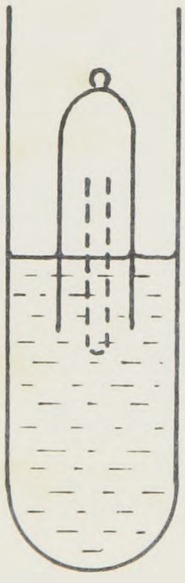


HE I:

INNER LEVEL $\frac{1}{2}$CM ABOVE BATH

FOLLOWS WITH TIME LAG ~1 SEC

FIG. 21



HE II:

INNER LEVEL FIXED AT BATH LEVEL

FOLLOWS WITH NO DISCERNABLE LAG

Jackson had reported, as mentioned in Chapter 1, (p.10), the observation of what appeared to be thick masses of film on shutting off the pump over the helium bath. It was therefore decided to make measurements of the transport rate under these conditions. It took approximately two minutes after shutting off the pump for the cryostat to warm from 1.32 to 1.5°K, at which point the transport rate, as determined by Daunt and Mendelssohn, is still at its maximum value, (fig.3), and a further four minutes to reach 1.9°K, where the rate is approximately half the maximum. Numerous tests of this kind were made, with the beaker emptying and filling, and in no case was any unusual transport rate observed.

As a related experiment under more easily controlled conditions, the transport rate was later also measured while a glass hood was placed over the beaker, as indicated by the dotted lines, in fig.21 . Here any vapour evaporating from the surface of the beaker or the bath in the immediate vicinity was forced to condense in the same neighborhood, instead of being pumped away. Again no influence on the transport rate was found, but a most interesting phenomenon was encountered, as shown in fig.21 .

When the temperature of the bath was below the λ-point, it was impossible to produce any difference

between the levels inside and outside the hood. Even when the hood was raised as quickly as possible (at several cm. per second) clear of the bath, or pushed down equally quickly, completely under the surface, no difference between the two levels could be observed, even momentarily.

With the beaker half-immersed, the cryostat was allowed to warm up slowly. Just as the λ -point was reached, the liquid level inside the hood suddenly jumped up about one-half centimetre above the outer. On raising and lowering the hood, it was now found that while this half a centimetre level difference always re-established itself, it could easily be seen to lag by about a second behind any sudden shift in level of the hood, the inner level tending to follow the motion of the hood. On shining a 100-watt electric light bulb directly into the cryostat, the inner level was observed to fall in several seconds almost to the outer, and remain there. On removing the lamp, the inner level rose again, in a somewhat longer time, but only to 3 or 4 mm. above the outer.

It is clear from the above tests that above the λ -point the inside of the hood was initially about $5 \times 10^{-4}{}^{\circ}$K cooler than the outside, as measured by the difference in vapour pressure. Below the λ -point, however, the two temperatures were as nearly as could be seen the same,

and when the vapour was subjected to a slight under-pressure or over-pressure the heat conductivity of the helium II was so great that condensation or evaporation could take place apparently instantly.

The fact that a measureable time was taken for the levels to attain equilibrium when the hood was moved in helium I, whereas it was reached so rapidly as to be undetectable in helium II, is a direct evidence of the great thermal conductivity of helium II, as compared with helium I. It is interesting that in this case the thermal contact concerned is directly between the free liquid and the vapour, and no question arises as to the heat contact between the liquid and a solid, as has been a difficulty in former experiments. Compare, for example, Meyer and Mellink's [34] criticism of Kapitza's experiments on thermal conductivity of the free liquid.

Conclusions:

The experiments with the hole beakers have established that with certain unusual geometrical arrangements high transport rates can occur. The dependence on the size of the hole is not marked, but it would appear that higher rates are associated with the smaller holes. It seems possible that there is a dependence on the inner

surface of the beaker, particularly for the highest transfer rates encountered when the hole is nearer the bulk liquid. Such a dependence would certainly seem to have some relationship to Atkins' observations on the effect of bulbs.

There are no signs, however, of the greatly increased transport observed by Atkins when a bulb is attached to a long capillary. Clearly more experiments are required to elucidate these discrepancies, and there are indications of unexplored factors not disclosed by previous experiments on frictionless transport.

The very fact that different cryogenic techniques are followed in different laboratories must be borne in mind. For instance, the practice in some laboratories of dispensing with the hydrogen bath around the cryostat leads to much higher evaporation rates, and both the observations of Jackson on thick films and the tentative Born-Green explanation of the creeping film show a possibility of this being a significant factor.

Another possibility, which can not be excluded as yet, is the effect of any thin layers of adsorbed or condensed impurities on the surface of the transport vessels. On occasions it is possible to see

small amounts of foreign matter floating in the helium, presumably due to gases, such as hydrogen, which have come past the charcoal cleaners in traces, or entered through leaks on the cryostat. In general, however, and in particular for some of the experiments in which high transfer rates have been observed through holes, the liquid helium has been clean so far as the eye can tell.

A factor which can be excluded as responsible for high transfer rates is the simple proximity of a large surface to the edge of a cylindrical vessel, such as was demonstrated with the thick sleeve added to the thin-walled beaker attached to the bulb (p.42), and by the experiments on the umbrella-shaped vessels, (p.48).

It is also possible to exclude from consideration the effect of conditions where the vapour evaporating from the bath could condense on the transport surfaces. This was demonstrated both by the measurements made after cutting off the pump from the bath, and those carried out under the glass hood, (p.49).

An explanation can now be suggested for the apparently high transport rates observed by Atkins, but not by us, in the experiment with the heater in the Dewar vessel having a ground joint. It would appear that the source of

the discrepancy lies in the ambiguous geometry of Atkins' transport vessel, where it is necessary to decide whether the inner or outer circumference of the Dewar is taken as setting the limit on the film flow. The saturation value of high transport with Atkins' arrangement occurred when the temperature inside had been raised by an amount such that the corresponding fountain effect height was of the sane order as the values of film height, H, which he used. In this connection it should be noted, too, that the zero calibration of the thermometers would be such that this recorded temperature increase was additional to any due to stray heat influx apart from that supplied electrically. Such stray heat influx can be sufficient to provide quite significant fountain heights, as for example, that shown at the beginning of the run in fig.20. (and it is to be noted that Atkins had, in fact, observed part of the reported increase without any current in the heater). Thus the conditions would be such that bulk liquid could exist in the slit formed by the ground glass joint. It is noted, too, that Atkins' ground joint was horizontal, being right on the lip of the Dewar, though with the very narrow spacing of the joint, surface tension could probably hold liquid there in any case. Now the experiments of Meyer and Mellink,[34] and Kapitza,[20] have

shown that bulk liquid in a slit can give transport rates, and possibly even velocities, very much larger than those of supra-surface films. It would therefore seem that the limit to the transport would not be set by the inside circumference of the slit, for bulk liquid could fall down the walls here, and gas could penetrate into the slit as far as the liquid present. Rather, the limit would be the rate at which film could creep up the outside wall of the Dewar. The actual dimensions of Atkins' transport vessel are in accord with such an explanation. The fact, that, when this geometrical ambiguity had been avoided with our Dewar arrangement, no high transport rates were observed, makes the explanation given here seem feasible.

As a final conclusion, it may be mentioned that the observations on the rate of condensation of vapour over helium I and helium II, as shown in fig.21 , provide a direct qualitative demonstration of the high thermal conductivity of helium II as a free liquid, apart from any sub-surface films. It is possible that this experiment could be refined to give quantitative results.

ACKNOWLEDGEMENTS.

It is a pleasure here not only to acknowledge the guidance of my supervisor, Dr. K. Mendelssohn, and his valuable assistance throughout the course of these investigations, but also to record my gratitude to him for initiating me into the field of low temperature research.

BIBLIOGRAPHY

(This bibliography is not exhaustive, but is intended merely to give representative references pertaining to the text.)

1. J. F. Allen and H. Jones, Nature, 141, 243, 1938.
2. J. F. Allen and A. D. Misener, Nature, 141, 75, 1938.
3. _____, Proc. Roy. Soc. A., 172, 467, 1939.
4. J. F. Allen, R. Peierls, and M.Z. Uddin, Nature, 140, 62, 1937.
5. E. Andronikashvilli, J. of Phys. U.S.S.R., 10,201, 1946.
6. K. R. Atkins, Clarendon Lab. Conference, June 28, 1947.
7. K. R. Atkins, Nature, 161, 925, 1948.
8. A. Bijl, J. de Boer, and A. Michels, Physics, 8,655,1941.
9. M. Born, Royal Society Lecture, 26 July, 1947.
10. M. Born and H. S. Green, Proc. Roy.Soc.A, 191,168,1947.
11. J.G. Daunt and K. Mendelssohn, Proc. Roy.Soc., A, 170,423,1939.
12. _____ Nature, 143, 719, 1939.
13. _____ Nature, 157, 839, 1946.
14. _____ Journal of Sci.Instr.25, 318,1948.
15. J. G. Daunt, R.E. Probst, H.L.Johnston, J.Chem.Phys. 15, 759, 1947.
16. H. Fröhlich, Physica, 4, 639, 1937.
17. H. S. Green, Paper, Clarendon Lab. Conference, June 28/48 _____ Nature, 161, 391, 1938.
18. L. C. Jackson, Physical Society Conference, Oxford, July 24, 1948.

19. H. Kammerlingh Onnes, Commun.Leiden No. 159
Trans.Faraday Soc.18,No.53, 1922.

20k. P. Kapitza, Nature, 141, 74, 1938.

20. _____ Jour.of Phys.U.S.S.R. 4, 181, 1941.

21. _____ " " " " 4, 59, 1941.

22k. W. H. Keesom and Miss A.P.Keesom, (Commun.Leiden No.235d.
(Physica, 2,557, 1935.

22. W. H. Keesom and G.E. MacWood, (Commun.Leiden No. 254 a.
(Physica 5, 737, 1938.

23. W. H. Keesom, B. F. Saris and L. Meyer, (Commun.Leiden
(No.260a.
(Physica,7,817,1940

24. W. H. Keesom and K. W. Taconis, (Commun.Leiden No.252c.
(Physica 5,270, 1938.

25. A. K. Kikoin and B. Lasarew, (Nature, 141, 912, 1938.
(Nature, 142, 289, 1939.

26. N. Kurti and F. Simon, Nature, 142, 207, 1938.

27. L. Landau, J.Phys. U.S.S.R., 5, 71, 1941.

27k. C. T. Lane, H.A.Fairbank and W.M.Fairbank, Phys.Rev.71,
(600, 1947.

28. F. London, Proc. Roy.Soc. A, 153, 576, 1936.

29. F. London, Nature, 141, 643, 1938.

30. F. London, Rev. Mod. Physics, 17, 310, 1945.

31. F. London and P.R. Zilsel, Phys.Rev. 74, 1148, 1948.

32. H. London, Nature, 142, 612, 1938.

33. _____ Proc. Roy.Soc. A., 171, 484, 1939.

34. L. Meyer and J. H. Mellink, Physica, 13, 197, 1947.

35. L. Page, "Introduction to Theoretical Physics, 2nd ed.,
(p. 255.

36. V. Peshkov, J.Phys. U.S.S.R., 8, 381, 1944.

37. B. V. Rollin, Actes du 7e Congr.intern.du Froid, 1,187, (1936.

38. M. Ruhemann, Z. Phys. 65, 67, 1930.

39. L. I. Schiff, Phys. Rev. 59, 838, 1941.

40. F. Simon, Z. Phys. 41, 806, 1927.

41. L. Tisza, Nature, 141, 913, 1938.

42. _____ J. de Phys. et Rad. (8), 164 & 350, 1940.

43. _____ Phys. Rev. 72, 838, 1948.

44. J. O. Wilhelm, A. D. Misener and A. R. Clark, Proc. Roy. (Soc. A, 151, 342, 1935.

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$|x + b|$ (really $8|$ for 2, 3, 4, 8, 16, 20, 26, 27, 29, 30, 34 - 38, 40-2, 44, 48 are double)