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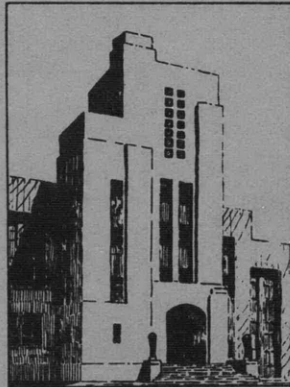
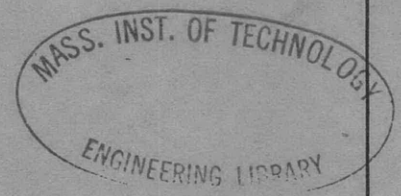
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THE DAVID W. TAYLOR MODEL BASIN

UNITED STATES NAVY

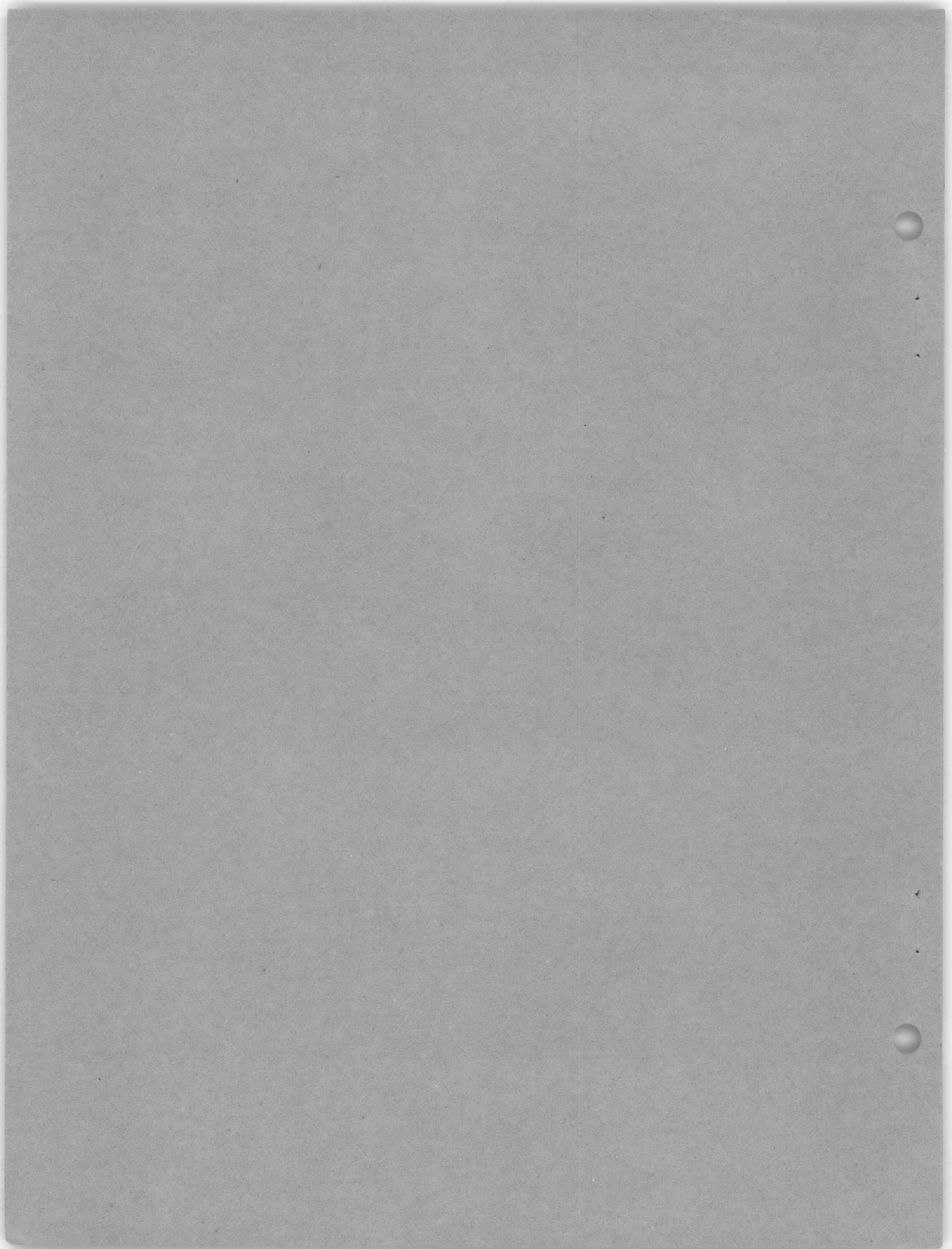
ON THE SIZE OF GAS BUBBLES
AND DROPLETS IN LIQUIDS

BY SIEGFRIED HALBERSTADT AND PAUL H. PRAUSNITZ



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ON THE SIZE OF GAS BUBBLES AND DROPLETS IN LIQUIDS

(ÜBER DIE GRÖSZE VON GASBLASEN UND FLÜSSIGKEITSTRÖPFCHEN IN FLÜSSIGKEITEN)

by

Siegfried Halberstadt and Paul H. Frausnitz

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The David W. Taylor Model Basin
Bureau of Ships
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DIGEST*

An apparatus is described which for the first time permits the size of gas bubbles and drops in liquids to be measured accurately.

The size of gas bubbles which emanate from diaphragms of variable pore diameter is studied in water and ether. The resultant curve with respect to the pressure is approximately hyperbolic. The pore diameters, calculated from the pressure and capillary constants by Bechhold-Einstein method, give comparable values at least with respect to the order of magnitude for water and ether.

Variation in the size of gas bubbles produced by extrusion of gas through the same filter plate into various liquids is determined. It would seem plausible to consider the surface tension as the determining factor for the size of the bubbles, even though the viscosity which was emphasized by Schnurmann has a certain effect. The dielectric constant is not considered. The fact that aqueous electrical solutions drop out of the picture might be traced to a charge effect of the gas bubbles. Substances of high capillarity sharply decrease the size of the bubbles.

The size of the bubbles as a function of pressure is observed at clearly defined individual orifices and diaphragms. As the pressure increases the bubble size decreases. When occasionally larger bubbles occur on diaphragms as the pressure is increased, a result of the form of the orifice of those narrow pores which only permit gas to escape under stronger pressure may be suspected.

The size of the droplets of liquid, which occur in perforations, is determined for diaphragms of varying pore diameters. In the system composed of acetic ester and water the drops are larger than in the system of ether and water. Finer filter plates give finer droplets. To do this, however, they require higher pressure to pass through the diaphragm. A surface-active material in water decreases the size of the drops.

After this study was completed Andrade's (26) article was read in which he points out for water, that the curves for the $\log \eta$ against l/T and for α against T are mirror images of each other. This indicates that the viscosity and the surface tension must be functions of the liquid which bear an actual relationship to each other.

* This digest is a condensation of the text of the report, containing a description of all essential features and giving the principal results. It is prepared and included for the benefit of those who cannot spare the time to read the whole report.

ON THE SIZE OF GAS BUBBLES AND DROPLETS IN LIQUIDS

Science and engineering are equally interested in the problem of bringing gases into closer contact with liquids. Generally, one of the three following problems is involved:

1. Reaction between the gas and a component of the liquid. A problem of this kind is presented by aeration in biological reactions, for example in yeast suspensions in liquid foods (1)* (2).

2. Absorption of individual components from the gaseous phase, for example absorption of SO_3 vapors (3) of nicotine from tobacco smoke (4) (5) (6) and the production of pure nitrogen (7).

3. The saturation of gases with liquid vapor, for example in air conditioning in the textile industries or in the determination of water absorption by artificial fertilizers (8).

In each of the foregoing cases the problem of the actual size of the gas bubbles has become increasingly prominent (9) because absorption is supported by a finer distribution of the gas and by increasing the surface area.

An extensive literature dealing with this problem has accumulated in the course of time. A study by Bechhold (10) in the year 1908, in which he gives a formula to calculate the pore size of filters, is fundamental. The same formula was published in 1923 by A. Einstein and H. Mühsam (11) (12). The diameter of a pore is $D = 4\alpha/p$, where α denotes the capillary constant of the liquid, and p the pressure necessary to cause the pore to discharge gas. This work has recently been complemented by Bechhold's school (13) (14).

Coehn and Neumann (15) (16), Kohlschütter (17), and Schnurmann (18) have quite recently studied the size of gas bubbles in liquids. Coehn and Neumann investigated electrolytically developed gas bubbles. Schnurmann devoted his studies exclusively to bubbles produced by forcing air through diaphragms or produced by entrainment by a jet of liquid. He concluded that the size of the bubbles is a function of the viscosity and, moreover, a result of the electrostatic interaction of the charged bubbles and the liquid in electrolytes. However, in his experiments Schnurmann could only estimate the size of the gas bubbles according to the categories "large, medium, small." In order to effect an actual measurement the present authors developed an apparatus which permits direct observation and measurement of the

* Numbers in parentheses indicate references on page 15 of this translation.

bubble size. Thus, for the first time the range of estimate was superseded and exact bases to judge the factors which affect bubble size were determined.

The escape of gas from individual capillaries can be studied in an ordinary cuvette. In this respect reference is made to Hatschek's (19) excellent investigations of gas bubbles in isotropic and deformed gelatin gels. As soon as the problem of investigating diaphragms suitable for testing arises, a difficulty occurs. They must be fitted into a very narrow cuvette in order to segregate a single stratum of ascending bubbles for measurement. Therefore the authors fused two tubes into a large beaker made of Duranglas.* These tubes are situated exactly opposite each other. One tube is provided with a smooth plane-parallel glass plate fused inside one end in the manner of a colorimeter tube. An identical colorimeter tube is tightly fitted into the other open tube by a ground joint similar to that in a surgical glass syringe. The result is an "internal cuvette" in which the distance between the plain glass plates can be adjusted to meet the size of the bubbles to be observed. This permits any arbitrary L-shaped diaphragm and clamp to be conveniently installed in the beaker to segregate the necessary thin stratum of ascending bubbles.

The gas used was nitrogen which was released from a flask. The pressure required to force the gas through the porous filter-plate was read from an open manometer connected into the line, see Figure 1. The specific weight, viscosity, and surface tension were determined for each liquid investigated.

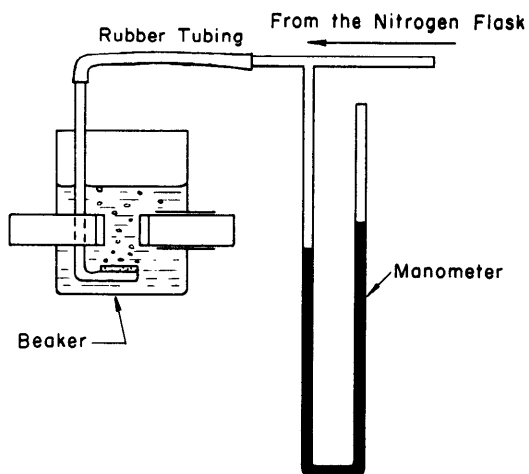


Figure 1

Glass filters made by the firm Schott and Company in Jena were used. They were fused into glass spoons like those with which Jena gas-washing flasks are equipped. Individual tests with glass capillaries and perforated platinum plates were used as controls.

An attempt to determine the size of the gas bubbles with the naked eye by comparison with a scale etched on one of the glass plates was

* Translator's Note: "Duranglas," a type of glass developed and manufactured by the Schott and Company Glass Works in Jena, has a high thermal resistance and its coefficient of expansion is only about 1/3 that of ordinary glass. It is very superior for large-scale apparatus such as flasks, cylinders, retorts, coils, pipe and tube lines, and similar apparatus.

unsuccessful. Hence measurements were made photographically.

The arrangement shown in Figure 2 was developed for this purpose. An arc lamp was set in such a way that the crater formed by the electrodes was situated at the focal point of a convex lens of $f = 20$ cm

(7.87 inches). A screen was arranged to block off interfering light. The parallel rays entered the vessel through the sliding tube inside of the beaker previously described. This telecentric (Telezentrisch) type of resolution obviated any effects of slight changes in the distance of the bubbles from the walls of the "inner cell" on the sharpness and magnification of the image. The photographs were taken with an amateur camera, 6.5 by 9 cm (2.56 x 3.543 inches), tessar 1:4.5, $f = 12$ cm (4.72 inches), which was extended to twice the focal length. Moreover, with the help of a meander shutter it was possible to attach a camera bellows to the apparatus and thus to increase magnification even more. However, this was only used in one case, i.e., Experiment 29. For this one exception the photographs were taken at 0.785 of the natural size. The photographs reproduced here are of the same size as the original photographs.

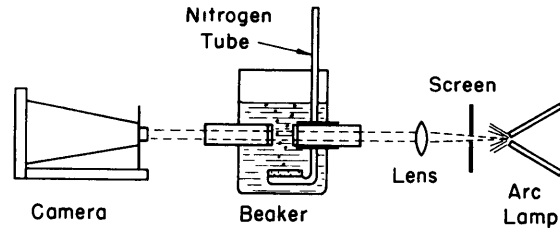


Figure 2

The photographs were evaluated by measuring the bubble diameter with a micrometer microscope or with a Zeiss measuring lens. The change in scale compared to the actual bubble size was determined from the image of a millimeter scale etched on glass, which was double-printed on the image of the cuvette.

In general, the bubbles were elliptical in section. The horizontal axis was the longer. Whenever the photographs permitted, both axes were measured and their average was taken. If a number of bubbles of various sizes occurred in a photograph, all sizes were measured and the arithmetical mean was taken. Only such mean values appear in the tables. Moreover, they are converted to the actual size in microns. In most cases individual values varied as much as 50 per cent from the mean in a test. However, it was determined by controls, that under constant pressure conditions the experiments could be repeated more satisfactorily. The variations amounted to about 10 per cent of the mean.

In microscope measurements, an accuracy of 5 per cent was considered sufficient. Depending on the size of the photographs, a measuring lens (1 calibration of the ocular micrometer = 523μ) or a microscope (1 calibration of the ocular micrometer = 131μ) was used. The same microscope

equipped with the ocular screw micrometer was used for the smallest bubbles. (1 calibration of the scale, divisible into 100 subdivisions, indicated 80μ .)

TESTS WITH CAPILLARIES AND PERFORATED PLATINUM PLATES

For individual capillaries it appears self-evident that the capillary must produce increasing frictional resistance as its length and the velocity of the gas are increased, which must cause a rise of the manometric level. This is clearly evident for a capillary of 90μ . However, the size of the bubble is but slightly affected. For a coarse capillary of 630μ , the corresponding values are much less perceptible. To eliminate the effect of the length of the capillary as far as possible, two very thin platinum plates 20μ thick were fabricated at the firm of Carl Zeiss in Jena. Holes which were as nearly round as possible were drilled in them with precision drilling tools. These plates were then fused into a tube of Jena Normalglas (Jena Standard Glass). The diameters of the orifices were 243μ and 61μ and hence compared favorably with the size of those of fine glass capillaries. In these platinum-plate filters the size of the bubbles is practically independent of the pressure. For glass capillaries the bubble size decreased inversely with the pressure in three cases. Exactly why it increased in the fourth case, Experiments 5 and 6, could not be determined; see Table 1.*

TABLE 1
Gas Bubbles Escaping from Glass Capillaries and Perforated Platinum Plates
Fluid: Water

Type of Orifice	Length mm	Diameter μ	First Pore Emits Gas (Threshold value)			Entire Plate Emits Gas (Mean value)		
			Test	Pressure mm Hg	Bubble Diameter μ	Test	Pressure mm Hg	Bubble Diameter μ
Glass Capillary	44	90	1*	180	1470	2	280	1400
Glass Capillary	3	90	3	35	2020	4	220	1340
Glass Capillary	43	630	5*	8	4330	6	14	5040
Glass Capillary	4	630	7	8	5000	8	14	4760
Perforated Platinum Plate	0.02	61	9	62	1440	10	132	1390
Perforated Platinum Plate	0.02	243	11*	16	3050	12	35	3100

* See photographs on page 17 for tests designated by *.

* In all cases the numbers of those tests which are photographically reproduced in the special tabulation of photographs are designated with an asterisk. In each pair of experiments the lower pressure corresponds to the threshold value in all tables.

TESTS ON DIAPHRAGMS (GLASS FILTER PLATES)

In comparing the foregoing experiments with similar ones made with glass filter plates, certain basic differences appear with respect to the simple conditions found to exist for perforated plates or glass capillaries. First of all it would certainly be expected that the pressure should manifestly be a function of the thickness of the plate. This does not directly follow. One of the collaborators performed tests in September 1924 by the Bechhold-Einstein method with glass filter disks of the serial number G 5-7 which approximately corresponds to the present serial number G 3. According to the formula cited previously the pore diameter should not be a function of the thickness of the plate under consideration. Moreover, it should not matter which face of the filter is turned upward. Therefore, the pressure at which a single pore or many pores of the filter permitted gas bubbles to escape into the water above them was determined for a number of filter plates. For this purpose, the filter plate was alternately clamped with the one or the other surface facing upward between rubber packing rings in a scissors-shaped metal clamp with a glass cylinder cemented to its upper surface. The height of the water above the plate was constant at 18 mm (0.7087 inch). After the entire plate had been tested at its original thickness, its lower surface was ground until the plate was reduced to 1/2 the thickness of the original. Hence, the "upper" surface remained unchanged. This permitted collection of the data given in Table 2.

TABLE 2

Tests on Filter Plates of Varying Thicknesses

Plate	Thickness mm	Pressure mm Hg			
		"Upper" Face Up		"Lower" Face Up	
		First Pore Emits Gas (Threshold value)	Entire Plate Emits Gas (Mean value)	First Pore Emits Gas (Threshold value)	Entire Plate Emits Gas (Mean value)
2	8.8	38	54	46	60
	4.0	38	74	32	60
3	8.0	36	62	42	76
	4.0	22	62	50	72
4	8.0	30	72	44	67
	4.0	40	61	32	64
5	8.3	44	66	48	62
	4.0	44	74	46	70
6	7.8	43	72	50	67
	4.0	40	57	52	68

It is evident from Table 2 that it is not a negligible factor for the production of the first bubble which face of the filter is turned upward. Moreover, from a rigorous standpoint the first bubble only may be used for comparison. However, it can be seen that it is entirely a matter of chance whether a pressure variation will or will not occur when the thickness of the plate is decreased. In contrast to conditions for a single straight capillary, the manometric measurement of the particular threshold value of a diaphragm is a function of the greatest width of the entire filter plate. This width must be defined as the diameter of the narrowest point of the widest capillary channel.

If this point is removed by grinding, the pressure drops. If the channel is accidentally constricted, say by the intrusion of dust due to grinding, the pressure must rise. At any rate, no prominent pressure variations appeared when the filter plates were reduced by grinding. Therefore, at approximately equal ratios of thickness of the filter plates, the formula of Bechhold-Einstein can be used as an approximate value for comparative purposes. Bechhold himself cautioned against converting measurements directly from one type of filter to a completely different one unless a very rough approximation is desired. A microscopic measurement of the pore apertures or orifices on the surface of the filter plates was avoided, because it is practically not possible to precisely determine those points from which the gas bubbles emanate. Microphotograms were informative with respect to the structure of the surfaces of the filter plates. These have recently been published (16).

EXPERIMENTS WITH FILTERS OF VARYING FINENESS

In most recent measurements filter plates of varying fineness were studied in a single liquid and the pressure was determined as a threshold value where only the first pore allowed gas to escape, and then in turn the pressure at which the entire plate uniformly emitted gas. The size of the bubbles was measured by the method previously described. These measurements for water are shown by two curves in Figure 3 and by Table 3.*

In the discussion of studies on determination of the pore diameter of filters it has already been noted that a formula for the calculation of the pore diameter of porous diaphragms shows that this value is a function of the manometric pressure and the capillary constant of the liquid used. To prove

* The designations of the glass filters correspond to the catalog Nr 4211 g of the Schott and Company Glass Works in Jena.

this and to simultaneously determine the size of the bubble, the same series of glass filters was tested in ether. The two remaining curves in Figure 3 and Table 4 show the values thus obtained.

In contrast to H. Bechhold and R. Schnurmann (14) we thus obtained fairly good agreement with respect to orders of magnitude between the calculated pore diameters, after determination of pressure of gas against water or gas against ether. The families of curves, Figure 3, show an extensive similarity and approach hyperbolic contour. This indicates a certain similarity between the size of the bubbles as a function of the pressure measured by the authors and the ratio of pore diameter to the pressure required by Bechhold's formula. Therefore, decreasing the pore diameter below a certain

TABLE 3 (WATER)

Filter	First Pore Emits Gas (Threshold value)				Entire Plate Emits Gas (Mean value)			
	Test	Pressure mm Hg	Bubble Diameter μ	Pore Diameter†	Test	Pressure mm Hg	Bubble Diameter μ	Pore Diameter†
G 1	13	14	2360	169	14*	18	2870	132
G 2	15	26	490	91	16*	42	1240	56
G 3	17*	40	250	59	18*	70	870	34
G 4	19*	110	90	22	20*	170	520	14

† Pore diameter calculated according to Bechhold-Einstein ($\alpha = 72.4$ dyne/cm).

* See photographs on page 17 for tests designated by *.

TABLE 4 (ETHER)

Filter	First Pore Emits Gas (Threshold value)					Entire Plate Emits Gas (Mean value)				
	Test	Pressure mm Hg	Bubble Diameter μ	Pore Diameter†	Ratio of pore diameters cal- culated for values derived for water and ether	Test	Pressure mm Hg	Bubble Diameter μ	Pore Diameter†	Ratio of pore diameters cal- culated for values derived for water and ether
G 1	21*	4	2110	137	1.23	22	5	2340	109	1.21
G 2	23	11	440	50	1.82	24*	14	1660	39	1.44
G 3	25*	12	270	45	1.31	26*	20	930	27	1.26
G 4	27	16	90	34	0.65	28*	34	250	16	0.88
G 5	29	190	60	2.9		30*	290	150	1.9	

† Pore diameter calculated according to Bechhold-Einstein ($\alpha = 72.4$ dyne/cm).

* See photographs on page 17 for tests designated by *.

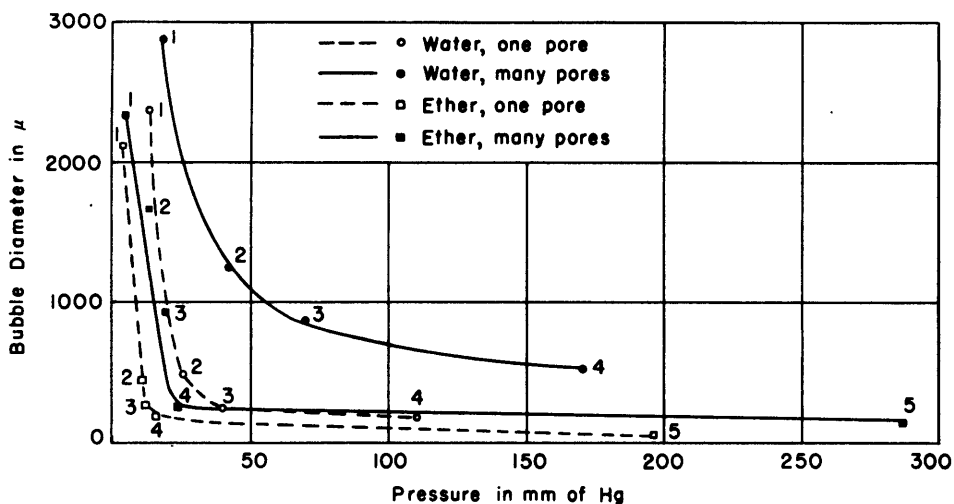


Figure 3 - The Size of the Bubble as a Function of the Fineness of the Filter Plates

size appears useless in general for the production of small bubbles. However, the pore diameter must be made increasingly small the higher the surface tension of the liquid used. It was impossible to determine the basis for the scattering of the ratios between pore diameters of the same plate.

EXPERIMENTS WITH VARIOUS LIQUIDS

The authors also investigated the change in size of bubbles produced with one filter plate in various liquids. A G 2 filter plate was used in all tests and in every case the beaker was filled to the same height, just above the upper edge of the tube.

Meticulous care was exercised in cleaning of the beaker and the filter. After tests of substances with surface activity, the filter was burned out at the cooling temperature of the glass used for constructing the apparatus. This produced no change of pore diameters as was checked by pressure measurement, since the firing temperature of the filter is considerably higher.

The viscosity of liquids was determined with an Applebey (20) viscosimeter. To maintain pressure ratios as constant as possible, the viscosimeter was connected to a pressure flask and all measurements were made under a constant super-pressure of 200 mm (7.87 inches) of mercury. Considering that only technically pure liquids were used, the agreement of the values for η which resulted is favorable compared to the data in the Landolt-Bornstein tables.

A stalagmometer, designed by I. Traube and built by C. Gerhardt in Bonn, was used to determine surface tension. The same instrument was used in

each case. Here also, great care was exercised in cleaning, some of which was done with chromo-sulphuric acid and some by burning. From a count of the drops and the specific weight, the weight of the drops in milligrams was calculated, which is directly proportional to the surface tension. The specific weight was determined by weighing out in the same pyknometer every time. As far as could be checked, the values herein determined agree well with those in the Landolt-Bornstein tables.

The liquids were chosen, on the one hand, for high viscosity; on the other for high capillarity, for example, Turkey-red oil (Monopol-Brilliant oil of the firm Stockhausen and Company in Krefeld) in water. The values derived are summarized in Table 5.

TABLE 5
The Size of Bubbles in Various Liquids
with the same Diaphragm G 2

Liquid	Viscosity Observed η	Surface Tension Observed α	Dielectric Constant ϵ	First Pore Emits Gas (Threshold value)			Entire Plate Emits Gas (Mean value)		
				Test	Pressure mm Hg	Bubble Diameter μ	Test	Pressure mm Hg	Bubble Diameter μ
Water	0.010	72.4	81	15	26	490	16*	42	1240
Water + 2 per cent T.R. Oil	0.0102	40.8		31*	20	350	32*	30	500
Ether	0.0045	21.5	4.3	23	11	270	24*	14	1650
Acetic Ester	0.0060	24.2	6.1	33	14	480	34*	16	740
Alcohol 93.6 per cent	0.0132	22.8	26	35*	14	450	36	22	1660
Alcohol 38.6 per cent	0.0223	29.8	26	37	14	540	38	22	820
Toluol	0.0068	28.8	2.4	39	14	410	40*	18	890
Carbon Tetrachloride	0.0104	26.0	2.2	41	16	450	42	20	800
Glycerin 88.2 per cent	1.42	61.0	56	43*	26	2330	44	38	2890
Glycerin 50.7 per cent	0.0449	54.9		45*	30	1770	46	40	1900
Sulphuric Acid Concentrated	0.1813	52.7	84	47*	28	1060	48*	38	1330
Sulphuric Acid 3n	0.0118	73.0		49	30	980	50	52	2370
Sodium Hydroxide, 2n	0.0141	74.7		51*	30	1030	52	46	1270

* See photographs on page 18 for tests designated by *.

It was attempted to represent the numerical progression of this table for the threshold value of one pore in the form of two curves. Figure 4 shows the relation of the bubble size to the $\log_{10} \eta$; Figure 5 shows the relation to the surface tension represented by the weight of the drops in milligrams. Unlike Schnurmann,

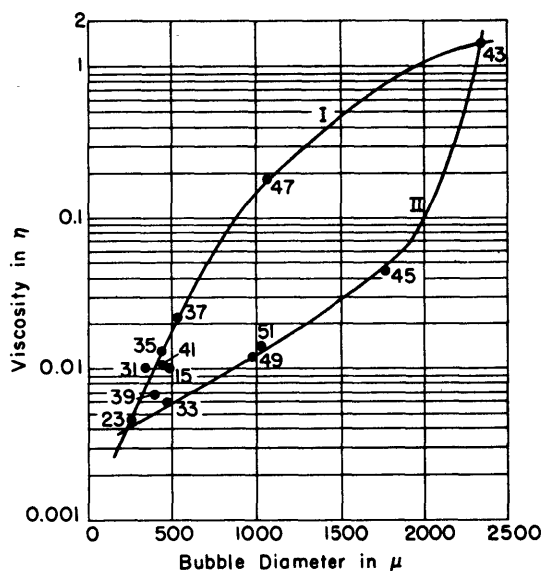


Figure 4

15 Water	41 CCl_4
31 Water and Turkey-red oil	43 Glycerin 88.2 per cent
23 Ether	45 Glycerin 50.7 per cent
33 Acetic ester	47 Concentrated H_2SO_4
35 Alcohol 93.6 per cent	49 3n H_2SO_4
37 Alcohol 38.6 per cent	51 2n NaOH
39 Toluol	

Unlike Schnurmann, the authors are unable definitely to determine from the result of Curve I, Figure 4, the most favorable point of viscosity for representing the bubble size because Test 45 with 50.7 per cent glycerin drops out completely, and there seems to be no justification for Curve II. In Figure 5, on the other hand, Curve III includes the values of the surface tension for other materials which are to a certain extent related by viscosity. Here, however, only water and aqueous solutions drop out. The straight Curve IV which unites ether, water and Turkey-red oil, and water seems to be still incomprehensible in this respect.

Strong electrolytes, as Schnurmann has already represented, also drop out completely. No effect whatever of the dielectric constant* can be perceived. The usual physical constants of the liquids alone apparently fail to furnish a clear picture which would give a complete representation of the size of the bubble as a function of the nature of the liquid. However, even this limited number of measurements suggests the conclusion that the surface tension is especially important. This also appears of very considerable practical importance. The technical problem of aerating or ventilating biologically important liquids, for example yeast suspensions, by ceramic filter plates was already mentioned at the outset. Hitherto it was thought that the porosity of the plates would have to be as small as possible for this purpose. This

* Values according to Landolt-Bornstein Tables, Fourth Edition, 1912.

is also supported by the absolute measurements given in Tables 3 and 4. Beyond this, however, the effect of surface reaction which diminishes the size of the bubbles shows that it is not necessary to decrease the pore diameters of the filter plates arbitrarily. Decreasing the surface tension brings the advantage that by this means very fine gas bubbles can be produced with medium fine filter plates at low gas pressure. In washing gases in the laboratory it might be a good idea, other things being equal, to favorably affect both the size of the bubbles and the cleaning process whenever possible by the addition of materials which are highly surface-active.

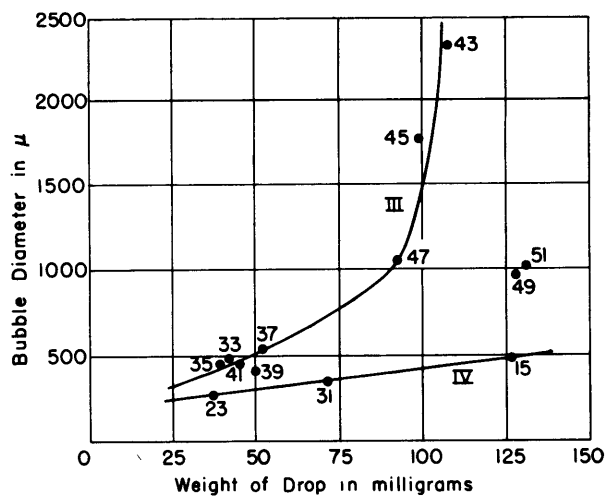


Figure 5

15 Water	41 CCl ₄
31 Water and Turkey-red oil	43 Glycerin 88.2 per cent
23 Ether	45 Glycerin 50.7 per cent
33 Acetic ester	47 Concentrated H ₂ SO ₄
35 Alcohol 93.6 per cent	49 3n H ₂ SO ₄
37 Alcohol 38.6 per cent	51 2n NaOH
39 Toluol	

EFFECT OF PRESSURE

In all these test series two measurements were always taken. One of these was related to the excess pressure at which a single pore emitted gas, whereas the other measurement designated the limit value, as accurately as possible, at which the entire surface of the filter plate discharged gas. Table 1 shows that circular orifices, i.e., perforated platinum plates and glass capillaries, of the size of coarse and medium filter plates cause no important variations in the size of the escaping gas bubbles, occasionally even at considerable pressure variations. Thus, if it is found that with a given filter both fine and coarse bubbles occur at increased pressure, the reason must be sought. There are two possible explanations:

1. The size of gas bubbles depends chiefly on the diameter of the orifice at the surface of the plate. The following experiment substantiates this explanation:

Two capillaries of different diameters were fused to a wide tube at the top. The size of the rising gas bubbles was read against a millimeter scale. Then the widened upper portion was cut off and the diameter of the rising bubbles was remeasured. The following data were obtained:

	Bubble diameter in mm (approximate)	
	Widened or Flared Tube	Capillary Section
Capillary 90 μ diameter	3.5	1
Capillary 630 μ diameter	5	2

It could accordingly be assumed for filter plates that a relatively uniform pore is the widest and develops a relatively small gas bubble in spite of this. As the pressure is increased, finer pores whose orifices, however, are considerably larger than those of the widest pore can be made to emit gas. Large bubbles would be discharged from the large aperture.

2. It could be that several closely adjoining small bubbles would coalesce to large ones on the surface of the plate as the pressure is increased. This explanation is supported by the fact that larger bubbles are always observed, if a filter is inserted into the liquid upside down so that the bubbles have an opportunity to unite before they rise along the edge of the gas-distributing tube. However, as it did not seem technically possible to explain these conditions with certainty, measurements with filter plates which faced downwards, i.e., upside down, were omitted.

A third explanation, namely that larger bubbles were formed in one and the same pore simply by increasing the pressure, seems very improbable in view of the measurements cited for clearly defined individual orifices.

In all the cases hitherto considered the column of liquid terminated at the upper end of the colorimeter tube. Hence, the bubbles were photographed under approximately uniform conditions of pressure. A few experiments for purposes of orientation at increased and decreased pressure above the column of liquid were performed.

The increase in pressure was effected by attaching a glass cylinder of the diameter of the beaker in a vertical position to the top of the beaker by a rubber tube ligatured with wire. The height of the column of liquid in the beaker extended in this manner was 1550 mm (61.02 inches). The value which corresponds to this water pressure must be considered in evaluating the manometer reading, see Table 6.

To produce negative pressure the beaker was sealed with a two-hole perforated rubber stopper through which one tube led to a pump and the other to the diaphragm. A stationary condition had to be maintained by a small, continuous supply of air. This was achieved by a screw petcock in the air line. In this case a second manometer was connected in the line between the beaker and pump, see Table 7.

TABLE 6

Bubble Size at Positive Pressure Above the Vessel

Filter	Liquid	First Pore Emits Gas (Threshold value)				Entire Plate Emits Gas (Mean value)			
		Test	Pressure mm Hg		Bubble Diameter μ	Test	Pressure mm Hg		Bubble Diameter μ
			Divided	After correc- tion for the water column			Divided	After correc- tion for the water column	
G 2	Water	53*	143	24	780	54*	146	27	440
<u>Comparative test with low column of liquid</u>									
G 2	Water	16*	42		1240				

* See photographs on page 19 for tests designated by *.

TABLE 7

The Size of the Bubbles at Negative Pressure in the Vessel

Filter	Liquid	Test	Entire Plate Emits Gas (Mean value)				Comparative Tests at atmospheric pressure	
			Pressure mm Hg			Bubble Diameter μ	Pressure mm Hg	Bubble Diameter μ
			Manometer 1	Manometer 2	Difference			
G 2	Water	55	271	320	49	1510	42	1240

It is very clear from the experiments that the size of the bubbles depends only on the pressure variation on the filter plate.

PERFORATIONS

In a number of recent references (21) (22) (23) (24) the possibility has been suggested of utilizing similar methods, but without diaphragms, to effect a basic improvement in the extraction of liquids with liquids by means of perforations.

It was proved by one of the authors, for example, that the extraction of an aqueous solution of 3 ferric-sulfocyanide with ether actually occurred eight times as rapidly by use of a coarse glass filter which covered the whole section of the cylindrical extraction tube, as by use of a single glass tube about 5 mm (0.2 inch) in diameter. There is a twofold reason for this. First the favorable cross section of diffusion, second the small

surface area of the rising droplets of ether. Under these circumstances the present apparatus was further used to make some provisional experiments on perforation. The extraction liquid was poured into the beaker through a funnel attached to the top of the tube which bore the filter plate. The liquid flowed into this funnel from a tubulated flask equipped with a glass cock. As a result of the resistance offered by the diaphragm it was easy to maintain a constant pressure in the conducting tube. The height of this pressure was noted as shown in Table 8.*

TABLE 8
Perforations

Test	Pair of Liquids	Diaphragm	The height of the liquid in the auxiliary or attached tube above the surface in the beaker in mm	Diameter of the Drop μ	Boundary Surface Tension (25) dyne/cm
56*	Ether-Water	G 1	95	1330	10.6
57*	Ether-Water	G 3	215	700	10.6
58*	Acetic Ester-Water	G 1	80	5240	6.65
59*	Acetic Ester-Water	G 1	25	4500	6.65
60*	Acetic Ester-Water	G 3	220	2270	6.65
61*	Acetic Ester-Water plus 2 per cent Turkey-red oil	G 1	20	540	3.48

* See photographs on page 19 for tests designated by *.

As occasional tests with the same filter plate have shown that ether in water produces much smaller drops than acetic ester or benzol, tests were carried out to compare water with ether in this respect, as well as with acetic ester. Filter plates of various pore diameters were installed. Results show that the scale of the decrease in size of the bubbles is the same for both liquids when a finer filter plate is used. It should be expected from the coefficients of viscosity and surface tensions as compared to air, that the drops ought to be about equal in size for acetic ester and ether. Actually, however, very considerable differences must be mentioned. These are perhaps based on the boundary surface tension or perhaps also on

* The data were taken by Dr. Weber, Charlottenburg. For methodology, see reference (25).

mutual solubility of the liquids. In any case, the size of the drops for acetic ester is much greater than for ether. The solubility of acetic ester in water is greater, the boundary surface tension is smaller compared to water than for ether.

Since the effect of Turkey-red oil, which has high capillary action, was very pronounced when diaphragms were tested with air, an experiment was undertaken in which acetic ester was perforated through water plus 2 per cent Turkey-red oil. The difference in pressure varied but little from a comparative test with water. In contrast the size of the droplets of acetic ester was markedly decreased. Thus it was found that a surface-active material dissolved in water has an effect on gases similar to that on a non-miscible liquid.

The same apparatus was tried out with water and an extraction medium of higher specific gravity. This naturally required a reversal of method. This was achieved by introducing the water, as the lighter fluid, from above, so that it rose into the heavier fluid through the glass filter. Carbon tetrachloride was chosen as a typical heavier fluid. In this case the effect which was noted in all other cases was completely absent. Even at very great velocities of flow, the water flowed together directly on the surface of the filter and rose along the feed tube while continually moistening the glass and then again spread on the surface of the carbon tetrachloride. Addition of a small quantity of Turkey-red oil to the water did not alter the behavior.

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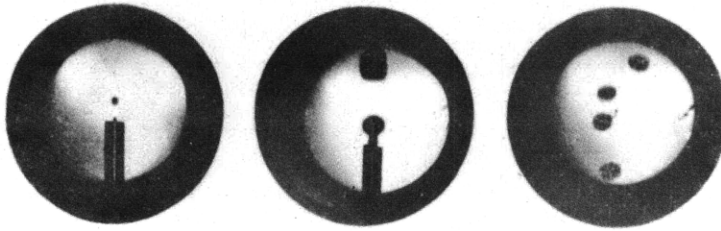


Table 1, Test 1
Diameter of
capillary 90
length 44 mm
180 mm Hg
Water

Table 1, Test 5
Diameter of
capillary 630
length 43 mm
8 mm Hg
Water

Table 1, Test 11
Platinum Plate
20 thick
Diameter of
bore 243
16 mm Hg
Water

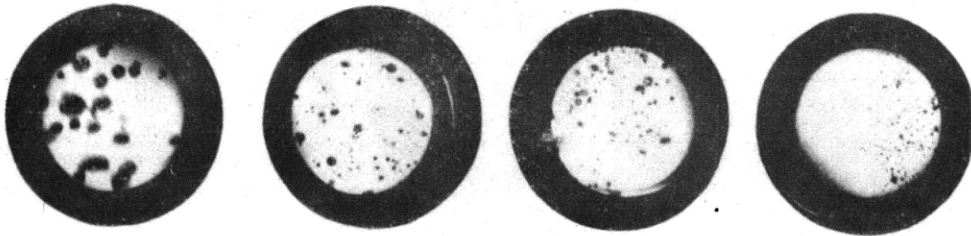


Table 3, Test 14
Glass Filter G 1,
Many Pores
18 mm Hg
Water

Table 3, Test 16
Glass Filter G 2,
Many Pores
42 mm Hg
Water

Table 3, Test 18
Glass Filter G 3,
Many Pores
70 mm Hg
Water

Table 3, Test 20
Glass Filter G 4,
Many Pores
170 mm Hg
Water

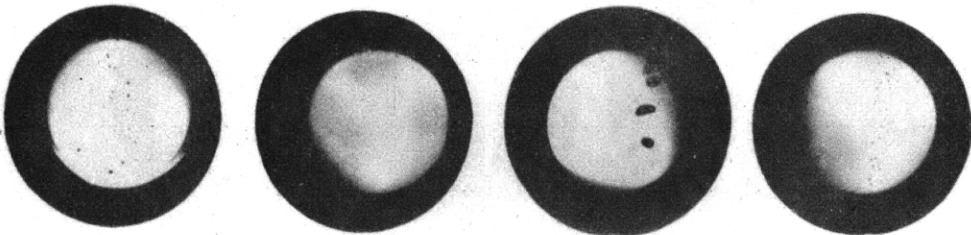


Table 3, Test 17
Glass Filter G 3,
One Pore
40 mm Hg
Water

Table 3, Test 19
Glass Filter G 4,
One Pore
110 mm Hg
Water

Table 4, Test 21
Glass Filter G 1,
One Pore
4 mm Hg
Ether

Table 4, Test 25
Glass Filter G 3,
One Pore
12 mm Hg
Ether

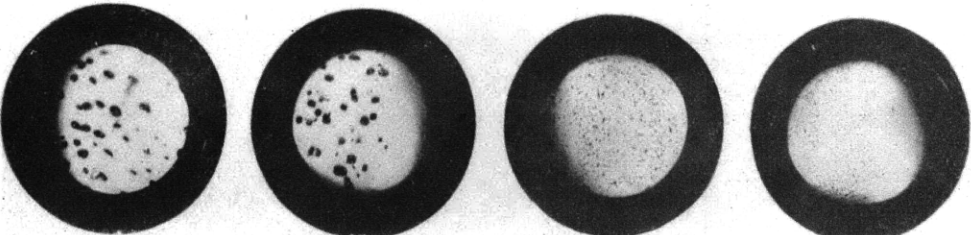


Table 4, Test 24
Glass Filter G 2,
Many Pores
14 mm Hg
Ether

Table 4, Test 26
Glass Filter G 3,
Many Pores
20 mm Hg
Ether

Table 4, Test 28
Glass Filter G 4,
Many Pores
34 mm Hg
Ether

Table 4, Test 30
Glass Filter G 5,
Many Pores
290 mm Hg
Ether

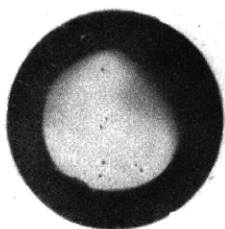


Table 5, Test 31
Glass Filter G 2,
One Pore
20 mm Hg
Water plus
Turkey-red oil

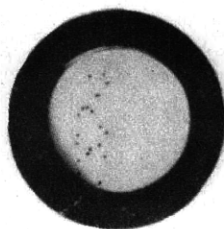


Table 5, Test 35
Glass Filter G 2,
One Pore
14 mm Hg
93.6 per cent
Alcohol

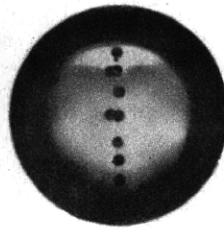


Table 5, Test 43
Glass Filter G 2,
One Pore
26 mm Hg
88.2 per cent
Glycerin

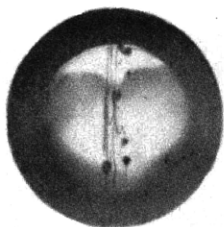


Table 5, Test 45
Glass Filter G 2,
One Pore
30 mm Hg
50.7 per cent
Glycerin

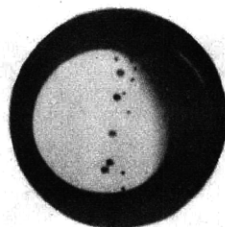


Table 5, Test 47
Glass Filter G 2,
One Pore
28 mm Hg
Concentrated
Sulphuric Acid

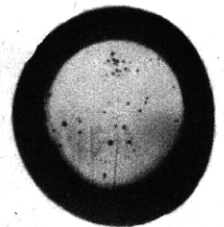


Table 5, Test 51
Glass Filter G 2,
One Pore
30 mm Hg
2n Sodium
Hydroxide

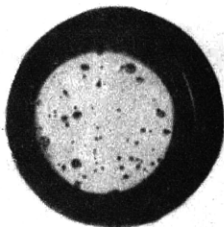


Table 5, Test 16
Glass Filter G 2,
Many Pores
42 mm Hg
Water

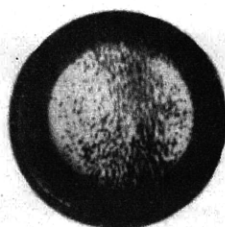


Table 5, Test 32
Glass Filter G 2,
Many Pores
30 mm Hg
Water plus
Turkey-red oil

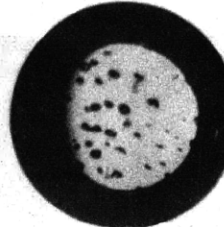


Table 5, Test 24
Glass Filter G 2,
Many Pores
14 mm Hg
Ether

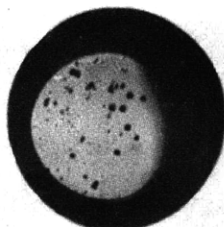


Table 5, Test 34
Glass Filter G 2,
Many Pores
16 mm Hg
Acetic Ester

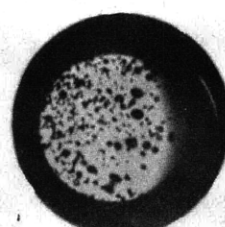


Table 5, Test 48
Glass Filter G 2,
Many Pores
38 mm Hg
Concentrated
Sulphuric Acid

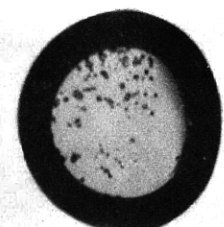


Table 5, Test 40
Glass Filter G 2,
Many Pores
18 mm Hg
Toluol

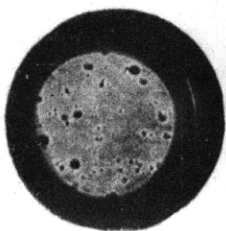


Table 6, Test 16
Glass Filter G 2,
Many Pores
40 mm Hg
Water
(Low water
column)

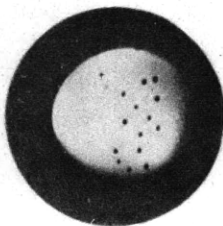


Table 6, Test 53
Glass Filter G 2,
One Pore
143 mm Hg
Water
(High water
column)

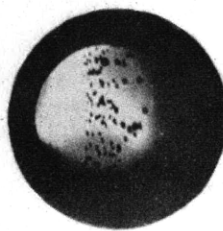


Table 6, Test 54
Glass Filter G 2,
Many Pores
146 mm Hg
Water
(High water
column)

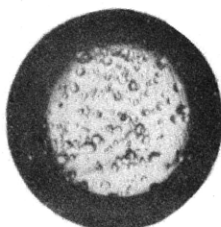


Table 8, Test 56
Glass Filter G 1
Superpressure of
the light liquid:
95 mm
Ether/Water

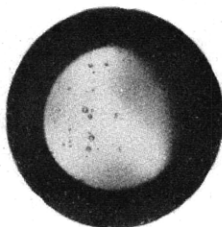


Table 8, Test 57
Glass Filter G 3
Superpressure of
the light liquid:
215 mm
Ether/Water

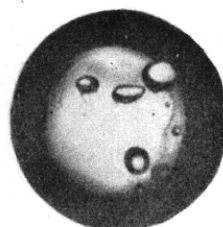


Table 8, Test 59
Glass Filter G 1
Superpressure of
the light liquid:
only 25 mm
Acetic Ester/Water

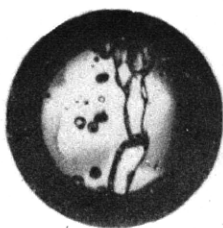


Table 8, Test 58
Glass Filter G 1
Superpressure of
the light liquid:
80 mm
Acetic
Ester/Water

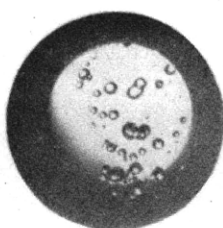


Table 8, Test 60
Glass Filter G 3
Superpressure of
the light liquid:
220 mm
Acetic
Ester/Water



Table 8, Test 61
Glass Filter G 1
Superpressure of
the light liquid:
only 20 mm
Acetic Ester
(Water plus
Turkey-red oil)

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