Helium II Film Transport. I. The Role of Substrate*

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Liquid helium II film transport from aluminum, silver, copper, nickel, nickel-silver, stainless steel, Pyrex, quartz, and Lucite beakers has been measured using a variation of a previously described electrical technique. The degree of reproducibility and background variation observed in separate experiments on the same or on similarly prepared specimens of the same material was studied in detail. Rates on machined metals were found to be considerably lower than would be expected from many previous reports. In fact, rates measured over all the aforementioned materials were so similar in magnitude and reproducibility that the background variations involved prevent the resolution of any systematic dependence on substrate material which might exist. This is consistent with the size of the helium-substrate interaction as calculated by Schiff for copper, silver, and glass.

INTRODUCTION

ACCORDING to the two-fluid model of liquid helium II, only superfluid atoms are capable of flowing through narrow channels whose width is of the order of 10^{-4} cm or less. Since the thickness of the creeping film is considerably smaller than channels which may conveniently be constructed, flow through the film appears to be the nearest approximation to ideal superfluidity and should present very favorable conditions for the study of superflow in liquid helium II.

In spite of the widespread attention that the phenomenon of film flow has received in laboratories throughout the world, study of the literature reveals not only lack of agreement on quantitative theoretical predictions, but also a more serious lack of agreement on the quantitative aspects of many experimental results. Owing to the difficulties presented by such measurements, many of the reported results depend on a rather meager amount of data. Moreover, a proper evaluation of conflicting reports is frequently hampered by insufficient discussion of experimental details due to the brevity imposed on journal publications. Thus the progress of the theory tends to be retarded by the lack of agreement upon the precise observations which must be explained, while the experimental work suffers from the concomitant lack of sound theoretical guidance.

The present studies of the bulk transport rates of the helium II film are concerned with the clarification of the answers to a number of basic and closely related questions. The first of these may be stated as follows: How do the measured transport rates vary with the nature of the substrate? The answer to this question has varied considerably since the problem was first considered in 1938 by Daunt and Mendelssohn, who concluded that "the rate of transfer is a characteristic quantity which only depends on the thermal state of liquid helium II."[1] Thus they remarked that "although a higher rate of transfer per unit surface was observed on drawn copper wires, the rate on polished copper was found to be exactly the same as on glass. We attribute the higher rate on drawn wires to the influence of surface inhomogeneities, and conclude that the rate of transfer is not influenced by the underlying material."[1] From these experiments it was also concluded that the high "transfer over a given surface can be reduced by making the surface smooth."[2]

After the war the subject was re-examined and, on the basis of new experiments with glass, platinum, and nickel beakers, it was reported that the absolute values of the rate of transfer "on metals were found to be much higher than on glass,"[3] or more specifically, "the conclusion therefore seems inescapable that the transfer is actually higher on a surface of platinum or nickel than on glass."[3] The situation was further complicated by the very large range of transport rates reported by various observers for metals, in comparison with the much smaller range of values reported for glass (see Table I).[4–18] Indeed, in an article[10] accompanying the

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TABLE I. Summary of previously reported transport rates. Since these rates vary slowly with temperature between 1°K and 1.5°K, the tabulated values may be compared even for slightly different temperatures in this range. All rates quoted in the table are usually assumed to have been obtained for uncontaminated specimens.

Material	T°K	Rate in cm³/cm-sec $\times 10^5$	Observational technique	Reference	Remarks
Glass	1–1.5	7.5	Visual	2, 4[b]	
Glass	1.4	9.1	Visual	5[b]	
Glass	1.4	12.3	Vaporization	6[b]	
Glass	1.6	~8	Vaporization	7	
Glass	1.47	7.5–8.7[a]	Visual	8[b]	
Glass	?≤1.5	7.5–12[a]	Visual	8[b]	
Glass	?≤1.5	8.6–14.3[a]	Visual	8[b]	
Glass	1.5	7.1	Visual	3[b]	
Glass	1.5	8.6	Visual	3[b]	Baked at 130°C
Glass	?≤1.5	8	Gravimetric	9	
Glass	?≤1.5	9	Gravimetric	9	
Glass	?≤1.5	11	Gravimetric	9	Baked at 300°C
Glass	1.25	7.5	Electronic	13	
Glass	1.5	9	Visual	12[b]	
Glass	1.5	~9–12[a]	Visual	11[b]	
Copper	1–1.5	~7.5	Visual	2, 4, 10	
Copper	1.3	14.8	Electronic	13[b]	Machined
Copper	1.3	23	Electronic	13[b]	Burnished
Copper	1.3	51.2	Electronic	13[b]	Etched
Copper	1.3	26	Electronic	13[b]	Etched and oxidized
Copper	1.3	19	Visual	14	
German silver	1.6	~8	Vaporization	7	Tubing
German silver	1.5	~8.5	Vaporization	15[b]	Tubing
Stainless steel	1.3	10.4	Electronic	13[b]	Machined
Stainless steel	1.3	31	Visual	14	
Stainless steel	1.3	16.9	Visual	16[b]	Barium stearate on outside surface
Stainless steel	1.3	8.3	Visual	17[b]	Polished
Stainless steel	1.3	26	Visual	17[b]	Polish damaged by bringing to "red heat"
Nickel	1.5	22.7	Visual	3[b]	Polished, baked
Iron	1.3	10.5	Electronic	13[b]	Machined
Platinum	1.5	16.9	Visual	3[b]	Drawn tubing, acid cleaned
Platinum	1.5	20.8	Visual	3[b]	Baked tubing
Platinum	1.5	21.0	Visual	3[b]	Polished, baked tubing
Lead	1.5	16	Electronic	13[b]	Oxidized
Lucite	1.3	14	Electronic	13[b]	Rouge polished, uncorrected for contraction
Lucite	1.3	11.5	Visual	18[b]	Rouge polished
Perspex	1.3	10.3	Visual	18[b]	Rouge polished
Perspex	1.3	15	Visual	18[b]	Liquid polished

[a] Height dependence noted in these data.
[b] These references contain rate *vs* temperature or height dependence data for this particular material (in this connection see papers III and IV of the present series).

one in which rates "on metals were found to be much *higher* than on glass,"[3] one finds that the reported properties of the thermomechanical effect were based on measurements and calculations in which the transport rate over copper wires was *identical* with that over glass surfaces. In the light of this background some observers have been led to the conclusion that "glass appears to be the only surface over which simple and reproducible phenomena of film flow have been observed."[19]

One widespread interpretation of these conflicting reports has been based on the supposition that, in contrast to glass, ordinary metal surfaces (e.g., machined, drawn, etc.) are characterized by a high degree of surface roughness[1,2] which acts either to present a microperimeter many times larger than the measured macroperimeter,[14,20] or else to produce surface cracks which enhance the flow of bulk liquid.[3,17] According to this view, "there may be only one transfer rate (that exhibited by the glass surfaces) and any higher rates would be due to the microstructure of the substrate."[17] The finding of Chandrasekhar and Mendelssohn that highly polished stainless steel yielded a rate "practically the same as that for a baked-out glass surface"[17] as observed by Mendelssohn and White,[3] is frequently cited in support of this interpretation.[20] Aside from the experimental conditions to which we shall have occasion to refer in paper II of this series, these results (in the absence of a pre-polishing control measurement) do not seem sufficiently different from previous measurements on unpolished, machined iron and stainless steel[13] (or indeed from other results which have been reported for metals from time to time),[1,2,10,15] to justify definitive conclusions concerning the effect of surface polish. Furthermore, just as low rates have been reported for unpolished metals,[7,10,13,15] so also have observations on polished metals on occasion yielded high rates.[3,13]

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Furthermore, there are situations[14,16,21,22] (in addition to the one already cited[10]) in which it is desirable to determine a significant physical quantity from a calculation involving a separate knowledge of the film transport rate. For example, the film thickness, transport rate, and flow velocity are thought to be so related,[4,8,14,16,20–23] that knowledge of two of these quantities may be used to infer the third. However, the present state of knowledge is so unsatisfactory that in a recent publication such calculations are omitted because "until the present controversy as to the interpretation of the observed creep rates is finally settled it is perhaps inopportune to publish values of the calculated film velocities."[21]

The present paper is therefore concerned with an investigation of the variation of transport rate with substrate material. Since, as has already been noted, proper evaluation of such a study requires a knowledge of the influence of surface roughness on transport rates, the second paper in this series (designated as II) will describe control experiments on the role of surface finish. In combination, these studies will in turn be seen to require consideration of the roles of film height and temperature; consequently the influence of the latter parameters will be considered in papers III and IV.

EXPERIMENTAL TECHNIQUES AND APPARATUS[24]

I. Basis of the Electrical Method

A high-frequency electrical technique, using basic circuits which have already been described,[13,25] was adapted for use in these experiments by redesign of of capacitor transport vessels.[26] The dielectric properties of liquid helium are used to detect the helium liquid level in a cylindrical capacitor. Changes in the amount of liquid present in these capacitors are accompanied by frequency changes which ultimately manifest themselves as variations in the voltage which is fed to a recording potentiometer.[25]

II. Modified Capacitor Design

The results for metals were obtained with combined transport vessel-capacitors wherein each metal beaker also comprises one electrode of the capacitor. This eliminates the previous need to fabricate an extra cylindrical vessel of precisely known dimensions. Furthermore, this arrangement decreases the volume of liquid to be emptied from each beaker, thereby permitting measurements to be made more rapidly. However, in the case of dielectric specimens, where this technique is inapplicable, separate capacitor depth gauges[25] were used.

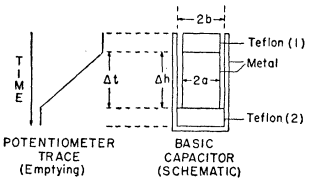

FIG. 1. Schematic representation of basic capacitor design and potentiometer record of emptying vessel by creep.

The present version of capacitor design and measuring technique is illustrated in Fig. 1. If we suppose the capacitor to be filled by immersion and raised to permit emptying by creep, then the fall of the liquid level in the region where the inner member (core) is composed of teflon (1) does not cause any change in capacitance. However, the arrival of the annular meniscus at the top of the metallic central section of the core is heralded by the onset of changes in capacitance which persist until the liquid level reaches the Teflon base (2), in which region changes in capacitance cease. The frequency-proportional voltage fed to the Brown Recording Potentiometer reflects regions of constant capacitance (and frequency) as traces parallel to the time axis, and regions of variable capacitance as traces inclined to the time axis, the angle being determined by the potentiometer chart speed, voltage sensitivity, and the transport rate. Thus the potentiometer chart, driven at a known, constant speed, serves as a clock providing a direct measure and permanent record of the time Δt consumed in emptying the known annular volume associated with the height Δh in the capacitor. These quantities, when correlated with the appropriate limiting perimeter lead directly to a determination of the rate. Thus, if in Fig. 1, $2b$ represents the inner diameter of the capacitor shell and $2a$ the diameter of the metallic section of the core, the transport rate R, given by the volume transferred in unit time per unit width of path, may be expressed as

$$R=[\bar{r}(\Delta r)(\Delta h)]/b(\Delta t), \tag{1}$$

where $\bar{r}=(a+b)/2$ and $(\Delta r)=b-a$.

The present capacitor design has the following advantages over that previously reported: (a) Although frequency is used as the basic observable, no actual measurement of frequency is required since only the temporal location of discontinuities in the voltage trace is employed quantitatively. The previously required calibration of the "frequency dependence of the potentiometer circuits"[13] is completely eliminated, and the transport rate data so obtained are independent of

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[26] B. Smith and H. A. Boorse, Proceedings of Schenectady Cryogenics Conference (General Electric Research Laboratory, The Knolls, Schenectady, 1952), p. 34; Phys. Rev. **90**, 156 (1953); Phys. Rev. **92**, 505 (1953). These brief progress reports were issued at stages in the research when the information they contained appeared to be of immediate interest. The present paper, inasmuch as it represents the first comprehensive report on this work, supersedes these. Slight numerical discrepancies between the present and previous reports stem from a careful recalculation of the preliminary results to remove sources of error.

the frequency characteristics and stability of the electronic circuits. (b) In the previous work each new depth gauge required calibration based on simultaneous frequency readings and cathetometer observations to permit the conversion of the observed time rate of change of frequency to the time rate of change of the position of the liquid level.[13] The present capacitor design is "self-calibrating" since the arrival of the liquid level at various heights in the capacitor is detected automatically during the course of a transport measurement.

III. Beakers and Radiation Shield

Figure 2 illustrates the important features of the actual capacitor and radiation shield assembly used in most of the measurements to be described. Although some of the results reported in this paper were obtained using earlier versions of this design which differed somewhat from Fig. 2 in scale and in the omission of some Teflon bushings, the design shown in Fig. 2 has proven so convenient that most of the data to be reported in the present series of papers were secured using this type of capacitor.[24]

The schematic, single "live-section" core of Fig. 1 has been replaced by one containing four sections (labelled 1–4), capped by Teflon bushing T–1 and supported by Teflon bushing T–5, both of which are secured to threaded projections of the core C. The core is machined in one piece, with the narrow connections between "live" sections encircled by Teflon bushings T–2, T–3, and T–4, having longitudinally split walls permitting them to be spread open and "snapped" into the positions shown. It may readily be seen that the potentiometer trace in emptying such a "four section beaker" consists of a fourfold repetition of the basic pattern of Fig. 1. Application of Eq. (1) to each metal section in turn leads to an average transport rate corresponding to the appropriate level in the beaker. Teflon bushing T–5, which fits snugly in the beaker serves not only to provide the final discontinuity in the potentiometer trace, but also provides insulation and alignment for the core in the shell S. Space for liquid helium in the vicinity of T–5 is provided by longitudinal grooves cut in the Teflon at convenient intervals on the circumference of the bushing. The transport vessel S was always machined in one piece in order to avoid spurious effects due to superleaks at the base.

Electrical connection is made to the core at a and to the shell at b, using double Teflon covered copper wire (#36 B&S) soldered with Wood's metal to the projections machined for this purpose.

The nut N serves to fasten the capacitor to the radiation shield. In the diagram, the shield and the capacitor are in electrical contact, whereas in some applications a special Teflon insulator replaced N and fastened the beaker to the shield while providing electrical isolation.

Typical capacitors had shells of $\frac{1}{2}$-in. o.d. with

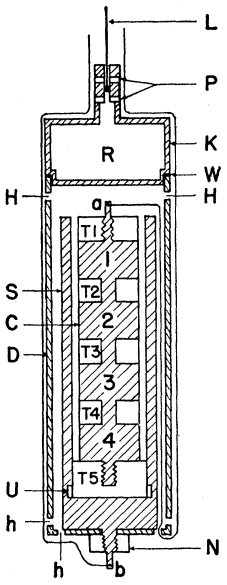

FIG. 2. Cross section of typical transport vessel-capacitor assembly in radiation shield (not to scale).

0.050-in. wall thickness. Using the notation of Eq. (1), other typical nominal sizes were $\Delta r = 0.005$ in. and $\Delta h = 0.350$ in., with beakers of 2.4-in. over-all inner depth. Further specifications of dimensions will be found in the data pertaining to each particular beaker.

Transport over dielectric surfaces was measured by using capacitor depth gauges which differ from the capacitor shown in Fig. 2 only with respect to the provision of holes in the base to insure equality of the helium levels in the depth gauge and dielectric beaker.[13] The extension of Eq. (1) to the case of a capacitor gauge within a beaker is straightforward.

Radiation shields of copper and brass were employed on different occasions. The shield (containing the capacitor) was suspended by a nylon thread L, to which the two electrical leads from a and b were loosely fastened at intervals of a few inches to provide a parallel wire line leading out of the cryostat (Fig. 3). The cap K, soldered to the shield body at W (Fig. 2) with Wood's metal, was provided with a reservoir R of liquid helium to reduce any possible temperature gradients.

IV. Determination of Annular Volume in Capacitors

Accurate measurement of the geometrical quantities appearing in Eq. (1) presents a problem only with respect to the value of b which, in contributing both to $\bar{r}$ and Δr, exerts its greatest influence on the calculated transport rate via Δr, since b and a are of the same order of magnitude. Bore measurement at various heights in the shell was accomplished with a special Brown and Sharpe "Intrimik" (Internal Tri-point Micrometer) which is read while in position; the tool's three jaws are retractable so that the micrometer may be inserted and removed from the hole without touching the walls between measurements. Thus the actual

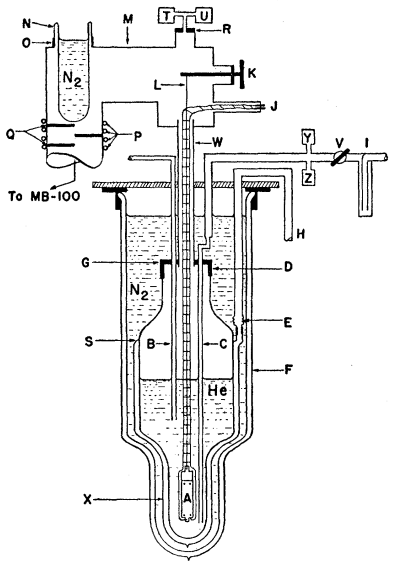

FIG. 3. Helium cryostat: Schematic representation of significant components (not to scale) showing: A: radiation shield assembly shown in Fig. 2; B: liquid helium filling tube; C: vapor pressure tube; D: copper-glass seal; E: Kovar-glass seal and bellows leading to Dewar vacuum line; F: liquid nitrogen Dewar; G: solder joint to copper cap; H: helium Dewar vacuum line; I: cold trap; J: multiple Kovar electrical seal for capacitor leads; K: vacuum tight metal winch; L: nylon thread; M: structure coupling helium bath to MB-100 diffusion pump backed by Kinney pump; N: Pyrex cold trap; O: Kovar-glass seal; P: cooling water circulation coils; Q: brass baffles; R: detachable cap for inserting specimens; S: ring seal of helium Dewar; T: thermocouple vacuum gauge; U: ionization gauge; V: stopcock; W: thin walled stainless steel tube; X: helium Dewar tail; Y: thermocouple vacuum gauge; Z: ionization gauge.

variation of bore with height is measurable to 0.0001 in. without damage to the walls, even in the case of a slightly tapered hole which enlarges with distance from the rim. The possibility of such measurement appears to be a distinct advantage of the geometry employed herein over that employed in conventional visual determinations of transport from capillaries about 1 mm in diameter.

Wherever necessary, appropriate corrections for contraction on cooling to liquid helium temperatures have been applied on the basis of published data for metals[27,28] and dielectrics.[29–31] The need for such corrections was minimized by making each capacitor core and shell from the same material.

The problem of accurate determination of the annular volume has been emphasized because of the importance of eliminating uncertainty due to geometric factors in interpreting any variations of transport rate with height in the beaker which might be observed (see paper III). Due to such uncertainty in the volume occupied by the Teflon bushings in Fig. 2, quantitative calculations of transport rate were restricted to the metallic sections labelled 1–4.

V. Helium Cryostat and Temperature Measurement

Figure 3 shows the radiation shield assembly A in the tail of the helium Dewar X.

Temperatures were determined from measured vapor pressures according to the "agreed scale of 1948."[32] The vapor pressure tube C is connected, via a copper-glass seal to the Pyrex stopcock V, which in turn leads to a liquid nitrogen cooled trap I before communicating with various pressure regulating and measuring devices. These include a mercury contact monostat,[13,33] permitting maintenance of constant vapor pressure, a 12 mm bore absolute mercury manometer, a calibrated Dubrovin vacuum gauge covering the range 0–20 mm Hg with ninefold magnification, and a special McLeod gauge reading pressures from 4.4 mm Hg to 2 microns. These gauges were supplemented by the thermocouple gauge Y (RCA–1946) which was calibrated against the McLeod gauge during runs.

VI. General Pre-Run Procedure

Inasmuch as contamination free operation is highly desirable in these measurements (see papers II and III) these procedures must be described in some detail.

Capacitor elements were washed in pure acetone and blown dry in a stream of pure helium gas before assembly and installation in the cryostat. As a final step, glass and quartz beakers were heated to dispel moisture. According to McBain, "heating glass in air at atmospheric pressure always lessens the quantity of gas evolved upon subsequent vacuum heat treatment, even though the glass may be under normal atmospheric conditions for an interval of several months between the two processes."[34]

Installation was invariably followed by immediate evacuation of the helium Dewar chamber using a Kinney pump which backs the MB–100 diffusion pump specified in Fig. 3. If this operation did not betray the presence of an obvious leak, the chamber was successively charged with pure helium gas and re-pumped to pressures of a few microns, this cycle being repeated five or more times. The pressures in this range were observed with thermocouple gauges located at T and Y.

This dilution of foreign gases was followed by pumping to pressures of about 2×10^{-5} mm Hg as read with an ionization gauge (type VG–$1A$) at U. A similar gauge Z is also provided near the stopcock V. All newly made joints were carefully tested at these pressures, even if the rate of evacuation appeared normal.

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TABLE II. Identification of beakers. Specimen symbols are assigned for convenient shorthand reference in the text. The measurement sequence may be inferred from the numbers assigned to runs; dates associated with these runs are indicated in subsequent graphical representation of the data.

Beaker material	Specimen symbol	Surface condition	Run numbers referred to in text
Aluminum, Alcoa alloy 11*S*, 5.5% Cu, 0.5% Pb, 0.5% Bi	Al-I (*B*)	Bored	38, 39, 48
	Al-II (*B*)	Bored	55
Copper, oxygen free high conductivity	Cu	Bored	59, 66
Glass:			
Pyrex, Kovar base	G-I	Untreated	9, 10
Pyrex, precision bore	G-II	Untreated	30, 31
Pyrex, precision bore	G-III	Untreated	56
Lucite	...	see reference 13	21
Nickel, Type "A," 99% pure	Ni-II (*R*)	Reamed	53
Nickel silver, 46.5% Cu, 40.75% Zn, 2.75% Pb, 10% Ni	Ni-Ag-I (*B*)	Bored	33–35, 37
	Ni-Ag-II (*B*)	Bored	45, 46, 49
Quartz			
Fused, transparent	Q-I	Untreated	23, 27, 32
Fused, transparent capillary	Q-II-V	Untreated	26, 27
Fused, translucent	Q-III	Untreated	24, 25
Silver, fine (99.9% pure)	Ag	Bored	58
Stainless steel, Type 303, 18% Cr, 8% Ni, 2% Mn, 1% Si	S. St. (*B*)	Bored	41–44, 47

The experimental chamber was then filled with pure helium gas, in which condition the apparatus remained overnight. The apparatus was then outgassed at about 2×10^{-5} mm Hg for periods which varied from about eight hours to several days before each helium run. No systematic correlation of transport rates with the duration of the outgassing period was observed.

The stopcock V was ordinarily closed and was opened only when the trap I was immersed in liquid nitrogen to prevent mercury vapor from entering the experimental chamber. With V closed, the pressure gauges beyond the trap I could be evacuated, leak tested, and recharged with helium gas using a separate pumping system and gas line.

VII. General Run Procedure and Performance of Apparatus

A single charge of liquid helium (approximately $\frac{1}{2}$ liter at the boiling point) consistently proved sufficient for about 15 hours of transport rate measurement. Typical values of heat influx to the helium bath, inferred from flowmeter measurements throughout each run, varied from about 15 cal/hr with the bath at the level indicated in Fig. 3, to about 7 cal/hr when the level was in the Dewar tail. Transport rates were measured in successive cycles of decreasing and increasing temperatures to determine the possible effects of variations in bath level or to disclose progressive contamination during the run. No such effects were ever observed.

During transport measurements the lower portion of the radiation shield was always immersed in the helium bath to provide a chamber with each extremity in thermal contact with liquid helium at the same temperature. In addition to the transport rate data, further evidence of the efficacy of such shielding was provided by a number of special exploratory runs using carbon resistance thermometers,[35] with and without such helium capped shields. As expected, these tests showed that the shielding remained effective even when contact with the helium bath was temporarily broken.

Capacitors were designed to yield transport times of 100 sec or more; these were then measurable to within one second from the Brown Recording Potentiometer chart which was usually driven at a speed of two inches per minute. The chart speed was checked continuously against a Standard Electric Timer (model S–10), which could be read to the nearest 0.1 second. As in previous work,[13] interruption of the rf signal had no effect on the observed transport rates, thus reconfirming the absence of dielectric losses.

EXPERIMENTAL RESULTS

When this investigation was begun in 1950, it appeared from the most recent data then available[3,13,16,36,37] that transport rates varied considerably with substrate and/or surface finish.[38] Since the reported variations did not seem to follow any recognizable pattern, the present survey was undertaken in an effort to discern any systematic variation of transport rates with substrate which might exist. This would of course constitute an essential prelude to a study of the influence of surface finish (see paper II).

It was recognized that the wide range of previously reported rates (Table I) would make the results of such experiments very difficult to interpret unless the bounds of reproducibility characterizing such measurements were established. Many experiments were therefore devoted to the determination of the extent of the "unavoidable background" variation which could be

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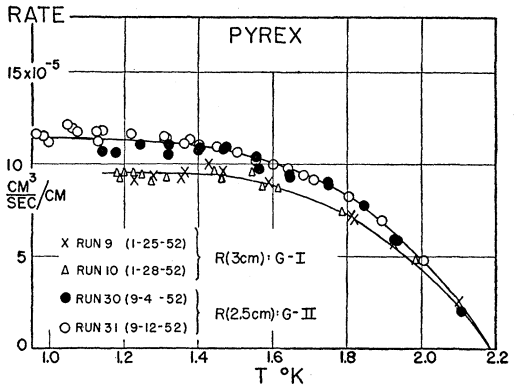


FIG. 4. Transport rates over Pyrex. Specimen G-I: averaged over distance from 1.9 cm to 4.1 cm from rim (lower curve); Specimen G-II: averaged over distance between 1.5 cm and 3.6 cm from rim (upper curve).

expected if one merely removed a beaker from the cryostat, dismantled the capacitor and radiation shield, and then re-subjected them to standard installation procedures before the next run. Unless otherwise specified, this procedure was always followed between consecutive runs with the same specimen. Due attention was also directed to the effect of merely "ageing" beakers outside the cryostat between runs. As a final precaution, transport was also measured from different specimens of the same material.

Beaker specimens are identified for future reference in Table II. The standard machining operation consisted of careful turning of the outer surfaces and boring (*B*) of the interiors, except in the case of specimen Ni-II where difficulty in boring to the proper tolerances necessitated the substitution of the reaming (*R*) process. No polishes or abrasives were used to modify the microfinish imparted by the initial machining operations. The copper, silver, aluminum, and nickel silver beakers were turned and bored without the use of any cutting fluid except for the sparing application of pure acetone. All metal beaker materials had to meet the obvious requirements of ready availability, satisfactory machinability, and reasonable corrosion resistance. Among those possessing these qualifications, further selection was based on various combinations of the desire for comparison with previous measurements on the same material, for comparison with theoretical estimates, and for materials which would also be suitable for use in later control experiments on the role of surface finish (see paper II).

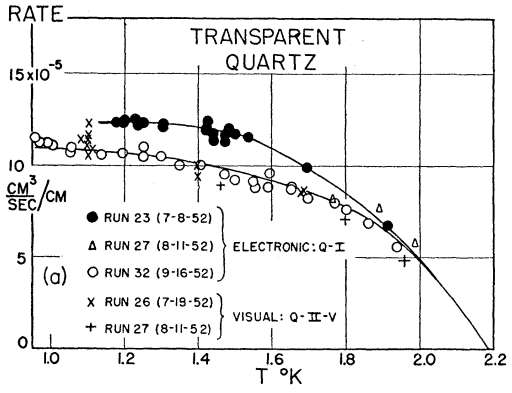
Glass

Pyrex Specimen G-I

The lower curve in Fig. 4 presents data obtained in two runs with a Pyrex beaker whose base consisted of a Kovar-glass seal into which a close fitting Kovar plug was soft-soldered. This plug served to establish electrical connection to the shell of a nickel depth gauge. The beaker was left undisturbed in a helium atmosphere in the cryostat, except for repumping between the two runs, thereby providing information on reproducibility under these conditions. The data represent rates averaged over the distance from 1.9 cm to 4.1 cm from the beaker rim. It was evident that the Kovar seal base began to leak in the course of later work, and so no further measurements were performed with beakers which relied on solder joints or glass to metal seals for leak tightness.

Pyrex Specimen G-II

Since none of the data in the literature had described transport over glass of precision bore, measurements were undertaken with a beaker constructed from commercial precision bore tubing. The base of this beaker was carefully fused and annealed; the lower region, distorted in the fabrication of the beaker, did not overlap the sensitive region of the nickel depth gauge. The results, shown in the upper curve of Fig. 4 represent



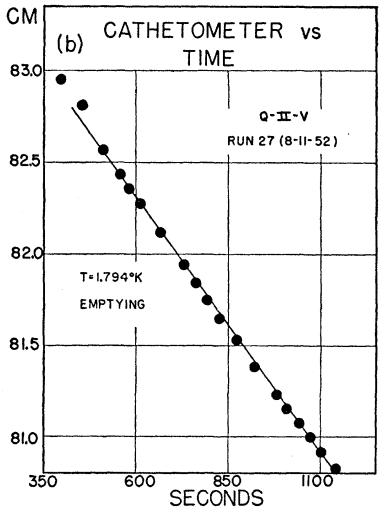


FIG. 5. (a) Transport rate over transparent quartz specimen Q-I, upper curve between 1.9 cm and 2.7 cm from the rim, lower curve between 1.5 cm and 3.6 cm from the rim. (b) Typical record of visual observation of rate of fall of helium meniscus in quartz capillary used in calculating rates shown in (a) for specimen Q-II-V.

rates averaged over distances from 1.5 cm to 3.6 cm from the beaker rim. Here too, the beaker was left undisturbed in the cryostat except for repumping between the two runs.

Quartz

Fused quartz was selected as a source of data for vitreous materials other than glass. Beakers were made from specimens of commercial tubing in each of the two available grades: transparent and translucent.

Transparent Quartz Specimen Q-I

Some of the results obtained with specimen Q-I, using a "three-section" nickel depth gauge, are given in the upper curve of Fig. 5(a), which represents the average rate between 1.9 cm and 2.7 cm from the beaker rim. Similar curves based on data associated with the other two calibrated regions (not shown) yielded rates 8 percent higher between 1.5 cm and 1.8 cm, and 8 percent lower in the region between 2.8 cm and 3.6 cm from the rim (see paper II).

Data obtained one and two months later are shown in the lower curve of Fig. 5(a). In these measurements the depth gauge which was used with specimen G-II was employed to provide data for comparison of transport over the two materials averaged over the same 1.5 cm to 3.6 cm distance from the rim.

Transparent Quartz Specimen Q-II-V

Visual observations of transport, averaged over similar heights of a carefully shielded clear quartz capillary (4 cm long, 0.1 cm bore), are also indicated in the lower curve of Fig. 5(a). A sample curve, indicating the course of cathetometer readings with time is shown in Fig. 5(b).

Translucent Quartz Specimen Q-III

The results of measurements similar to those on Q-I and G-II, covering film heights between 1.5 cm and 3.6 cm from the rim, are shown in Fig. 6. The beaker remained undisturbed in the cryostat, except for outgassing at room temperature between the two runs.

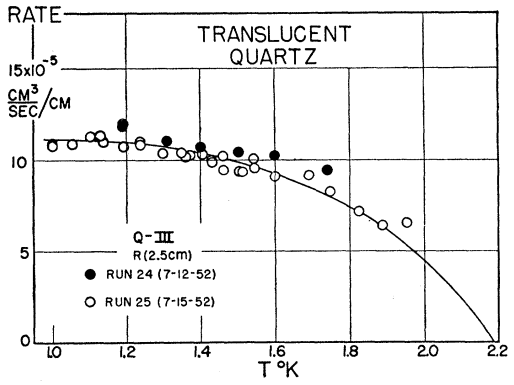


FIG. 6. Transport rates over translucent quartz specimen Q-III between 1.5 cm and 3.6 cm from the rim.

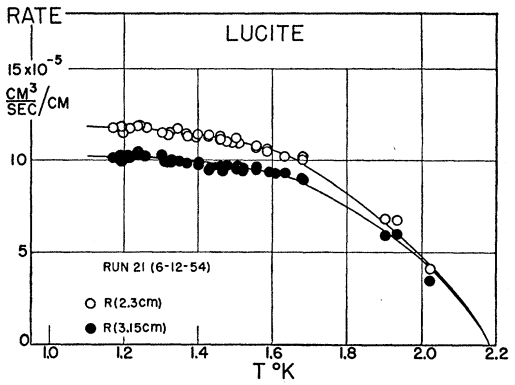


FIG. 7. Transport rates over Lucite, averaged between 1.9 cm and 2.7 cm from the rim (upper curve) and between 2.8 cm and 3.6 cm from the rim (lower curve).

Lucite

Chandrasekhar's report[18] on transport over methyl methacrylate polymers (Lucite and Perspex) provided new impetus for reinvestigation of a previous tentative result obtained in this laboratory.[13] Measurements were therefore undertaken using the original Lucite beaker with the addition of a new capacitor depth gauge. Rates averaged over distances from 1.9 cm to 2.7 cm and from 2.8 cm to 3.6 cm from the rim are shown respectively in the upper and lower curves of Fig. 7. Thus the current data do not duplicate the appearance of a maximum in the vicinity of 1.5°K. Instead, the results show a smooth variation with temperature, with departures in absolute value from the previous report[13] (omitting the peak) due primarily to the correction of the present data for the appreciable contraction of Lucite on cooling to helium temperatures, using expansion coefficients[29,30] which were unavailable at the time of the earlier work. Since interest in the present discussion is limited to a comparison of the magnitudes of the transport rates observed for various materials, a discussion of the peaks sometimes associated with rate-temperature characteristic curves is reserved for the

TABLE III. R_4: Average transport rate between 4.45 cm and 5.33 cm from beaker rim (midpoint at 4.89 cm).

Specimen	Run no.	Rate in cm³/cm-sec ×10⁵ 1.1°	1.3°	1.5°	1.7°	1.9°	2.1°
Al-I (*B*)	38, 48	9.7	9.6	9.1	7.9	5.9	2.5
Al-I (*B*)	39	11.3	11.2	10.8	9.4	7.2	3.5
Al-II (*B*)	55	9.2	9.0	8.7	7.8	6.1	2.6
Cu	59	10.1	10.0	9.7	8.6	5.8	2.0
Cu	66	9.4	9.3	9.0	8.0	5.7	2.0
Ni-Ag-I (*B*)	33–35, 37	12.1	12.0	11.9	10.4	7.2	2.6
Ni-Ag-II (*B*)	45, 46, 49	10.1	10.0	9.6	8.6	6.5	2.8
Ni-II (*R*)	53	12.9	12.5	11.7	10.3	7.4	2.9
Ag	58	8.6	8.4	8.0	7.3	5.9	2.5
S. St. (*B*)	41–44, 47	9.2	9.1	8.7	7.7	5.7	2.4
G-III	56	11.2	10.8	9.9	8.4	6.2	2.4

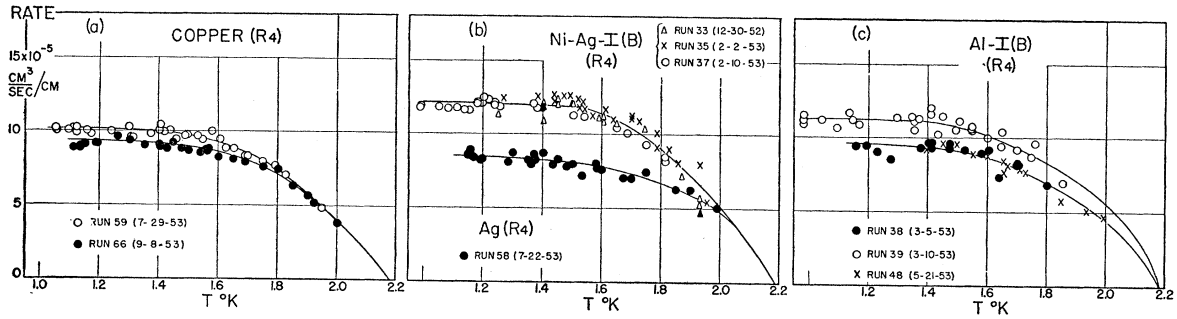


FIG. 8. Transport rates over various machined metal specimens: (a) copper, (b) nickel silver (upper curve), and silver (lower curve), (c) aluminum. In each case the transport rates were calculated for distances between 4.45 cm and 5.33 cm from the rim, corresponding to beaker region "4" in Fig. 2 and therefore designated as R_4.

last paper in this series (IV) which is devoted to a general study of the functional dependence on temperature of the transport rates.

The remainder of the data to be presented are summarized in Table III (where tabulation is facilitated by the adoption of the same geometry for all beakers listed). The designation R_4 corresponds to a measurement of transport in the beaker region occupied by the sensitive element labelled 4 in Fig. 2. In Table III, the numerical values were abstracted from smooth curves drawn through the experimental points. The original data for four of the nine specimens are shown in Fig. 8. Similar curves for the other five specimens will be found in paper II in connection with control experiments on surface finish (see part (a) of Figs. 2–6 of paper II). This allocation of curves is dictated by the desire to conserve space without losing sight of the fact that a complete display of the data is vital where so many conflicting reports exist. Reproducibility and scatter may also be judged from these curves.

DISCUSSION

Rates observed for all materials varied so little in comparison with the factor of three or more which one is led to expect from other investigations,[3,14,17] that the background variation prevents the resolution of any small systematic dependence on the chemical composition of the substrate which might exist. It is interesting to note that this does not preclude the existence of such a dependence in view of Schiff's calculation[39] of the size of the helium film-substrate interaction to be expected for a number of materials employed in this investigation. From consideration of the van der Waals and gravitational energies involved, Schiff found that the thickness, d, of the film at a height h above the free surface of the liquid would be given by

$$d=4.3\times10^{-6}/h^{\frac{1}{3}} \text{ cm} \qquad (2)$$

for copper, whereas "the numerical value 4.3 for copper is replaced by 4.7 for silver" and "about 4 for glass."[39] Since the denominator of Eq. (2) remains the same for all substrates, the numerator is a direct measure of the expected film-substrate interaction. Thus the present observations, in combination with the calculations of Schiff argue against the assignment of a fundamental role to the results of a particular measurement of transport over glass.

The great similarity of the data for all these materials focuses attention on the desirability of ascertaining the contribution of surface roughness to those differences which were observed. Furthermore, there is sufficient evidence in Figs. 4–8 to indicate that a reliable comparison of the data averaged over different beaker heights also requires a careful consideration of the extent to which film height may influence the various data. Further discussion of these results will therefore be found in subsequent papers of this series.

[39] L. I. Schiff, Phys. Rev. **59**, 839 (1941).

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Dr. J. G. Dash for assistance in the construction of the helium cryostat; to Albert Brown, Leonard Lesensky, and Robert D. Worley for valuable assistance during the course of the measurements; and to Professor Mark W. Zemansky for his active and stimulating interest in these experiments.