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Helium II Film Transport. II. The Role of Surface Finish*

BERNARD SMITH† AND HENRY A. BOORSE‡
Pupin Physics Laboratories, Columbia University, New York, New York

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The effect of surface finish has been studied by comparing transport rates measured on four metal beakers (aluminum, nickel, stainless steel, and nickel-silver), before and after they had been "superfinished." Deliberately roughened surfaces were employed in similar control experiments on glass. Measured values of beaker microfinish are reported for comparison with flow rates. The data obtained with these specimens, as well as with a nickel beaker whose inner wall was broached to provide, in effect, a capillary covered surface, are consistent with the hypothesis that transport rates adjust to the prevailing microscopic perimeter and do not require the added hypothesis of anomalous flow in surface cracks. A scheme for estimating the difference between macro- and micro-perimeter is proposed, and the flow data are found to be consistent with its predictions. These include the result that a large increase in surface roughness may not imply a very large change in the microscopic perimeter "seen by the film."

THE present study is concerned with the clarification of the answer to the question: How do measured transport rates vary with the surface finish of the substrate? Since the background of the problem has already been discussed in a previous paper,[1] further introduction is omitted here.

EXPERIMENTAL RESULTS[2]

The first results of interest were obtained from a preliminary investigation of the effect of systematic roughening of beaker surfaces. Various observers[3–6] have often speculated on the effect of what Daunt and Smith have recently aptly described as the "semicapillary nature of the rough surfaces."[7] Nickel beaker specimen Ni-I (see Table I) was therefore broached, with the resulting longitudinal striations on the inner wall providing, in effect, a capillary covered surface. The original inner circumference of the beaker was covered by 100 equally spaced, slightly trapezoidal striations, 0.001 in. deep, 0.002 in. wide, and 0.010 in. apart. The size and distribution of these grooves were dictated by the mechanical requirements of the broaching operation. The broached surface extended from the rim to a depth of 0.985 in., the over-all inner depth being 1.530 in. By using a core with three calibrated regions (instead of the four shown in Fig. 2 of I),[1] with only two corresponding to liquid levels in the broached region, it was possible to compare flow rates obtained when the bottom of these narrow channels was above and below the liquid level in the beaker. In order to free the measurements from any ambiguity associated with a possible height dependence (to be described in paper III), a brief prebroaching control experiment (run 13) was performed using the same three-section core to check the average rates associated with these heights in the original bored beaker. The midpoints of Secs. 1, 2, and 3 were respectively 1.2 cm, 2.1 cm, and 3.0 cm from the rim, with Sec. 1 beginning 0.8 cm from the rim. The data for the broached beaker (runs 17 and 22) appears in Fig. 1, together with the average rates obtained at 1.25°K for the same heights before broaching. Transport rates

TABLE I. Identification of beakers. Since symbols (including the numbers assigned to identify runs) have the same meaning as in Table II of the preceding paper (I),[1] the composition of various specimens is omitted here.

Material	Specimen symbol	Condition of surface	Run numbers referred to in text
Aluminum	Al-II (B)	Bored	55
	Al-II (ES)	Externally superfinished	62,65
	Al-II (IS)	Internally superfinished	68
Glass: precision bore Pyrex	G-III	Untreated	56
	G-IV (FG)	Fine ground	54
	G-V (CG)	Coarse ground	57
Nickel	Ni-I (B)	Bored	13
	Ni-I (Br)	Broached	17,22
	Ni-II (R)	Reamed	53
	Ni-II (ES)	Externally superf.	60
	Ni-II (IS)	Internally superf.	67,69,70
Nickel silver	Ni-Ag II (B)	Bored	45,46,49
	Ni-Ag II (ES)	Externally superf.	52
	Ni-Ag-II (IS)	Internally superf.	64
Stainless steel	S.St. (B)	Bored	41-44,47
	S.St. (ES)	Externally superf.	50,51
	S.St. (IS)	Internally superf.	61,63

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* Assisted by the Office of Naval Research and the Linde Air Products Company.

† Present address: Bell Telephone Laboratories, 463 West Street, New York 14, New York.

‡ Barnard College, Columbia University, New York 27, New York.

[1] B. Smith and H. A. Boorse, Phys. Rev. **98**, 328 (1955). (This paper is designated by the symbol I in the text.)

[2] Preliminary accounts of some of these results have already been presented in: (a) B. Smith and H. A. Boorse, Proceedings of the Third International Conference of Low Temperature Physics and Chemistry, Houston, December, 1953. (b) B. Smith and H. A. Boorse, Phys. Rev. **94**, 772 (1954). (c) B. Smith, Bull. Am. Phys. Soc. **30**, No. 1, 57 (1955).

[3] J. G. Daunt and K. Mendelssohn, Proc. Roy. Soc. (London) **A170**, 423 (1939).

[4] K. Mendelssohn and G. K. White, Proc. Phys. Soc. (London) **A63**, 1328 (1950).

[5] B. S. Chandrasekhar and K. Mendelssohn, Proc. Phys. Soc. (London) **A65**, 226 (1952).

[6] B. S. Chandrasekhar, Phys. Rev. **86**, 414 (1952).

[7] J. G. Daunt and R. S. Smith, Revs. Modern Phys. **26**, 172 (1954).

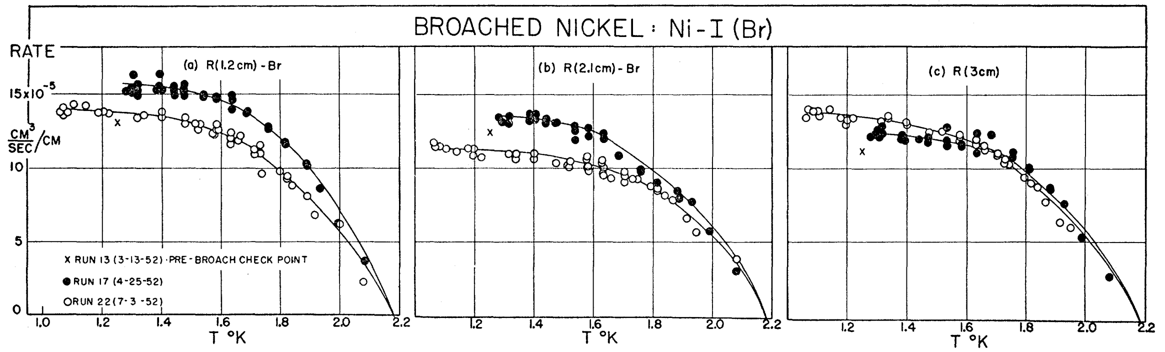

FIG. 1. Transport rates over broached nickel specimen Ni-I (Br), (a) between 0.8 cm and 1.6 cm from rim, (b) between 1.7 and 2.5 cm from rim, and (c) between 2.6 cm and 3.4 cm from rim. In each drawing, an average value at 1.25 °K, obtained in a prebroaching check run, is included for comparison. The key to symbols given in (a) also applies to (b) and (c).

were calculated using the added macroscopic volume and perimeter contributed by the broaching in Secs. 1 and 2, while the calculation for Sec. 3 was the same as before broaching. On the basis of the background variation in rates observed between runs 17 and 22, and similar evidence which will appear in subsequent discussion of other data, as well as the results reported in I,[1] it follows that surface capillaries of the size employed here did not enhance the flow of bulk liquid in an anomalous fashion.

A thorough study of the literature of metal surface finishing was undertaken to determine the feasibility of producing very smooth beaker surfaces. This led to the conclusion that the "superfinishing" process,[8] developed by the Chrysler Corporation, not only gave promise of producing the finest microfinish attainable,[8–11] but was also sufficiently flexible to be applicable to small scale cylindrical geometry. In the interests of brevity, the description of the process will be confined to the official definition formulated by D. A. Wallace: "Superfinishing is the name of a method of mechanically developing on metal parts a surface finish which is optically smooth and metallurgically free of any fragmented or smear metal, such as is created by the dimensional operations of turning, grinding, honing, lapping and/or burnishing. The superimposing of this process over previous machining operations removes the defective boundary layer material and exposes, for heavy duty load-carrying contact, the unworked and undisturbed crystalline base metal. The resultant superfinished surface is a true, geometrically developed, wear-proof bearing area, free of oil-film rupturing protuberances, and accurate to within submicroscopic range."[8] Aside from the purely industrial considerations of load carrying capacity and wear, which are irrelevant here, these specifications are seen to be admirable for transport vessel surfaces. For further information, including a complete description of the superfinishing process accompanied by many photomicrographs and profilograms illustrating the quality of the surfaces which may be produced using various techniques, as well as a discussion of the measurement of surface finish, one may consult the literature.[8–15]

A program for superfinishing metal beakers was arranged with the cooperation of the Production Research Department of the Chrysler Corporation. Specimens of nickel, aluminum, stainless steel and nickel-silver (in the compositions specified in I: Table II)[1] were selected as sufficiently representative of the materials which were deemed satisfactory for ultimate superfinishing. The design (shown in Fig. 2 of paper I)[1] incorporating four calibrated regions, was adopted as standard for all beakers. The undercut, labelled *U* therein, was added to facilitate the subsequent superfinishing operations.

Initial observations of film transport were made for each beaker in the original machined state, as delivered by the Columbia University Physics Department shop. The machining operations and the results of these measurements have already been described (for specimens Al-II, Ni-II, Ni-Ag-II, and S.St. in Table II of paper I)[1] in connection with the study of the role of substrate.

Prerun and installation procedures were the same as those previously described.[1]

Upon completion of the initial transport measurements, each beaker was mailed to Detroit for superfinishing of the outer surface only. During this operation the specimen was gripped by the approximately $\frac{1}{2}$ in. long bearing surface provided by the solid base of the

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[8] A. M. Swigert, *The Story of Superfinish* (Lynn Publishing Company, Detroit, 1940).

[9] G. Schlesinger, *Surface Finish* (The Institution of Production Engineers, London, 1942).

[10] J. J. Bikerman, *Surface Chemistry for Industrial Research* (Academic Press, Inc., New York, 1948).

[11] B. C. Brosheer, American Machinist, September 9 and 23 (McGraw-Hill Book Company, Inc., New York, 1948). The first article contains a valuable bibliography.

[12] *Surface Treatment of Metals* (American Society for Metals, Cleveland, 1941), pp. 392–427.

[13] Reason, Hopkins, and Garrod, *Report on the Measurement of Surface Finish by Stylus Methods* (Taylor, Taylor, & Hobson Ltd., Leicester, 1944).

[14] R. E. Reason, J. Inst. Production Engrs. (October, 1944).

[15] L. P. Tarasov, Trans. Am. Soc. Mech. Engrs. **67**, 189 (1945).

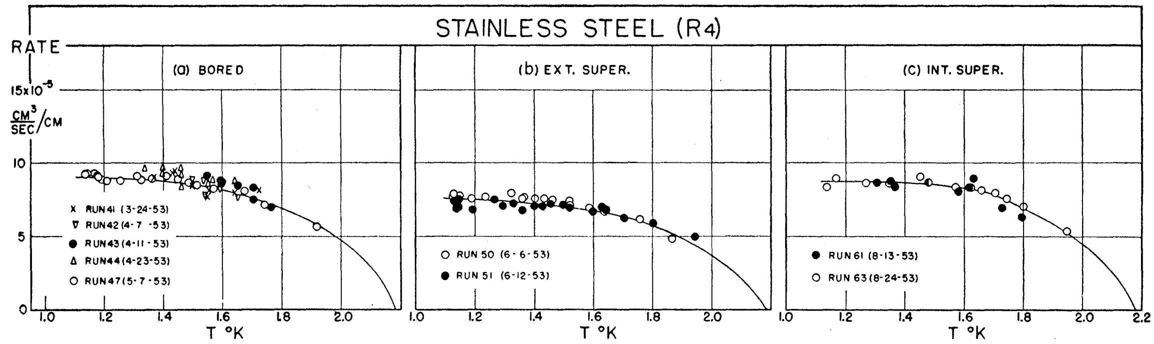

FIG. 2. Transport rates over a stainless-steel beaker in control experiments on surface finish. In each case the transport rates are averaged between 4.45 cm and 5.33 cm from the rim (R_4).

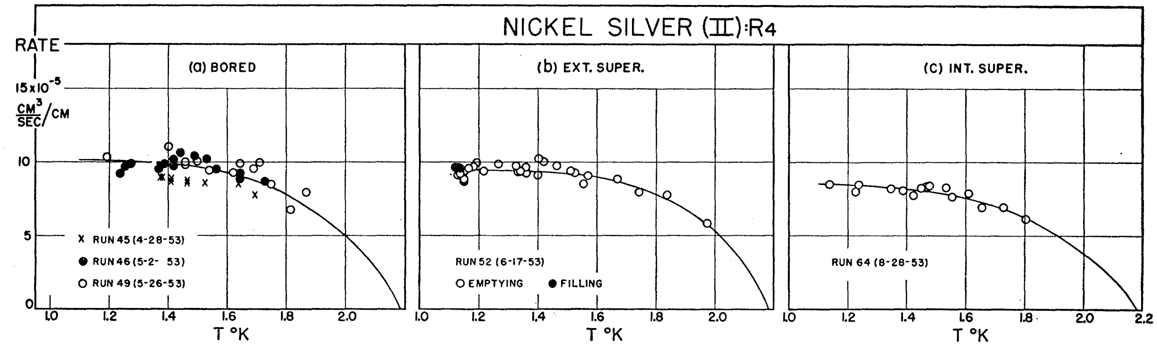

FIG. 3. Transport rates over a nickel-silver beaker (Ni-Ag-II) in control experiments on surface finish. All rates are averaged between 4.45 cm and 5.33 cm from the beaker rim (R_4).

capacitor shell (shown below T-5 in I: Fig. 2)[1]; thus the inner wall was absolutely untouched during this operation. Transport rates remeasured after this procedure are reported below under the general heading of transport over "externally superfinished" (ES) beakers. This step in each series of measurements was included to provide data under circumstances where the comparatively rough inner microperimeter might conceivably exceed the superfinished outer microperimeter.

Each beaker was then returned to the Chrysler Corporation for internal surface superfinishing. As before, specimens were gripped only at the unsuperfinished base so as to prevent marring of the already superfinished exteriors. The final series of transport measurements was then undertaken. All data reported below under the general heading "internally superfinished" (IS) will therefore pertain to beakers whose outer surfaces were still superfinished.

As a further precaution against inadvertent modification of the surface finish produced at any stage of the work, measurements of surface finish and exact beaker dimensions[1] were made only after the crucial transport measurements had been made. Microfinish was measured by the Chrysler Corporation, using Brush Surface Analyzers, models BL-103 and BL-110. All beakers were again forwarded to Detroit merely for additional measurements on the superfinished outer and inner walls after all transport data had been obtained. The microfinish of other specimens was measured under similar circumstances.

When it proved difficult to arrange a similar polishing program for glass beakers, a substitute program of systematic roughening of Pyrex beakers was evolved. Three identical containers were fashioned from lengths of precision bore Pyrex tubing obtained through the courtesy of the Corning Glass Works.[16] Specimen G-III was untreated while the other two had their inner surfaces ground with carborundum: No. 200 for "fine ground" (FG) specimen G-IV and No. 80 for "coarse ground" (CG) specimen G-V. The smooth outer surfaces and ground inner surfaces of these specimens are thus analogous to the surfaces of the metal beakers which have been described as "externally superfinished." The nickel-silver depth gauge used in conjunction with these glass vessels was designed to yield data for direct comparison of the Pyrex results with those obtained for identical heights in metal beakers.

It was recognized that the precautions specified in connection with previous work[1] would be of equal or

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[16] We are indebted to Dr. Paul M. Sutton and his colleagues of Corning's Research Division for appraising our requirements and supplying the tubing.

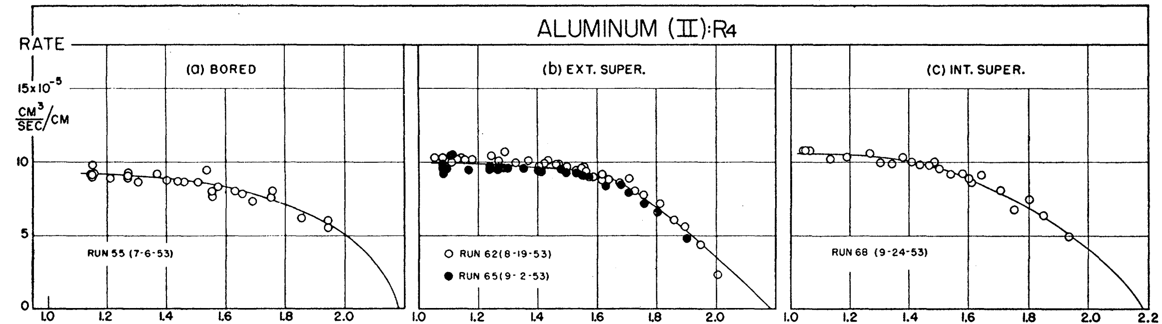

FIG. 4. Transport rates over an aluminum beaker (Al-II) in control experiments on surface finish. All rates are averaged between 4.45 cm and 5.33 cm from the beaker rim (R_4).

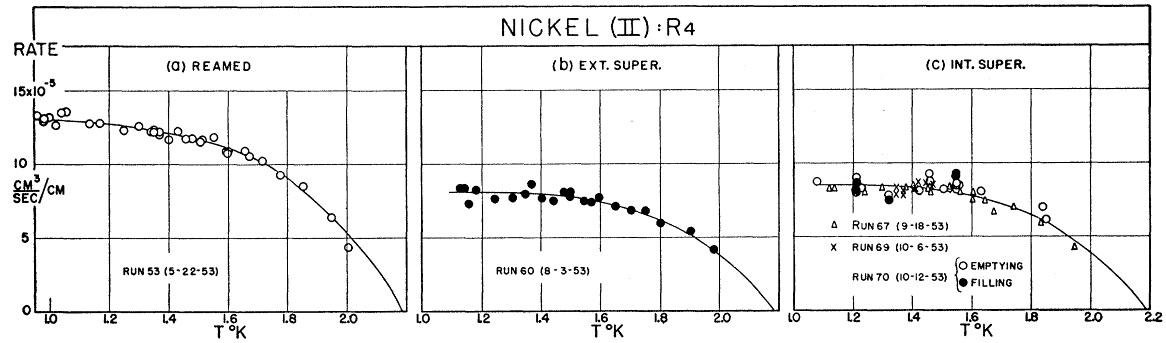

FIG. 5. Transport rates over a nickel beaker (Ni-II) in control experiments on surface finish. All rates are averaged between 4.45 cm and 5.33 cm from the beaker rim (R_4).

greater importance in the interpretation of the present experiments. The data previously acquired[1] on the "unavoidable background" variation observed after immediate and delayed reinstallation of a specimen in the cryostat were supplemented here in recognition of the necessity to establish statistical comparison as the dominant theme of the present work.

The data acquired in these control experiments are plotted in Figs. 2–6 where the horizontal display of the results for different finishes facilitates ready comparison. [It will be noted that part (a) of each figure reveals the original data from which the values tabulated for these specimens in Table III of paper I were obtained.][1] The corresponding tabulation of values obtained after special surface treatment is contained in Table II of the present paper, while similar tables of values obtained at other beaker heights will be found in paper III of this series.[17]

Values cited for the externally superfinished specimens, as well as for the ground Pyrex specimens G-IV and G-V were calculated using the geometrical inner circumference as the flow-limiting width of path, on the assumption that only a comparison of the results secured with all finishes would test the validity of this mode of calculation. This point will be discussed at greater length in a subsequent paragraph.

Since the data seem noteworthy in regard to the rather narrow range of flow rates which were observed (in comparison with the reports of previous observers summarized in I: Table I),[1] averaged values of the tabulated rates at identical heights have been calculated for each group of similarly treated specimens. These averages are the plotted points of Fig. 7. A conservative statistical estimate of the observed variability is given by the vertical lines which are drawn so as to extend above and below each average value by an amount equal to the average of the absolute deviations of the individual runs from the mean. The horizontal bars represent the highest and lowest values which contribute

TABLE II. R_4: Average transport rate between 4.45 cm and 5.33 cm from beaker rim (midpoint at 4.89 cm); superfinished metals and ground Pyrex.

		(Rate in cm³/cm-sec) ×10^5					
Specimen	Run No.	1.1°	1.3°	1.5°	1.7°	1.9°	2.1°
Al-II (ES)	62,65	9.9	9.8	9.5	8.3	5.3	1.8
Ni-Ag-II (ES)	52	9.5	9.4	9.3	8.5	6.8	3.1
Ni-II (ES)	60	8.1	8.1	7.8	6.9	5.2	2.0
St.S. (ES)	50,51	7.6	7.4	7.2	6.3	4.8	2.1
Al-II (IS)	68	10.5	10.3	9.7	7.9	5.6	2.2
Ni-Ag-II (IS)	64	8.5	8.3	7.9	6.9	5.2	2.1
Ni-II (IS)	67,69,70	8.5	8.4	8.1	7.2	5.3	2.0
S.St. (IS)	61,63	8.8	8.7	8.5	7.8	5.6	2.3
G-IV (FG)	54	11.9	11.7	11.1	10.1	7.9	3.6
G-V (CG)	57	12.6	12.4	12.1	11.1	8.5	3.3

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[17] B. Smith and H. A. Boorse, following paper [Phys. Rev. 98, 358 (1955)], designated as III in the text.

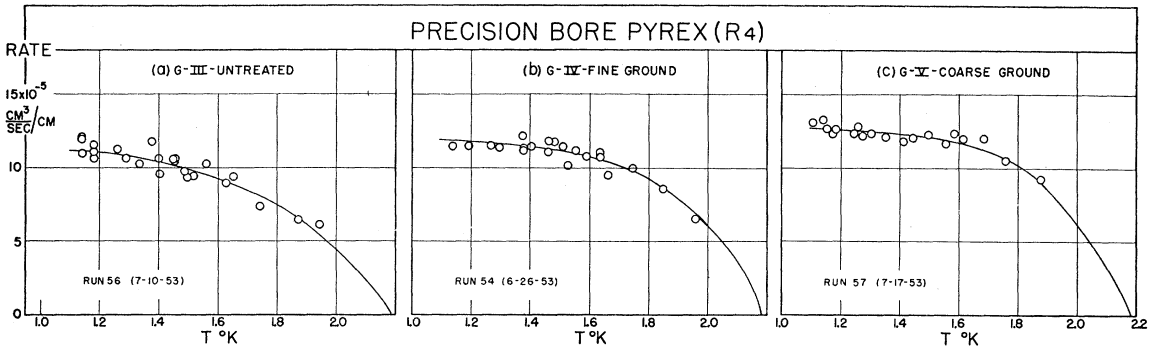

FIG. 6. Transport rates over three precision-bore Pyrex beakers in control experiments on the effect of surface finish. In each case the rate is averaged over the distance from 4.45 cm to 5.33 cm from the beaker rim (R_4).

to each average. As a further aid to visualization, histograms are included to map the distribution of the runs throughout each range of observed values at 1.1°K. In calculating averages and plotting histograms, the basic statistical unit was one day's run, with values which are identical for a number of runs weighted accordingly.

Microfinishes of various specimens are presented in Table III. Original rms micro-inch readings have been converted to angstroms to facilitate direct comparison with the helium II film thickness. Gaps in the table reflect inadvertent omission of the necessary measurements before the surface in question was modified.

The chronology of microfinish measurement may be inferred by noting that tabulated finishes were measured *after* the completion of the last run listed in each row. It will be observed that the microfinishes of the outer walls of the (IS) beakers were always appreciably worse than those for the same specimen in the (ES) condition although, as previously noted, the external surfaces were ostensibly the same in the two cases. However, the microfinish of (ES) specimens was measured *before* the handling accompanying precise determinations of beaker geometry for use in calculating flow rates, while these external microfinishes were then purposely remeasured *after* such handling in the case of (IS) beakers. This precaution provided a check on the durability of finish under such conditions. Similarity of handling and measurement sequences thus leads one to suspect that the tabulated (IS) bore finishes may differ from those present during the actual transport measurements by an amount comparable to the variations observed in the adjacent column for outer wall finishes.

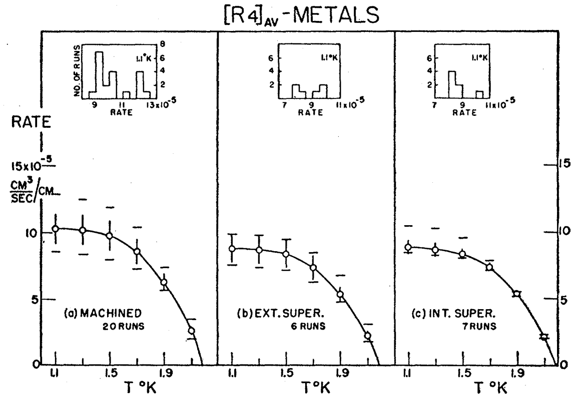

FIG. 7. Average values of transport rates for various metal surfaces, calculated from those listed in Table II of this paper and in Table III of the previous paper (reference 1). (R_4: 4.45 cm to 5.33 cm from rim). The plotted points are calculated arithmetic mean values; the vertical lines are drawn to extend above and below the points by an amount equal to the average absolute deviation from the mean and the horizontal bars represent the highest and lowest values contributing to each average. The histograms show the frequency distribution of the observed rates at 1.1°K.

As is evident from the graphical and tabular summaries in this and the previous paper,[1] variations from run to run were usually small enough to compare favorably with the scatter of the data on a given run. However, larger variations were observed sufficiently often to justify their careful consideration in the interpretation of the data, and so such behavior has been summarized in Table IV. The table includes the results of analysis which will be found in a subsequent paper[17] for data obtained with these specimens at different heights. These data account for the entries corresponding to beaker sections other than 4 (see Fig. 2 of paper I). Since omitted entries indicate agreement at some beaker heights, the observed discrepancies are seen to vary irregularly with height.

The results of the following paper (III)[17] have also been employed in compiling Table V, which indicates the degree of reproducibility which was observed for similarly prepared specimens of the same material. In spite of the fact that much more data were available for the compilation of Table IV than for Table V, the latter required roughly twice as many entries. Study of the data (in papers I[1] and III[17] as well as the present paper) thus indicates that the excellent reproducibility frequently exhibited from run to run by one specimen was not duplicated in observations on different specimens of the same material, although such variations as were observed were of the same order of magnitude in both cases.

DISCUSSION

I. Extent of Background Variation

A comparison of the background variations shown in Tables IV and V with those characterizing the reports of other observers (summarized in I: Table I)[1] is difficult since most investigators have usually preferred to seek the more interesting effects which might appear when experimental conditions are purposely varied between runs. Although variations observed under such altered conditions have frequently been attributed to deliberate beaker and cryostat treatment, many of the discrepancies among results appearing in Table I of paper I for similar materials fall within the range observed here in the absence of special treatment. In this connection it is of interest to note the following remarks of Eselson and Lazarev: "One must still note that the data obtained in different series of similar experiments differed. This circumstance was noted by all authors and the same is true in the work under our conditions. In all probability this scatter (within 20 percent) is caused by the influence of very minute quantities of impurities, the avoidance of which is very difficult."[18] Further evidence of widespread recognition of the limitations on agreement to be expected among various observations is implicit in the prevailing judgment that the different results obtained by many investigators for glass (see Table I of paper I) are in satisfactory agreement.[7,19–21]

TABLE III. Measured microfinish of various specimens: root-mean-square deviations from the mean surface in angstrom units. (Some specimens not subjected to special surface treatment but employed in the study of the substrate dependence[1] are also included.)

Specimen	Run Nos.	Surface condition	Rms microfinish in angstroms Inner wall	 Outer wall
Al-II	55	(B)	···	3560
Al-II	62,65	(ES)	···	50.8
Al-II[a]	68	(IS)	635	508
Cu	59,66	(B)	4064	11 430
Ni-Ag-I	33–35,37	(B)	8128	8636
Ni-Ag-II	52	(ES)	···	76.2
Ni-Ag-II[a]	64	(IS)	762	355
Ni-II	53	(R)	···	17 780
Ni-II	60	(ES)	···	25.4
Ni-II[a]	67,69,70	(IS)	610	254
Ag	58	(B)	12 192	22 352
S.St.	50,51	(ES)	···	76.2
S.St.[a]	61,63	(IS)	457	228
G-III	56	···	203	152
G-IV	54	(FG)	20 300	152
G-V	57	(CG)	50 292	152
Aluminum core[b]			12 700	
Nickel silver core[b]			39 624	
Nickel core[b]			13 208	
Stainless steel core[b]			35 576	

[a] Finishes in this row were determined after the handling described in the text. The extent of deterioration in each case is indicated by comparison of each (IS) result for outer wall finish with the one immediately above it in the table.
[b] These entries are included to supplement the data on the finishes which may be produced by turning solid cylindrical specimens.

TABLE IV. Background variation in transport rates observed for metal beakers which were untreated except for removal from the cryostat, reinstallation and outgassing between runs. Percentages were calculated by dividing the difference in rates at 1.1°K by the arithmetic mean of these two rates. Variations comparable to the scatter of the data on a given run are not tabulated.

Specimen	Comparing Run No.	*vs* run No.	Beaker section	Percent variation at 1.1°K
Al-I (B)[a]	38,39	48	2[b]	9.6
Al-I (B)[a]	38,48	39	4	15
Al-II (ES)	62	65	1[b]	25
			3[b]	27
Cu[a]	59	66	1[b]	10
			3[b]	15
			4	7
Ni-Ag-I (B)[a]	33,34,37	35	1[b]	20
Ni-I (Br)	17	22	Various heights	11–20

[a] See reference 1 for data pertaining to this specimen.
[b] See reference 17 for data pertaining to beaker sections other than 4.

It therefore seems clear that, in evaluating the significance of fairly small changes which may be observed for rates measured after subjecting a beaker to special treatment, one must take careful cognizance of the background variations which characterize the transport measurements. The source of such variations will be considered in subsequent discussion of the nature of beaker surfaces.

II. Role of Microfinish

A. Previous Views.—In the absence of a satisfactory theoretical formulation, the original observation that rates on metals were much higher than on glass[4] led to consideration of two alternatives: "either that the difference in intermolecular forces between the film and the different substrates causes a change in the flow rate or that simply, owing to its micro-structure, the effective perimeter of the underlying surface varies from case to case."[4] The intermolecular force picture seemed to involve excessive complexity since it leads to a variation of film thickness with height whereas the transport rates were believed to be independent of height (see paper III).[17] Consequently it was concluded that a purely geometrical increase in the solid surface carrying the transfer was somewhat more probable. In view of the range of rates which had been observed it was apparent that "the required increase in perimeter to account for the higher transfer on metal would have to be about threefold."[4] Moreover, this threefold difference between macroscopic and microscopic perimeters would

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[18] B. N. Eselson and B. G. Lazarev, J. Exptl. Theoret. Phys. (U.S.S.R.) **23**, 552 (1952). We are grateful to Dr. B. S. Chandrasekhar for supplying us, in April, 1954, with a translation of this paper prepared at the University of Illinois.

[19] K. Mendelssohn, Report of Proceedings of the Oxford Conference on Low Temperature Physics, August, 1951, discussion, p. 70.

[20] D. F. Brewer and K. Mendelssohn, Phil. Mag. **44**, 340 (1953).

[21] Dyba, Lane, and Blakewood, Phys. Rev. **95**, 1365 (1954).

TABLE V. Variation in transport rates observed for similarly prepared specimens of the same material. See Table II for surface finishes. Percentages were calculated as in Table IV. Results of comparison of data for different heights, necessitated by nonstandard beaker geometry, were corrected (by less than 5 percent) in accordance with the results to be presented in paper III, and are therefore listed as approximate. Variations comparable to the scatter of the data on a given run are not tabulated.

Specimen—runs	*vs* Specimen—runs	Beaker section	Percent variation at 1.1°K
Al-I: 38,39,48[a]	Al-II: 55	1[b]	24
Al-I: 38,39[a]	Al-II: 55	2[b]	30
Al-I: 48[a]	Al-II: 55	2[b]	20
Al-I: 38,39,48[a]	Al-II: 55	3[b]	17
Al-I: 38,48[a]	Al-II: 55	4	8
Al-I: 39[a]	Al-II: 55	4	21
Ni-Ag-I: 33,34,37[a]	Ni-Ag-II: 45,46,49	1[b]	15
Ni-Ag-I: 35[a]	Ni-Ag-II: 45,46,49	1[b]	34
Ni-Ag-I: 33–35,37[a]	Ni-Ag-II: 45,46,49	2[b]	11
		3[b]	16
		4	18
G-I: 9,10[a]	G-II: 30,31[a]	...	~14
G-I: 9,10[a]	G-III: 56	...	~30
G-II: 30,31[a]	G-III: 56	...	~14
Q-I: 23[a]	Q-III: 24,25[a]	...	~ 8
Ni-I: 22	Ni-II: 53	...	~10

[a] See reference 1 for these data.
[b] See reference 17 for data pertaining to beaker sections other than 4.

have to characterize the smoothest portion of each beaker since "a region of smooth surface on the wall of the beaker would clearly limit the transfer anywhere along the beaker wall below this level."[4] Since such a threefold variation might appear excessive, it was remarked that "once one admitted the existence of surface cracks allowing some kind of capillary flow, which would still be pressure independent, the required increase in effective perimeter would be much smaller."[4]

The view that surface roughness may thus enhance the flow of bulk liquid to an extent greater than would be indicated by purely perimetric considerations has been restated on a number of occasions.[5,6] Although the influence of the chemical nature of the substrate is still assigned a negligible role in this later work, one finds that high transport rates are ascribed to the "microstructure of the substrate" on the assumption that "narrow surface cracks of the order of magnitude of the film thickness or somewhat larger might be filled up with liquid helium and thereby produce a much greater transport of liquid,"[5] while mention of the simple picture of a large microscopic perimeter is now omitted. The experiment designed to test this hypothesis yielded a transfer rate "practically the same as that for a baked-out glass surface" for two stainless steel beakers "of a much better finish than any metal surface that had previously been used for helium transfer."[5] Later it was found that when "one of the beakers was brought to red heat, thus destroying the smooth surface finish, and it was then lightly polished with cotton wool to remove any deposit of oxide···the flow rate had changed considerably, being now more than three times the original value."[5]

On the other hand, the view that flow rates simply adjust to the prevailing microscopic perimeter continues to attract support as may be seen from the recent analysis of Daunt and Smith, which ends with the remark that "it presumably must also be concluded that the increase in transfer rate over rough surfaces is due to their increased periphery available for flow···."[7] However, apparently as a result of associating a plotted curve with the wrong set of ordinates, Daunt and Smith evaluated available data on the assumption that the experiments on polished stainless steel which have just been described, indicated a change of only about 50 percent due to the destruction of polish by heating,[7] instead of the change to three times the original value which was actually reported.[5] In view of the crucial role accorded this experiment in their discussion, this oversight had the regrettable effect of eliminating all but passing reference to the larger discrepancies which have induced others to postulate an anomalous flow in metal surface cracks.

B. Present Observations.—The effect of altered microfinish of metal beakers on the average rates exhibited in Fig. 7 is summarized in Table VI (which also includes additional results for beaker Secs. 1–3 from paper III).[17] The size of the observed diminution of rate with improved microfinish is much smaller than would be expected from many previous reports. It is abundantly clear that, in the face of the background variation, the resolution of this effect is made possible only by averaging of the data obtained for different specimens on many separate occasions.

The results for untreated and ground Pyrex beakers (see Fig. 6 and Table II) are in accord with those obtained for metal beakers. In fact, contrary to many previous reports, transport rates measured over the comparatively rough bored metallic specimens were found to exhibit a reproducibility and simplicity comparing favorably with that obtained with glass and quartz.[1,22] Such similarity of behavior appears consistent not only with the previously cited[1] calculation of Schiff,[23] but also with the known physical

TABLE VI. Comparison of average transport rates at 1.1°K for machined and superfinished (internally as well as externally-IS) metal specimens. Data for beaker SecS. 1–3 (see Fig. 2 of Paper I), tabulated in the columns headed R_1, R_2, and R_3 were obtained from the results to be presented in Paper III.

	(Average rate in cm³/cm-sec) ×10⁵ R_1	R_2	R_3	R_4
Machined metals	15.0	11.9	10.7	10.3
Superfinished metals (IS)	11.4	9.9	9.3	8.9
Percent difference with respect to mean	27%	18%	14%	15%
Ratio of machined to (IS) average rate	1.32	1.2	1.15	1.16

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[22] B. Smith and H. A. Boorse, Phys. Rev. **92**, 505 (1953).
[23] L. I. Schiff, Phys. Rev. **59**, 839 (1941).

properties of glass surfaces.[24–27] For example, in a section entitled "The Universal Corrosion of Glass Surfaces," McBain[24] remarks that "glass owes its power of resisting agents generally to the existence of an insoluble film of silica or highly silicated matter upon its surface. The silica is mostly left behind as a coating of silica gel upon the surface of the glass. This is amplified when the usual corrosive cleaning agents are employed. Surfaces so prepared for use are no longer glass and they possess appreciable depth and porosity." He therefore concludes that "the true extent of the surface of glass in its ordinary condition is not even approximately known; the uncertainty amounts to an order of magnitude." In commenting on what he terms the spongy nature of glass surfaces, Adam[25] observes that "glass is also rather liable to minute surface cracks" and adds that "glass surfaces seem to become dirty more quickly than most others; this is very likely due to the contamination having penetrated below the surface into cracks, and coming out gradually after cleaning the actual surface." Thus the observation of conventional transport rates for glass surfaces, including those cleaned with chromic acid,[4] is also in accord with the present indications of the small degree to which altered microfinish may influence transport rates.

Although the extent of the possible difference between macroscopic and microscopic perimeters for machined metals has always been discussed on intuitive grounds in connection with helium film transport,[3–7,28–30] it appears feasible to estimate this difference quantitatively. Consider the simple model of a rectangularly corrugated surface shown in cross section in Fig. 8, where p_0 represents the superficial macroscopic perimeter whose microscopic counterpart, p, is to be estimated. Let the average combined width of each adjacent hill and valley be designated by λ, which therefore equals the ratio of the measured geometrical perimeter p_0 to the number, n_0, of such elevation-depression pairs, where of course $p_0 \gg \lambda$. This definition of λ as an average width, frees the model from the restriction to the perfectly regular periodicity which has been depicited in Fig. 8 merely for convenience in drawing. If the depressions have a depth given by 2δ, then the sum of p_0 and vertical contributions to the perimeter yields an expression for the total microscopic perimeter given by

$$p = p_0[1 + 4\delta/\lambda], \tag{1}$$

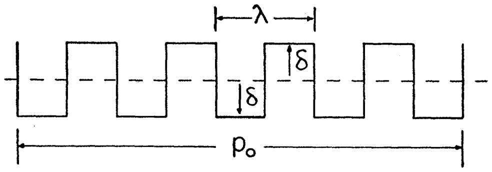

FIG. 8. Simple model of cross section of rough surface (not to scale).

where the definition of λ,

$$p_0 = n_0\lambda, \tag{2}$$

has been employed to eliminate n_0. Thus the dimensionless ratio $(4\delta/\lambda)$ is a direct measure of the contribution of surface roughness to p. It is of course assumed that only irregularities for which 2δ exceeds the helium II film thickness ($\gtrsim 200$ A) would qualify in altering the perimeter "seen" by the film.

Suitable numerical estimates of δ for various beakers are given by the measured values of rms microfinish (deviations from the mean surface) shown in Table III, whereas corresponding values of λ are not available for these metal specimens. However, study of the literature of machined surface finish[8–15] reveals that δ and λ are not entirely unrelated. The correlation between δ and λ is reflected by the necessity to employ different scales of horizontal and vertical magnification whenever it is desired to study surface contours as revealed by photomicrographs and profilograms. One usually chooses that ratio of vertical to horizontal magnification which will reduce δ and λ to a comparable scale much as is shown in Fig. 8. In practice, "experience shows that in the vertical direction the range of useful magnification extends from about 1000 to 100 000" while "in the horizontal direction, values from 6 to 800 have been used."[13] When fixed distortion of horizontal and vertical dimensions in a collection of such graphs is desired, "the best all-round value for measuring roughness would seem to be 100"[13] (i.e., ratio of vertical to horizontal magnification). Thus Reason[14] has observed that "what appear on these graphs to be slender projections and narrow crevasses are in reality nothing of the sort and are merely the compressed representation of gentle hills and broad valleys. A certain amount of care and practice is required to use these distorted graphs, and all the time to think correctly about them. There is a terrible tendency to forget the distortion and to discuss the effect of the various shapes just as though the graph were actually a true representation of the surface. On the graph it looks as though the slender projections could easily bend over or snap off: but when you consider reality you will see that this could hardly happen, for the actual inclinations of the flanks of the undulations to the horizontal are so small that there can be no question of simple bending or breaking." Therefore, an estimate of the range to be expected for (δ/λ) with actual machined metal surfaces may be made by observing the distortion ratios employed in most graphical

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[24] J. W. McBain, *The Sorption of Gases and Vapours by Solids* (Routledge, London, 1932). Most references are to Chapters 7 and 10.

[25] N. K. Adam, *The Physics and Chemistry of Surfaces* (Oxford University Press, London, 1941), third edition, Chaps. 5 and 7.

[26] S. Brunauer, *The Adsorption of Gases and Vapors* (Princeton University Press, Princeton, 1954), Vol. 1.

[27] J. E. Stanworth, *The Physical Properties of Glass* (Oxford University Press, London, 1950).

[28] J. G. Daunt and K. Mendelssohn, Nature **142**, 475 (1938).

[29] J. G. Dash and H. A. Boorse, Phys. Rev. **82**, 851 (1951).

[30] W. C. Knudsen and J. R. Dillinger, Phys. Rev. **91**, 489 (1953).

representations,[8,13,14] showing horizontal and vertical irregularities for machined surfaces to roughly the same scale. From such study it appears reasonable to consider the range

$$20 \lesssim (\lambda/\delta) \lesssim 200, \qquad (3)$$

where larger numbers indicate greater smoothness. Fragile projections characterized by smaller values of (λ/δ) seem unable to survive the rigors of the machining process. In combination with Eq. (1) this yields:

$$1.02 \lesssim (p/p_0) \lesssim 1.2. \qquad (4)$$

The replacement of the rectangular contour shown in Fig. 8 by another regular curve (e.g., sinusoid or sawtooth) would also lead to a correction term small compared with p_0 for contours satisfying the empirical condition (3). Furthermore, in view of (3), the transition from an ideally regular model to actual surface irregularities should not cause an appreciable modification of these conclusions.

These considerations therefore argue against the possibility that the smoothest portion of each beaker might be characterized by values of (p/p_0) even approaching two, while values of three or more such as are required by previously reported transport measurements would appear to be extremely unlikely. This lends support to the rejection of a purely perimetric explanation of such results by Mendelssohn and White[4] and Chandrasekhar and Mendelssohn.[5]

On the other hand, comparison of entries in the last row of Table VI with Eq. (4) indicates that the present data for metals are consistent with the hypothesis that transport rates adjust to the prevailing microscopic perimeter, while the added hypothesis of a large, anomalous flow in surface cracks is completely unnecessary. Recently Dyba, Lane, and Blakewood have also reported the absence of anomalous flow in transport from glass capillaries.[21]

Further support of the present view is provided by the data for Pyrex specimens G-III, IV, and V, if one assumes that the order of magnitude of λ is given by the diameter of the abrasive particles used in grinding the walls of beakers G-IV and V. Using measured microfinish values for δ, and particle size for λ, one obtains Table VII. Although G-V appears more than twice as rough as G-IV (from comparison of microfinish values), the calculated increase in perimeter over that of untreated specimen G-III is about the same in each case. Furthermore, $(4\delta/\lambda)$ is so small that one might expect the observed background variation to tend to blur the correlation of transport rates with (p/p_0) since only one run was taken on each specimen. This is indeed observed at various heights,[17] whereas averages of transport rate ratios observed at all heights yield the values shown in Table VII. The agreement of the data with the proposed model is most satisfactory, although the virtual identity of the last two columns of Table VII must be regarded as somewhat fortuitous. Thus, the assumption that increased surface roughness in general leads to higher transfer rates[31] is seen to involve considerable oversimplification.

TABLE VII. Comparison of calculated increase in perimeter with observed changes in transport rates for Pyrex specimens G-III, IV, and V. Tabulated values of (p/p_0) were calculated from Eq. (1), using measured microfinish for δ and carborundum grit size as a measure of λ. Transport rates observed at 1.1°K, for ground beakers G-IV and V were divided by the corresponding rate for untreated specimen G-III at each height; ratios obtained at different heights were then averaged to obtain the entries in the last column. (Data for beaker sections other than 4 were obtained from Paper III.)

Specimen	δ in micro-inches (rms)	λ (inches)	Calculated (p/p_0)	Measured $(R/R_{G\text{-III}})_{\text{Av}}$
G-IV (FG)	80	0.005	1.06	1.05
G-V (CG)	198	0.0125	1.06	1.04

In judging the quality of finish imparted to the superfinished beakers it is desirable to provide some standard of comparison. As previously noted, the most reliable estimates of the originally imparted superfinish appear to be those measured on the outer walls of (IS) beakers before handling. Such measurements, of which there is one for each of four metal beakers, range from 25.4 A to 76.2 A for rms surface irregularities on the cylindrical surfaces (see Table III). These values will be compared with the results of a recent study of the microscopic nature of optical flats, since specifications for such flats are generally regarded to impose the most stringent tolerances attainable. Using multiple beam interferometry to resolve irregularities that could not be revealed by the electron microscope, Koehler[32] offers the following description of an optical flat: "If one could obtain a collection of cones with conchoidal sides, mean height less than 60 A, average deviation from the mean about one-third the mean, and bases less than 0.01 mm in diameter, and then place them as close together as possible with their bases on a supersmooth surface, then one would have a model of a polished glass surface." The value of 60 A is in excellent agreement with the range of electromechanically determined microfinishes on superfinished metal beakers. Furthermore, substitution of 60 A for δ and Koehler's observed average distance between adjacent cusp points of 0.004 mm for λ, yields satisfactory agreement with the undisputed smoothness of optical flats as well as the previously specified correlation between λ and δ for mechanically prepared metal surfaces.

In the past, the proposed correlation of a very large range of transport rates for metals with changes in perimeter appeared incompatible with the lack of clear evidence of changes of comparable magnitude accompanying the surface modifications which would be expected to result from the mere aging and handling of beakers.[29] The present results are not open to this

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[31] D. F. Brewer and K. Mendelssohn, Phil. Mag. 44, 559 (1953).

[32] W. F. Koehler, J. Opt. Soc. Am. 43, 743 (1953). We are grateful to Dr. Koehler for communicating these results to us prior to publication.

objection since changes of the same order of magnitude as those to be expected from Eq. (4) have been observed as background variations with individual beakers (Table IV), in variations among similarly prepared beakers (Table V), and in changes resulting from deliberate alteration of microfinish (Tables VI and VII). The details of the background variations as previously discussed are thus seen to play a vital role in any scheme which attributes differences in transport rates to substrate microstructure. Their existence is to be expected, and only their absence from the data would require special explanation.

In this connection, another aspect of the virtual impossibility of exact duplication of microscopic surface conditions is deserving of attention. Since the discovery, by Bowers and Mendelssohn,[33] that anomalously high transport rates were associated with condensed layers of solidified gases, all investigators have taken great pains to exclude foreign gases from their apparatus. The preventive measures employed by Atkins[34] (outgassing etc.) were very similar to those already described for the present experiments.[1] Mendelssohn and White[4] outgassed glass vessels at temperatures up to about 130°C for $1\frac{1}{2}$–2 hours in a vacuum of about 10^{-3} mm Hg. Both metal and glass beakers were cleaned with acid. Their treatment of platinum and nickel specimens included degassing at about 600°C at a pressure of approximately 10^{-3} mm Hg for an hour. In what appears to be the most ambitious effort thus far undertaken to minimize contamination, van den Berg used glass apparatus which was evacuated for four hours at 300°C and then sealed off, following which it was immersed in the liquid helium where the pressure was reduced to about 1 mm Hg before the seal was broken.[35] He reports a transport rate of 11×10^{-5} cm^3/cm-sec (presumably at temperatures below 1.5°K) when the level was not very close to the rim. The same rate was observed in a separate experiment where helium was condensed into the measuring beaker through a spiral and several charcoal traps immersed in liquid hydrogen as well as a spiral immersed in liquid helium.[35] (We note in passing that this rate of transport is in excellent agreement with the present data for glass and quartz[1] as well as with the recent work at Yale.[21]) Eselson and Lazarev[18] repeatedly refer to "measures which excluded the contamination of the walls of the vessel by solid impurities" although they furnish no description of these measures other than the statement that "before starting the experiment, the apparatus is carefully evacuated and filled with pure gaseous helium."

Although these precautions have proven sufficient to exclude obvious contamination of the sort described by Bowers and Mendelssohn,[33] it is by no means clear that they are sufficient to remove the "foreign matter in a thin layer" with which "a solid surface is nearly always contaminated."[25] It has already been noted that glass, particularly when acid cleaned, tends to be covered by a layer of silica gel. In commercial applications, for adsorption of water, silica gel is used probably more than any other adsorbent.[10] It has also been observed for borosilicate glasses like Pyrex, that 300°C is required to remove most *adsorbed* gases while *absorbed* gases begin to come off at the softening point (600°C).[36] It is therefore not surprising that suspicions of adsorbed water on glass transport vessels which have yielded conventionally low flow rates in previous measurements, have been voiced by Mendelsshon and White.[4] The possibility of contaminating metals in the machining process is obvious; furthermore, when cleaned by etching, "the metal surface is covered by the products of the reaction between metal and liquid or at least by their concentrated solution in the etching liquid."[10] Thus, "in many instances cleaning attempts only accentuate the chemical difference between the interior and the surface of a solid."[10] Furthermore, as has been observed by Bikerman[10]: "A complete removal of these adsorption layers requires a prolonged heating in high vacuum. For instance, Holm and Meissner[37] had to heat platinum wires for hours at 1100° in a perpetually evacuated glass vessel the walls of which were cooled with liquid hydrogen to prevent gas molecules striking these walls from returning to the wires. If the material to be cleaned cannot stand up to a degassing of such intensity, its surface will never have the composition of its interior." Adam[25] also observes that "if the surface is prepared by etching, chemical changes may be produced on the surface, oxide or other films being present" and that "most surfaces would have their structure much altered by heating, however, the small ridges and projections becoming sintered and rounded off." Consequently, complete cleanliness appears highly incompatible with the study of surfaces of known microstructure at helium temperatures.

Insofar as fluctuations in the composition and extent of minute residual contamination of "clean beaker surfaces" might alter the microscopic periphery of a beaker, such effects are completely consistent with the preceding discussion of present observations. This is also the mechanism used by Eselson and Lazarev to explain the background variation they observed for transport over glass.[18]

However, the probable existence of such residual deposits is disturbing when one endeavors to proceed further and dissociate the role of the helium-substrate interaction from purely geometric effects. It has already been noted[1] that differences in this interaction, as calculated by Schiff[23] for copper, silver and glass, are too small to permit their systematic resolution in the

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[33] R. Bowers and K. Mendelssohn, Proc. Phys. Soc. (London) **A63**, 1318 (1950).

[34] K. R. Atkins, Proc. Roy. Soc. (London) **A203**, 241 (1950).

[35] G. J. van den Berg, Report of Proceedings of the Oxford Conference on Low Temperature Physics, August, 1951, p. 67.

[36] J. E. Harris and E. E. Schumacher, J. Ind. Eng. Chem. **15**, 174 (1923).

[37] R. Holm and W. Meissner, Z. Physik **74**, 715 (1932).

present experiments. The apparent consistency between the present observations and Schiff's calculations,[1] however, may be fortuitous, since in the absence of precise knowledge of the composition of the surface of a "clean beaker," it is not known to what extent the direct helium-substrate interaction assumed in the calculation is applicable.

Contamination in the sense employed by Bowers and Mendelssohn has been observed to cause transport rates between ten and twenty times larger than the conventional "clean beaker" rates observed here.[38–41] It has frequently been assumed, "in view of many of the results obtained with the transfer over metal surfaces, that the increase in the transfer rate over contaminated surfaces is due to the increased perimeter due to the deposit."[7] Since this assumption now seems inadequate to explain many of the high rates previously reported for machined metals, its applicability to contamination must be re-evaluated. If the effect of contamination is truly one of enlarged perimeter, then it should be possible to show that values of λ and δ required in Eq. (1) to produce such large changes in perimeter are indeed compatible with the kinetics of the condensation process and the amount of gaseous impurity which is introduced. On the other hand, just as has been shown for machined metals, it may prove very improbable for the condensate to form needle-like projections of the requisite density and fragility to produce large enough values of (δ/λ). (This of course assumes that one must consider only irregularities larger than the film thickness so that mere granularity on an atomic scale would not suffice.) Solidified gases might then prove to be extremely useful in the study of the direct helium-substrate interaction. For example, Ham and Jackson[42] have already observed the formation of discrete drops from the helium II film only when the polished surface of the mirror was free from condensed gaseous impurities; otherwise, the bulk liquid could just be observed as a stream of liquid of uneven thickness flowing on an irregular substrate. Some unpublished results obtained at Leiden also appear to be of interest in this connection.[35] In any event, further theoretical and experimental study of these questions would be very valuable. Temperley's recognition of the importance of bound states of helium atoms which "are presumably present on any boundary wall, even if it is submerged in the liquid" and which "certainly will affect the transport properties profoundly"[43] might prove to be a useful point of departure for future studies.

Attention must also be directed to previous observations of transport over "clean metal beakers" for which measured rates greatly exceed those to be expected from a mere increase in perimeter. Since such observations now seem to be anomalous even for machined metal beakers, it appears that a completely satisfactory explanation must await further experiments in which such results are reproduced at will by controlled beaker treatment after normal, low rates have been observed for the same beaker in the original machined state. In those cases where some details of beaker history are available, it may be significant that very high rates have been associated with beakers which had previously been heated to 600°C in a vacuum of about 10^{-3} mm Hg,[4] heated (apparently in air) to "red heat,"[5] otherwise oxidized,[29] and/or etched in acid,[4,29] whereas lower rates such as those reported here have been observed in the past over metals[3,28,29,44–46] for which no mention of such treatment was made. Thus, in the absence of further experimental and theoretical knowledge of the role of surface impurities and the manner in which oxidation, heating, and chemical treatment may alter microfinish, it is difficult to judge the merits of the hypothesis of anomalous flow in surface cracks in explaining usually high rates. In this connection McBain remarks that "when discussing impermeable crystals, it is well to remember that it is now recognized that perfect crystals will spontaneously develop a network of surface cracks spaced about 100 atoms apart owing to contraction due to the unbalanced forces at the surface. This must appreciably increase the area available for the sorption of small molecules. The remarkable experiments of Griffith with fibres of glass and silica show than even a 'virgin fire-polished' surface of fused silica does not remain intact if exposed even for a few hours."[24]

Finally it must be noted that the statistical analysis of the data embodied in Fig. 7 (and similar graphs to appear in III),[17] reveals a somewhat curious situation which is not apparent from tabular summaries. Although tabulated and plotted values of transport rates over (ES) beakers were calculated by assuming that the limiting perimeter was still provided by the unchanged inner wall (just as for bored specimens), average (ES) transport rates as shown in Fig. 7 (and paper III) were virtually identical with average (IS) results. In terms of Eq. (1) of paper I,[1] it therefore appears that, on the average, the time Δt taken to empty identical volumes was different in the bored and (ES) cases. Such a result might be interpreted to mean that the rough microscopic inner circumference sometimes exceeded the smooth outer perimeter. However, if this were so, the use of the outer circumfer-

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[38] K. R. Atkins, Nature **161**, 925 (1948).

[39] W. J. deHaas and G. J. van den Berg, Revs. Modern Phys. **21**, 524 (1949).

[40] R. Bowers and K. Mendelssohn, Nature **163**, 870 (1949).

[41] R. Bowers and K. Mendelssohn, Proc. Phys. Soc. (London) **A63**, 1318 (1950).

[42] A. C. Ham and L. C. Jackson, Phil. Mag. **44**, 214 (1953). Also see reference 40 of paper III.

[43] H. N. V. Temperley, Proc. Roy. Soc. (London) **A198**, 438 (1949).

[44] B. V. Rollin and F. Simon, Physica **6**, 219 (1939) with the added explanation offered by H. A. Fairbank and C. T. Lane in Phys. Rev. **76**, 1209 (1949).

[45] J. G. Daunt and K. Mendelssohn, Proc. Phys. Soc. (London) **A63**, 1305 (1950).

[46] E. Ambler and N. Kurti, Report of the Proceedings of the Oxford Conference on Low Temperature Physics, August, 1951, p. 70.

ence in the calculation would be proper in certain cases. Some (ES) graphs in Figs. 2–5 would be lowered by about 20 percent and would then include results as low as 5.9 (10^{-5}) cm^3/sec-cm at 1.3°K, which is lower than any previous report for glass, metal, or plastic substrates. Furthermore, since the results for (IS) beakers would be expected to be just as low, one would be led to assume that some superfinished outer microcircumferences were smaller than their superfinished inner counterparts.

It is important to note that a revision of the data along these lines, if applied uniformly to all superfinished metal and ground glass beakers, would increase the consistency of some sets of results only at the expense of a comparable diminution of consistency in control experiments on other beakers. However, the background variations which were observed, when coupled with the small size of the statistical sample involved, argue against the propriety of applying such a correction only to those results whose consistency would be improved thereby. Fortunately, the fact that the corrections which might conceivably be applied are too small to permit their unambiguous justification, has the added effect of guaranteeing that the discussion of results as already presented would survive such revisions intact. Furthermore, the added possibility, however remote, that a polished outer wall can to some extent affect film flow, without providing the controlling perimeter, should not be overlooked in view of the incompleteness of the present state of knowledge. For example, the flow of the film is sometimes coupled with drop formation on the outer beaker walls[42,47] in a manner which varies with surface condition in a way that is not fully understood.[42] Consequently, until such time as conclusive evidence for the necessity of such revision may be forthcoming, it would be imprudent to alter the presentation of the data.

Although the question of outer *vs* inner perimeter is thus seen to be of relatively minor importance in these experiments, it appears to be crucial in the interpretation of some previous observations on stainless steel.[5] Apparently as a result of the difficulty of polishing the inner walls of small bore specimens, only the outer walls were polished,[48] thereby providing beakers similar to those labeled (ES) in the present work. Published rates were calculated using the polished outer circumference as the limiting perimeter.[48] If it be assumed that machined metals always yield spuriously high flow rates as a result of anomalous flow in surface cracks,[4] then the observed low rate of emptying of these steel beakers would appear to justify the assumption that the smooth outer surface was limiting the transport. However, previous observations of low rates on polished stainless steel and iron,[29] as well as the present observations on various machined metals indicate that, in the absence of a pre-polishing control experiment, the reported data on such externally polished beakers do not justify conclusions as to the effect of enhancing surface finish. On the contrary, the observations are in excellent agreement with the present results for ordinary machined metals.[1] Furthermore, polishing similarly restricted to the outer surface of a platinum beaker, had no appreciable effect in other experiments.[4] Although the polishing therefore may be irrelevant to the experiments on stainless steel,[5] these considerations do not affect the observation that the flow rate increased to more than three times the original value[5] after heat treatment of the beaker. However, the use of these data to draw conclusions about the surface smoothness required for the observation of low transport rates,[7] rather than on the effect of damaging beaker specimens by bringing them to red heat in air, is unjustified. This distinction is of particular importance in the interpretation of work in which flow rates are used in the calculation of other physical quantities.[30,45,49]

SUMMARY OF CONCLUSIONS

Variations observed from run to run with the same specimen, and from specimen to specimen of the same material in these and previous experiments,[1] indicate that trustworthy generalizations cannot be based on small amounts of data. In this connection, the line of demarcation between "clean" and "contaminated"[50] beaker surfaces is not sufficiently clear. Consequently, the apparent compatibility of the data for various materials with the calculations of Schiff (noted in I)[1] may be fortuitous, since the calculations assume a direct interaction between the helium film and a surface whose properties are identical with those in the interior of the solid.

The data are consistent with the hypothesis that transport rates adjust to the prevailing microscopic perimeter presented to the film. The effect of improved microfinish could be discerned only from a statistical comparison of the results for various groups of similarly treated specimens. The size of the observed background variations, as well as the effect of improved microfinish are in good agreement with the proposed calculations of the difference between microscopic and macroscopic perimeters "seen" by the film for mechanically finished substrates (considering irregularities greater than or equal to the film thickness). The calculated difference is much smaller than many previous intuitive estimates and it has been shown that an increase in surface roughness (as manifested by an increase in the height of surface irregularities) is not sufficient to guarantee an appreciable change in the microscopic perimeter

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[47] D. G. Henshaw and L. C. Jackson, National Bureau of Standards Circular 519 (U. S. Government Printing Office, Washington 25, D. C., 1952), pp. 189–190.

[48] B. S. Chandrasekhar (private communication).

[49] L. C. Jackson and D. G. Henshaw, Phil. Mag. **44**, 14 (1953).

[50] In this context, "contamination" includes chemical and physical surface damage as well as the condensation of foreign gases in the sense of Bowers and Mendelssohn.

presented to the film. The present estimates of the difference between geometric and microscopic perimeters give quantitative support to the rejection by some authors of a purely perimetric explanation of anomalously high flow rates which have sometimes been reported for metals. The inapplicability of the perimetric explanation to such results suggests the desirability of re-examining the accepted perimetric explanation of the very high rates which result from contamination (in the sense of Bowers and Mendelssohn), with specific attention to the probable values of the ratio (δ/λ) as employed in Eq. (1).

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Helium II Film Transport. III. The Role of Film Height*

BERNARD SMITH† AND HENRY A. BOORSE‡
Pupin Physics Laboratories, Columbia University, New York, New York

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Transport rates have been measured for film heights up to 5.3 cm. A variation with film height, whose average behavior is similar to that which has been reported for the film thickness, was observed. This height dependence of the flow rates was found to be temperature independent in the range under investigation $(1\text{°K}\lesssim T<T_\lambda)$. The results are also relatively insensitive to changes in substrate and microfinish. Consideration of this height dependence was essential to the analysis of the role of substrate and microfinish presented in the previous papers of this series.

INTRODUCTION

IN proceeding with the study of film transport rates inaugurated in previous papers,[1,2] the present investigation is concerned with the clarification of the answer to the question: How do measured transport rates vary with the distance of the liquid source from the rim of the beaker?

In the earliest relevant investigation, it was found that the rate decreased "only by 20 percent when the level had dropped from within 0.5 mm of the rim to some 20 mm from the rim."[3] It was concluded that "the rate of transfer depends only on the temperature and is practically independent of the difference in height between the two levels (except if the higher level is very near—1.5 cm or less—the top of the barrier)."[4] In a recent review, Daunt and Smith have given the following more quantitative description of these early results: "Daunt and Mendelssohn observed a small variation of the rate of transfer with height when observations were made over height differences as large as 6 cm. The variation in the rate was approximately 2 percent per cm change in height."[5] It was concluded that "the change in gravitational potential does influence the transfer but that this influence plays only the role of a correction of higher order."[6] Consequently, "to avoid the small error which might have been introduced by the slight influence of gravity, the determinations were all carried out in the same range of the beaker."[7] Later, on the basis of these experiments, the following summary was offered: "The most striking feature of the film transfer is its independence of the pressure head and of the length of the path over which it takes place. A beaker filled with liquid helium will empty itself at a steady rate · · · which does not depend on the position of the level or on the height of the intervening wall. These facts indicate that the film transport must be free of friction, since dissipation of the kinetic energy of flow would introduce a dependence of the flow rate on the pressure head and the length of path."[8]

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† Present address: Bell Telephone Laboratories, 463 West Street, New York 14, New York.

‡ Barnard College, Columbia University, New York 27, New York.

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