A PHOTOGRAPHIC INVESTIGATION INTO THE DISINTEGRATION OF LIQUID SHEETS

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CONTENTS

The types of apparatus used to produce liquid sheets are classified according to the manner in which the energy is imparted to the liquid. The factors influencing the development, stability and manner of disintegration of a liquid sheet are examined more particularly with flat sheets produced from the single-hole fan-spray nozzle and the spinning disk.

The development of the liquid sheet is influenced by the liquid properties. As the working pressure is raised the width of the sheet increases, but this development is hindered by high surface tension. It is shown that the effect of a surface-active agent on the development is only influential where the surface is not expanding or changing rapidly. Consequently its effect is more pronounced as the liquid moves farther away from the orifice.

Increase of viscosity at the same pressure causes the region of disintegration to move away from the orifice, and high viscosity maintains the sheet undisturbed by air friction. Density has little effect on the area of the sheet.

The effect of turbulence in the orifice is shown to be responsible for at least two types of disturbance in the sheet which results in holes being formed near the orifice. The depth of the disturbance in the sheet has to be equal to the thickness before disruption occurs. Similar disruption

through the formation of holes can be caused by suspensions of unwettable particles. Wettable particles in low concentration, irrespective of their size, have no effect on the manner of disintegration.

The most placid, stable and resistant sheet is obtained with a liquid of high surface tension, high viscosity, low density, giving low turbulence in the nozzle. Such a sheet will disintegrate when the velocity is raised and disintegration can occur through air friction.

The easiest sheet to disintegrate is obtained with a liquid of low surface tension, low viscosity, low density and with low turbulence in the nozzle. Disintegration will occur near the nozzle at low velocities through waves caused by air friction.

Disintegration through the formation of holes in the sheet can occur at low velocity with liquids of high surface tension, low viscosity and high density where turbulence obtains in the nozzle.

The formation of ligaments or threads is a necessary stage before the production of drops. Threads can be formed directly from any free edge or in the boundary.

A free edge is formed when equilibrium exists between surface tension and inertia forces. In the spinning disk, at low flow rates, where the sheet is in contact with the surface of the disk, drops are formed at the ends of threads which break down into a limited number of sizes.

At high flow rates a free edge of liquid exists outside the periphery of the disk with the formation of more irregular threads and a wider spectrum of drop sizes results.

Where perforations occur in the sheet, expansion of the hole by surface tension occurs very regularly so that the holes remain nearly circular until they coalesce forming long threads. These long threads quickly become unstable and break down into drops.

Threads being approximately uniform in diameter produce uniform drops, but the irregular areas of liquid which occur when a number of holes expand towards each other produce a wide variety of drop sizes.

When the velocity of the sheet in the atmosphere is high, air friction causes slight variations in the sheet to develop rapidly into major wave disturbances, and these can result in holes being blown through the sheet so that disruption starts before the formation of a leading edge.

With liquids having visco-elastic properties the sheet disintegrates through the formation of waves, but the rapid increase of viscosity, as the rate of shear is reduced, prevents further break-up of the threads into drops and a web of fine threads only is produced.

Notation

a_J	jet radius	r_0	orifice radius
g	gravitational constant (981 cm/s^2)	V	velocity
L	break-up length	γ	surface tension (dynes/cm)
P	working pressure (Lb./in.^{2})	ρ	liquid density (g/ml.)

1. Introduction

In recent years the use of the insecticides with residual effect has stimulated interest in the performance of spray nozzles used to coat large surfaces. In spraying for insecticidal use it is desirable only to stipple the surface with uniform particles at equal distance rather than to form a continuous film. It is also important to be able to spray very small quantities per unit area and yet achieve economy of material and uniformity of desposit by reducing losses to the minimum.

Pressure atomizers or nozzles which derive their energy for disintegration solely from the liquid pressure are most convenient for this use because they are simple in construction and, for liquids of low viscosity, the power required is small.

In other applications, such as in spray drying, modifications of the spinning cup or disk are now used with the object of obtaining a more uniform particle size than can be achieved with pressure atomizers. In oil firing there is a greater need for more powerful atomizers to deal with fuels of higher viscosity.

Means of controlling the drop size is desirable in many industrial applications, and this will only be achieved by a close study of the mechanisms of break-up of liquid sheets.

This paper deals with some of the factors influencing the manner of disintegration of sheets of liquid.

The fundamental principle of the disintegration of a liquid consists in increasing the surface area of a sheet or rod until it becomes unstable and disintegrates. Disintegration is achieved by this process in the simple cylindrical jet of liquid which breaks up into relatively large drops. To obtain smaller drops from a cylindrical jet, high working pressures have to be employed, and disintegration then occurs largely by the formation of thin threads which are drawn out of the main rod by air resistance. Lee & Spencer (1933) made an extensive photographic study of this process. A similar action occurs with 'twin fluid' atomizers, where threads are torn off by a surrounding high-velocity air stream.

The method usually employed to produce small drops at lower working pressures is to spread the liquid into a thin sheet. Such sheets of liquid may be produced by using orifices with specially designed approach passages or by feeding the liquid to the centre of a rotating disk or cup.

The disintegration of liquid sheets has been examined previously. Fogler & Kleinschmidt (1938), during a study of spray drying with swirl-spray nozzles, found that pronounced waves may be superimposed on the conical sheet. Fraser, Connor & Wolfe (1939) examined the disintegration of the conical sheet of liquid issuing from a swirl-spray nozzle by high-speed photography. They found that the spraying of an emulsion of soluble oil in water results in a network of unstable liquid threads caused by perforations in the sheet. Simons & Goffe (1946) extended this work, and their photographs show that disintegration can also occur through superimposition of a wave motion on the liquid. Sheets of liquid are torn off and tend to draw up under the action of surface tension but may suffer disintegration by air friction before a regular network of threads can be formed.

This paper gives further insight into the manner of disintegration of liquid sheets by the use of an improved photographic technique developed in this laboratory (Coulter & Dombrowski 1949). It establishes the basic mechanisms of thread and drop formation and shows that the liquid threads are principally caused by perforations in the sheet. It shows that the history of the perforations determines the stage of growth at which the threads break up. If the holes are produced by air friction the threads so produced are broken up very rapidly by the air and they may be difficult to observe. If, however, the holes are caused by other means, such as turbulence in the nozzle or suspensions of unwettable particles, the threads are broken more slowly by surface tension. We believe that the life history of the holes has an important bearing on the resultant drop size, and it would appear that if the perforations in the sheet could be made to occur at the same distance from the orifice, then the thread diameters and resulting drops could be made to be more uniform.

The study of liquids with visco-elastic properties is still being made. Anomalous behaviour has been found with certain sodium-mercury amalgams where the threads remain unbroken after leaving the sheet, and this is also being further investigated.

2. The energy to produce liquid sheets

The types of apparatus used to produce liquid sheets may conveniently be classified according to the manner in which the energy is imparted to the liquid.

(a) *Energy imparted by pressure*

The liquid is forced under pressure through an orifice, and the form of the resulting liquid sheet can be controlled by varying the direction of flow towards the orifice. By this method flat and conical sheets can be produced.

(i) *Methods of producing flat sheets*

To cause a fluid to flow into a flat sheet two streams of fluid of equal momentum are required to travel towards each other, either in space or behind an orifice. Where two jets of liquid are caused to strike each other at an angle usually greater than 90°, a thin sheet is formed in a plane perpendicular to the plane of the jets and containing their bisector as shown by figure 1*a*. Figure 1*b* illustrates the fully opposed jets at 180°, which will cause the liquid to spread out in a circular sheet. If a large part of such a circumferential slot is closed, the liquid behaves similarly, and a sector or fan-like sheet is produced. If the diameter of a tube is large, it is not necessary for the liquid to be flowing initially in both directions, because it will do so at the curved slot orifice (figure 1*c*).

If the boundary flow-stream lines towards a circular orifice are curved so that flow occurs radially inwards from all directions, they form a circular jet. When a circular orifice is distorted and made elliptical or eventually into a slot, the stream lines flow towards each other mainly from two directions, and thus the liquid issues as a sheet in the plane of the slot (figure 1*d*). If the slot is in a flat surface the sheet has a small spray angle, and if the slot is of uniform width, the flow contributed by the ends will cause thickening of the rims of the sheet.

If a short slot or rectangular orifice is formed at the end of a rectangular tube (figure 1*e*), the stream lines at the edges are diminished so that the flow is now almost entirely in opposite directions and a sheet is produced having a greater angle. In this case the centre of pressure is behind the rectangular orifice, and the edges of the sheet are restrained by the side walls of the rectangular tube. When the side walls are cut away, as in figure 1*f*, the edges of the sheet are not restrained and the divergence of the sheet is dependent only on the pressure and the properties of the liquid. These phenomena are made use of in the various designs of single-hole fan-spray nozzles such as type *C* in figure 8. The two opposed feed channels *A–A* cause the stream lines near the wall to converge towards the axis. This tends to increase the pressure at the axis and results in the formation of a fan-shaped sheet of liquid in a plane at right angles to the opposed feed channels.

(ii) *Methods of producing conical sheets*

For reasons of simplicity of analysis, we have studied the process of disintegration mostly with flat sheets, but the process of distintegration of a conical sheet is identical.

When liquid is caused to flow through a narrow divergent annular orifice or around a pintle against a divergent surface on the end of the pintle, a conical sheet of liquid is produced, where the liquid is flowing in radial lines. The angle of the cone and the root thickness of the sheet can be controlled by the divergence of the spreading surface and the width of the annulus. Where design calls for very small outputs this method is not so favourable because of difficulties in attaining an accurate annulus.

Where the liquid is caused to emerge from an orifice with a tangential or swirling velocity, resulting from its path through one or more tangential or helical passages before the orifice, a conical sheet is also produced. In such swirl-spray nozzles the rotational velocity is sufficiently high to cause the formation of an air core in the orifice and, also, in the swirl chamber before the orifice.

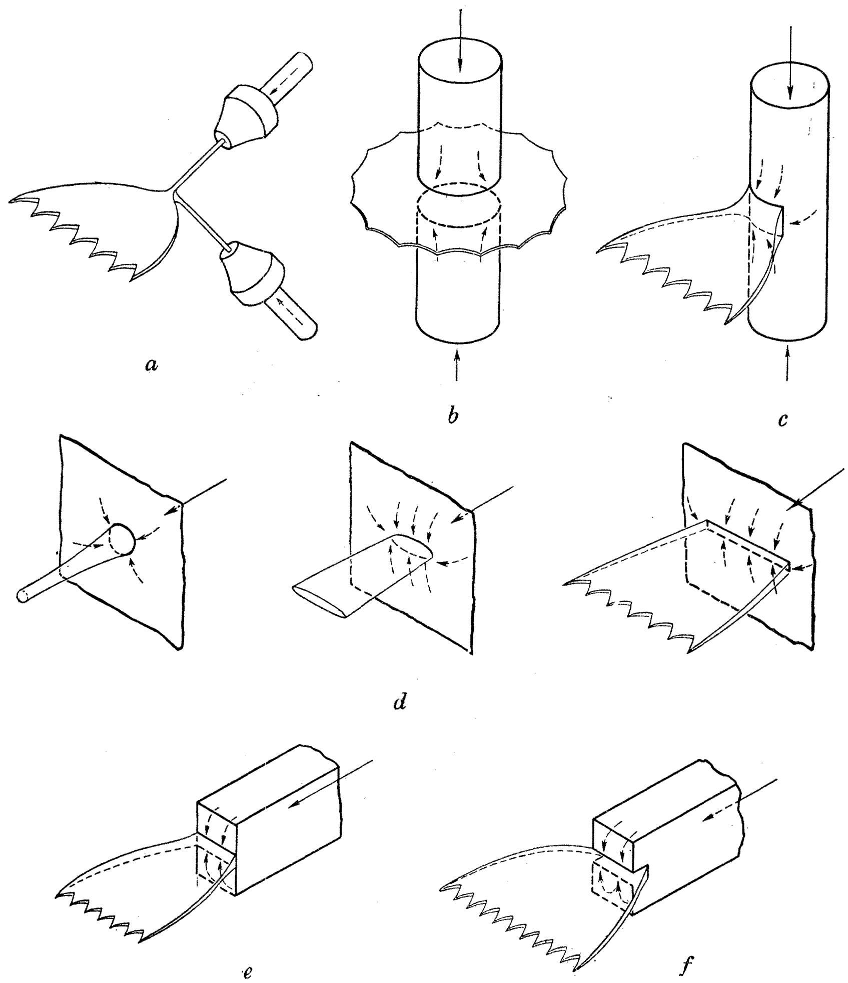

FIGURE 1. The formation of flat sheets.

Figure 2 is an example of a typical high-grade swirl-spray nozzle and shows the general arrangement of the swirl grooves, swirl chamber and orifice.

The hydrodynamics of flow through swirl-spray nozzles has been considered by many workers, but the most satisfactory treatments are those given by Taylor (1950), Hodgkinson (1950) and Binnie & Harris (1950), who have applied boundary-layer theory to the flow.* Taylor has pointed out that viscous drag at the surface of the swirl chamber retards the rotating liquid which is unable to remain in a circular path against the radial pressure balancing the centrifugal motion. Consequently, a current is set up directed towards the

* Work on this subject from this laboratory is being published elsewhere.

orifice through the surface boundary layer. It is shown that even for liquids of low viscosity such as water, a considerable proportion of the flow will reach the orifice by way of the boundary layer. In establishing the momentum equation for the boundary layer, Taylor assumed non-axial flow in the main stream. Binnie & Harris have derived momentum equations where the main stream has a finite axial velocity. Hodgkinson has further extended the boundary-layer method of approach and has shown that the flow through the orifice may also be contributed to by a boundary layer which surrounds the air core.

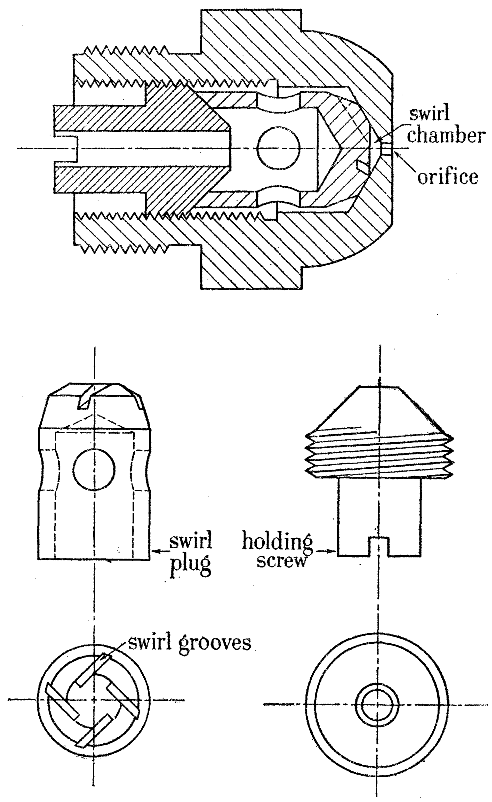

FIGURE 2. Typical small-volume swirl-spray nozzles.

The form of the conical sheet has been studied by several workers. It depends upon the working pressure and passes through a number of stages as the pressure is increased.

At low pressures, the liquid first forms a closed bubble. With increase of pressure the bubble opens to form a hollow cone and the region of disintegration moves away from the orifice. The pressure at which the bubble opens to a hollow cone depends upon the design of the nozzle and the physical properties of the liquid, particularly on the viscosity and surface tension.

As the pressure is further increased, the region of disintegration of the sheet moves back towards the orifice. Edge effects which are often marked in flat sheets do not, of course, arise in conical sheets.

(*b*) *Energy imparted by centrifugal force*

In mechanical atomization, energy is imparted to the liquid which is being fed on to a rotating surface and spread out by centrifugal force to the periphery. The surface can take many forms, such as a cup, a disk, or a slotted wheel.

Walton & Prewett (1947) showed that a spectrum of drops of uniform size was formed from a disk over a range of peripheral speeds and flow rates.

Straus (1950), in this laboratory, and Marshall & Seltzer (1950) studied the flow and drop sizes from a spinning disk. Hinze & Milborn (1950) studied the flow within and the break up of a liquid from a spinning cup.

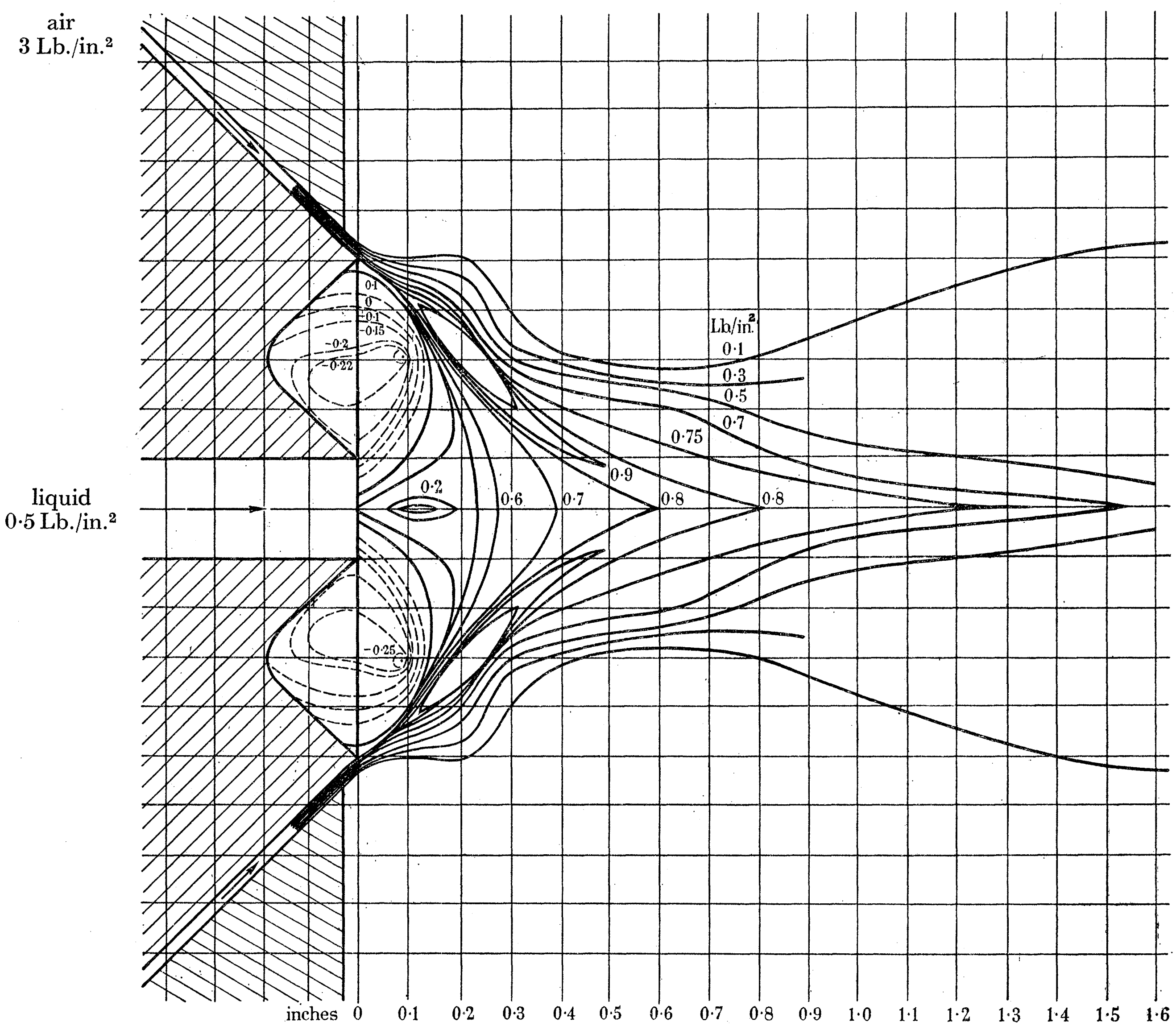

FIGURE 3. Isobaric diagram of vortex cup atomizer.

It has been shown that the liquid flows over the disk in the form of a spiral, and our photographs show that the streamlines in the liquid sheet extending from the edge of the disk are of involute form.

At relatively low rates of liquid flow the liquid collects into a thick rim at the periphery of the disk prior to disintegration. At high rates of flow the liquid rim is forced away from the edge of the disk to form a sheet extending some distance from the periphery.

(c) *Energy imparted by a gas*

In twin-fluid atomizers, energy is imparted to the liquid by allowing a high-velocity gas stream to impinge on it, either internally within the atomizer body, or externally. In the conventional external mixing annular nozzle, gas is passed through an annulus concentric with a plain orifice where the jet of liquid is fed at sufficient pressure to maintain a suitable flow rate. Fraser (1934) showed that the energy transfer in this system was very inefficient, and his study of the air flow outside such atomizers led to the principle employed in the wide-tip or 'vortex-cup' type. In this form the gas is made to issue from an annulus surrounding, but some distance away from the central liquid orifice, and the liquid is made to spread out into a sheet.

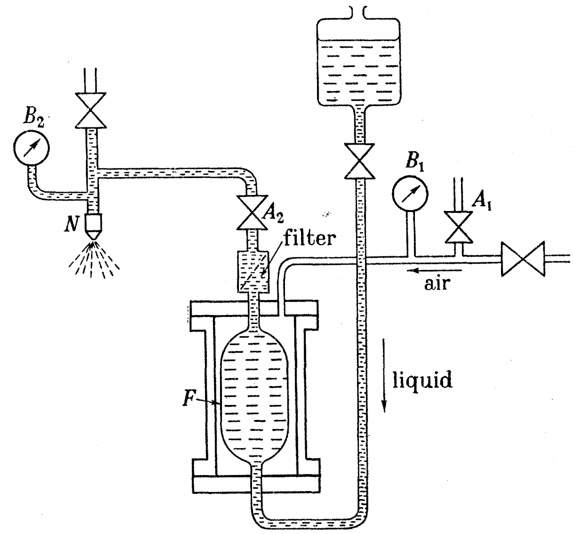

FIGURE 4. Spraying apparatus.

Figure 3 is an isobaric diagram showing the distribution of pressure of the air outside such a nozzle. The isobars show that a vortex ring is formed in the air in the cup-shaped depression around the liquid orifice. This vortex ring causes the air immediately around the orifice to be travelling in a direction opposite to the liquid leaving the orifice. By this means the liquid is constrained to flow along the surface of the cup-shaped depression around the orifice and to spread outwards as a sheet towards the periphery to meet the high-velocity air stream from the annulus at right angles. The liquid is then broken up by an interchange of momentum with the air stream and caused to flow towards the axis. The air pattern outside the nozzle can be likened to an inverted hollow conical sheet of air constraining a vortex ring against the face of the nozzle. Liquid is forced to rotate on the boundaries of the vortex ring until it can escape through the conical sheet of air itself and be propelled forward. Thus the time of contact between the liquid and the high-velocity air during which atomization can occur is greatly increased and the energy transfer improved.

3. EXPERIMENTAL METHODS AND APPARATUS

(a) *Spraying apparatus*

The apparatus which is illustrated diagrammatically in figure 4 was designed to supply gas-free liquid to a nozzle (N) under controlled conditions. The liquid was contained and isolated in a flexible bag (F), pressure being applied by means of compressed air acting on the outside of the bag. Valves (A_1) and (A_2) enabled the pressure to be controlled within fine limits, as indicated by the Bourdon gauges (B_1) and (B_2).

To spray mercury an all-steel apparatus was employed. The mercury was stored in a high-pressure container and was ejected by means of compressed air. The spray nozzles were made entirely from porcelain. Safety precautions had to be adopted while the mercury was being sprayed. For spraying the alkali metals an electrically heated all-steel autoclave was used. The general arrangement of the apparatus is shown in figure 5, which sufficiently indicates the control arrangements. The liquid metal was sprayed into a closed vessel filled with carbon dioxide and the photographs taken through a window. The metal particles were quenched by falling into liquid paraffin covering the floor of the chamber.

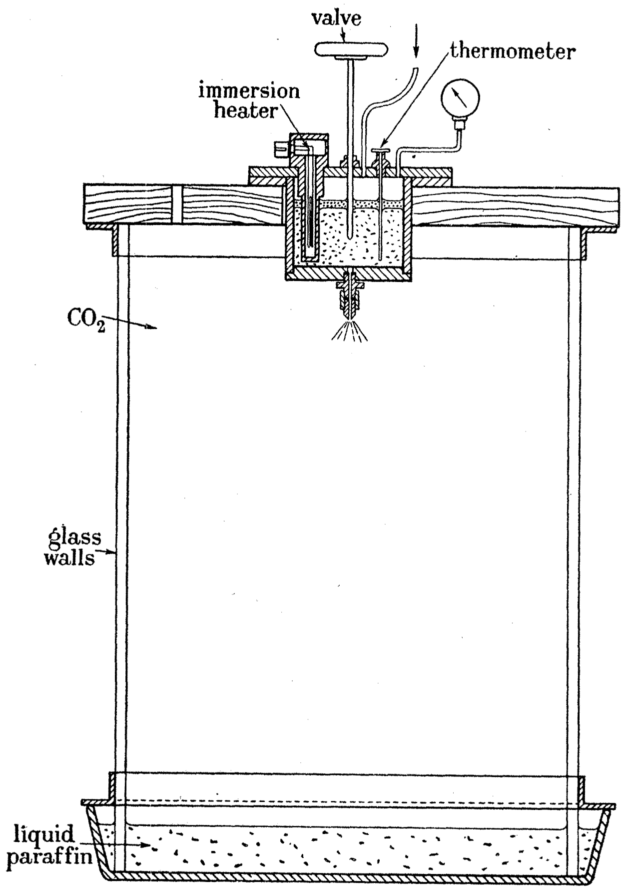

FIGURE 5. Spraying apparatus for liquid metals.

(*b*) *Photographic technique*

Fast-moving objects may be photographed either through the use of high-speed shutter mechanisms or by means of a light flash of very short duration. The fastest mechanical shutters have a duration of the order of 500 μs, during which time spray drops of average size may travel as much as one hundred times their own diameter. Rapid light flashes with an effective duration of only a few microseconds can be produced by electrical discharges, and they provide the only practicable method of obtaining 'still' photographs of spray particles.

In the light-flash method a choice must be made between the use of incident light from the object or transmitted light to form a shadow of the object. The method of incident lighting was chosen, although it is a more difficult technique, since a clearer picture is obtained of the nature of the surface of the liquid sheet as it leaves the orifice, and of its subsequent disintegration. A much greater quantity of light is required for this form of

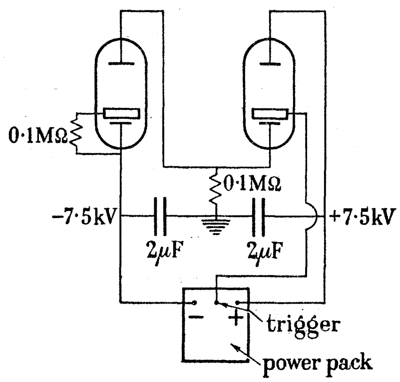

FIGURE 6. Circuit diagram of flash equipment.

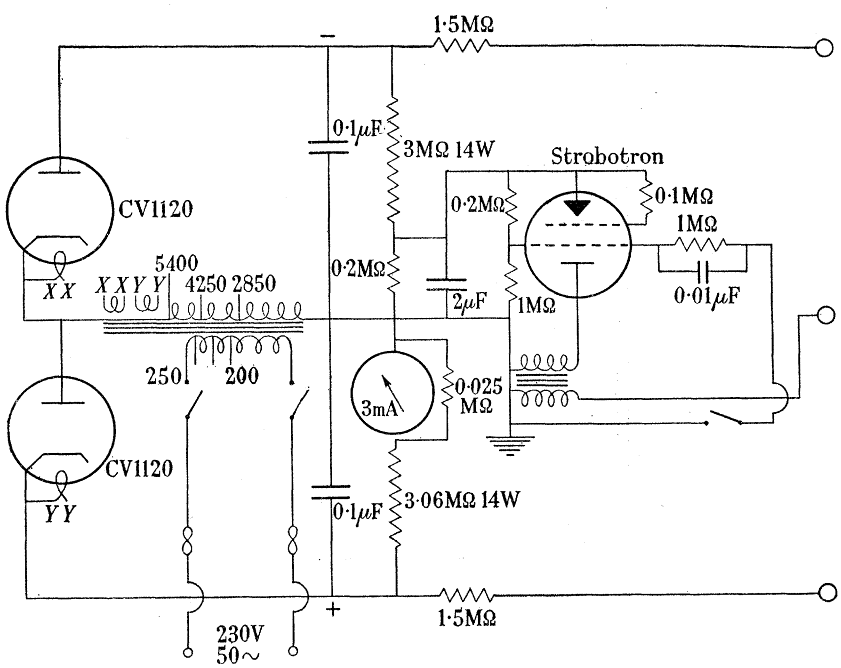

FIGURE 7. 7·5 kV power pack.

illumination than for the shadow method because a lens has to be used and because a small aperture is required to achieve the necessary depth of field. This results almost inevitably in a longer effective flash duration which limits the definition of the small fast-moving drops.

The lighting unit used during this investigation consisted of two Mullard LSD2 'Arditron' flash tubes. These were mounted in reflectors behind diffusing glasses and were connected in series with two 2 μF condensers as shown in figure 6. The condensers were charged to 7·5 kV from a power pack designed in the laboratory (figure 7). A single flash was obtained by means of a trip switch shown in the figure.

A long-focus lens is desirable because diffraction from the edges of the iris can be important at small iris diameters. An enlarging anastigmat is preferable because it is optically corrected for comparatively short object/lens distances. The lens selected for this work was a 7 in. *f*/5·6 Dallmeyer Enlarging Anastigmat lens. Ilford Press Ortho Series II plates were used.

(*c*) *Types of single-hole fan-spray nozzles*

Flat fan-shaped sheets of liquid are produced from four characteristic types of single-hole nozzles. The functional parts of these designs are usually constructed of metal or made from porcelain mouldings. Table 1 shows the range of sizes in each of the four types which have been employed in these experiments.

TABLE 1. DIMENSIONS OF SINGLE-HOLE FAN-SPRAY NOZZLES (FIGURE 8)

type	flow number $\left(\frac{\text{gal./h}}{\sqrt{(\text{Lb./in.}^2)}}\right)$	liquid	orifice dimensions (cm)
A	2·0	water	0·100 diam.
B	2·02	water	0·103 diam.
	4·20	water	0·150 diam.
	7·60	water	0·198 diam.
	13·20	water	0·285 diam.
C	2·40	water	0·122 × 0·061
	1·57	water	0·097 × 0·050
	0·93	water	0·086 × 0·042
	0·92	17 % glycerine/water	0·086 × 0·042
	0·89	37 % glycerine/water	0·086 × 0·042
	0·89	50 % glycerine/water	0·086 × 0·042
	0·87	60 % glycerine/water	0·086 × 0·042
	0·85	69 % glycerine/water	0·086 × 0·042
	0·83	76 % glycerine/water	0·086 × 0·042
	0·79	84 % glycerine/water	0·086 × 0·042
	1·06	acetone	0·086 × 0·042
	1·04	ethyl alcohol (98 %)	0·086 × 0·042
	1·03	kerosene	0·086 × 0·042
	0·99	benzene	0·086 × 0·042
	0·99	toluene	0·086 × 0·042
	0·85	methyl salicylate	0·086 × 0·042
	0·70	carbon tetrachloride	0·086 × 0·042
	0·62	ethylene dibromide	0·086 × 0·042
	0·23	mercury	0·084 × 0·037
	0·74	water	0·079 × 0·037
	0·35	water	0·049 × 0·030
D	3·0	water	0·218 × 0·091 elliptical

The nozzles are designated by a flow number which is a convenient way of comparing their output. Since the discharge of a nozzle is proportional to the root of flow pressure, the flow number is defined as gallons per hour/$\sqrt{}$(flow pressure).

Type A (figure 8)

Nozzles of this design consist of a plate of metal in which a slot is cut across the diameter of the top face and another slot is cut across the bottom face at right angles to the first. The two slots are cut to such a depth that they interpenetrate forming an orifice. In type A the entry slot is cut with a rectangular slotting cutter and the exit slot is milled with a V-shaped cutter, and the orifice is drilled circular.

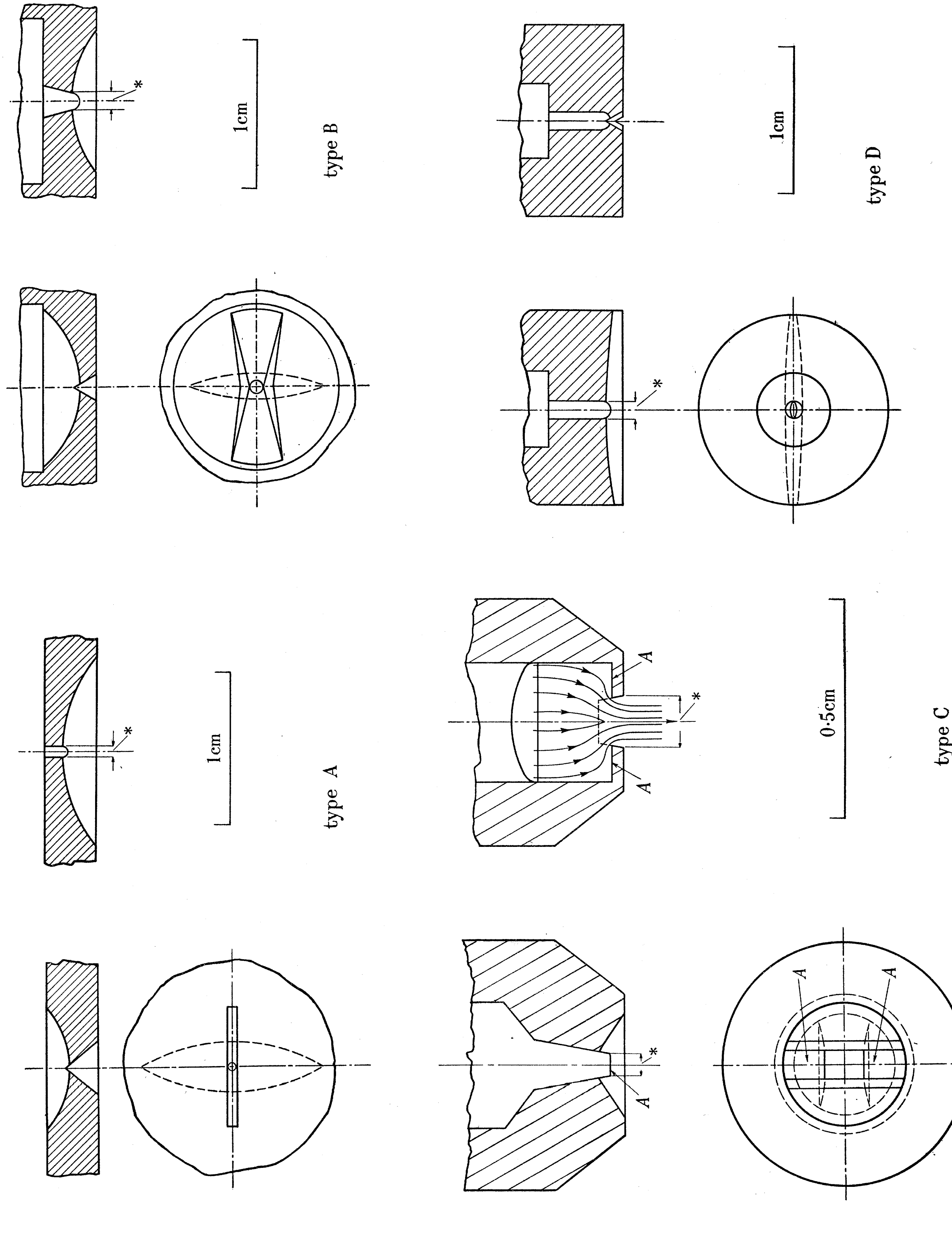

FIGURE 8. Design of single-hole fan-spray nozzles. * For orifice diameters see table 1.

Type B (figure 8)

As in type A, two interpenetrating slots are cut in a plate and the orifice is a circular hole drilled at the point of interpenetration. The entry slot may be formed by making several cuts with a slotting cutter, each one varying by a small angle from another. The exit slot is milled with a radiused V-shaped cutter.

Type C (figure 8)

The functional part of a nozzle to this design is made of porcelain in which two interpenetrating rectangular slots form a rectangular orifice. Both slots are tapered towards the orifice.

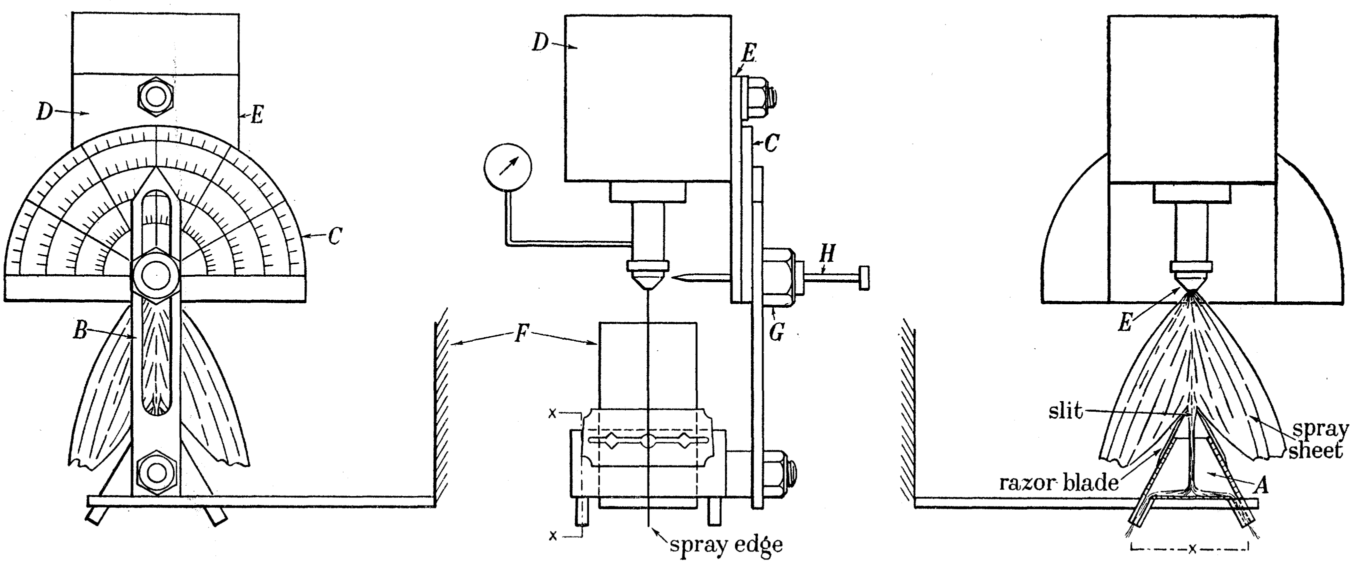

FIGURE 9. Apparatus for determination of spray sheet thickness.

Type D (figure 8)

This design differs from type C in that the entry passage is drilled with a round-nosed tool. The exit passage is milled with a V-shaped cutter of very small angle so that the orifice which is formed at the interpenetration, is elliptical.

The variations in design of these types of nozzle are responsible for marked differences in the spray distribution. Figure 11, plate 6, shows characteristic sheets of liquid produced by the four types and also illustrates the type of distribution curve obtained when spraying equidistant surfaces at the same pressure.*

(*d*) *Measurement of thickness of spray sheet*

In order to analyze some of our results it was necessary to determine the variation of the thickness of the sheet of liquid in a radial and circumferential direction. To do this, output measurements were made of a small section of the sheet at different distances from the orifice. Figure 9 illustrates the apparatus used.

A small section of liquid sheet was collected through a narrow slit in a box (*A*). The slit was formed by two thin blades attached to the tapering walls of the box on which were two outlets. The other parts of the apparatus enabled the slit to be accurately positioned. Pointer (*B*) and mirror (*F*) were fixed at right angles to the box, as shown. Protractor

* The character of the distribution from such nozzles will be discussed in another paper.

(C) was fixed to nozzle holder (D) by means of plate (E). The box was positioned by means of holding screw (G), through which was threaded a locating pin (H). Thus, (A), (B) and (F) could be turned as a whole through any angle, its apex being determined by the position of the pin. The operating procedure was as follows:

With the aid of the mirror the nozzle was positioned so that the spray sheet was set to cut the slit at right angles. The locating pin was set to the theoretical origin of the spray which was taken as the point of intersection of the edges of the sheet when produced backwards. The position of the slit could be varied by the holding screw and was recorded on the protractor by the pointer. The thickness of the sheet was then determined from the measured output and the known slit dimensions, assuming the velocity of the sheet to be equal to $\sqrt{(2gP/\rho)}$.

4. Development of the liquid sheet with increasing pressure

To enable us to compare the influence of pressure on the development of a flat liquid sheet with variations of viscosity, surface tension and density, comparative photographs were taken of a wide variety of liquids sprayed from the same type of single-hole fan-spray nozzle, namely, type C of $0{\cdot}086 \times 0{\cdot}042$ cm orifice. The properties of the selected liquids are shown in table 2.

Table 2. Properties of liquids

	temp. (°C)	density (g/ml.)	surface tension to air (dynes/cm)	absolute viscosity (centipoise)
mercury*	20	13·60	476†	1·55
mercury 98 %, sodium 2 %	100	11·50	435	—
mercury 80 %, sodium 20 %*	100	4·50	320	—
methyl iodide	20	2·28	27	0·50
ethylene dibromide	20	2·10	39	1·70
carbon tetrachloride	20	1·60	27	0·97
chloroform	20	1·50	27	0·54
84 % glycerine/water	20	1·22	66	99·60
methyl salicylate	20	1·20	40	3·30
78 % glycerine/water	20	1·20	67	49·60
71 % glycerine/water	20	1·19	68	25·00
55·3 % glycerine/water	20	1·14	69	8·15
47·5 % glycerine/water	20	1·12	70	5·30
37 % glycerine/water	20	1·09	72	3·30
17 % glycerine/water	20	1·04	73	1·60
aniline	15	1·00	40	5·30
	100	0·95	38	0·80
water + 1 % Teepol	20	1·00	30	1·00
distilled water	20	1·00	73	1·00
	55	0·99	67	0·50
15 % soluble oil/water‡	20	0·99	35	1·60
sodium‖	148	0·92	187	0·55
ethyl acetate	20	0·90	24	0·46
benzene	20	0·88	29	0·65
toluene	20	0·87	28	0·59
isobutyl alcohol	11·5	0·81	24	5·30
ethyl alcohol 98 %	20	0·80	23	1·28
kerosene	20	0·80	25	1·60
acetone	20	0·79	24	0·32

* Ceramic nozzle type C (0·084 × 0·037 cm).
† Puls, H. O., 1936, *Phil. Mag.* **22**, 970.
‡ For many of our experiments an emulsion of soluble oil in water was used. It will be seen that this mixture has properties midway between those of water and light oils such as kerosene.
‖ Dr J. W. Taylor, private communication.

(*a*) *The development of a liquid sheet with increasing pressure using a soluble oil/water emulsion*

The characteristic development of a flat sheet of liquid from a single-hole fan-spray nozzle with increasing pressure is illustrated in figure 12, plate 7.

Figure 12*a* (1 Lb./in.^{2}): A small sheet is formed bounded by thick rims which are drawn together by surface tension. The impinging rims then form another closed sheet at right angles to the first. This effect is repeated until the velocity of the liquid in the rims is reduced so that a plain jet is formed which breaks up into large drops.

Fig. 12*b* (3 Lb./in.^{2}): The area of the sheet has increased and its thickness is reduced. Oscillations start to develop in the rims and become evident about half-way down the sheet and, accordingly, the rims disintegrate regularly.

Fig. 12*c* and *d* (8 and 25 Lb./in.^{2}): As the pressure is increased further, the sheet continues to open until a pressure of 25 Lb./in.^{2} is reached. The region of disintegration which had been advancing slowly away from the nozzle now attains a maximum distance. The boundary of the sheet is no longer a thick rim but becomes a large number of threads or 'antennae'.

Fig. 12*e* and *f* (50 and 185 Lb./in.^{2}): A wave-motion disturbance is caused in the sheet near the region of disintegration. As the pressure is increased this disturbance becomes more pronounced and the region of disintegration begins to recede towards the nozzle. At these high pressures the rims are completely disintegrated at an early stage and variations in the thickness of the sheet can be observed. These variations cause greater delivery of liquid at different angular positions from the axis of the nozzle. Thus the photographs illustrate the effect on the spray pattern of applying too great a pressure for the nozzle and liquid.

A further occurrence is illustrated by these photographs. As the pressure becomes higher and the rims start to disintegrate at an early stage, the liquid in the sheet adjacent the rims becomes thinner and eventually, at higher pressure, the liquid at the edges leaves the nozzle as a stream separated from the sheet.

(*b*) *The development of the liquid sheet with increasing pressure with liquids of various surface tensions, viscosities and densities*

To demonstrate the development of a liquid sheet with *low surface tension, low viscosity and low density*, photographs were taken of sheets of ethyl alcohol 98 % (surface tension 23 dynes/cm, viscosity 1·28 centipoise, density 0·80). Figure 13, plate 8, photographs (*a*), (*b*) and (*c*), illustrate sheets of alcohol at 5, 15 and 20 Lb./in.^{2} respectively. It is observed that the alcohol sheet has opened out very considerably even at the pressure of 5 Lb./in.^{2}, and the region of disintegration is already at its greatest distance from the nozzle. Above 15 Lb./in.^{2} no further development of the sheet area occurs.

The cross-sectional diameter of the rims of the sheet is small and oscillations occur in them at an early stage, resulting in a number of serrations and the early formation of drops.

With liquids of such low surface tension and viscosity, waves occur in the sheet close to the nozzle at low pressure; they cause a considerable increase in air resistance and rapid disintegration. This early development of the sheet is also illustrated with liquids of similar properties such as ethyl acetate and kerosene (surface tension 24 and 25 dynes/cm).

To demonstrate the development of a liquid sheet at *higher viscosity and low surface tension and density*, photographs were taken of 55 % glycerine/water (viscosity 8·15 centipoise, surface tension 69 dynes/cm, density 1·14).

Figure 14, plate 7, shows the development of the sheet between 5 and 50 Lb./in.^{2} Up to 20 Lb./in.^{2} the sheets are large and almost completely undisturbed. At the higher pressure of 50 Lb./in.^{2} waves are eventually formed by air friction and, finally, holes are formed in the sheet and disintegration takes place. At all pressures the boundary rims persist until the last and thus produce a heavy stream of drops at the edges.

To demonstrate the effect of *high surface tension and density and low viscosity* on the development of the sheet, mercury was used (surface tension 476 dynes/cm, density 13·6, viscosity 1·55 centipoise). Figure 15, plate 9, photographs (*a*), (*b*), (*c*) and (*d*), represent a sheet of mercury at 25, 50, 130 and 480 Lb./in.^{2} respectively. A high working pressure has to be employed to form a sheet of liquid having such a high surface tension, and the sheet does not reach its maximum development until over 350 Lb./in.^{2}. In distinction from other pure liquids a perforated sheet is formed and disintegration occurs through this means. The photographs show that the holes are not caused by a wave formation on the sheet. They are formed near the orifice well away from the leading edge, which is quite placid.

If 2 % sodium is added to the mercury to form an amalgam and reduce the density to 11·5 and surface tension to *ca.* 435 dynes/cm, and the amalgam is sprayed at a temperature well over its melting-point (figure 5), a similar type of sheet is formed (figure 15*e*). When, however, 20 % sodium is added to reduce the density still further to 4·5 and the surface tension to *ca.* 320 dynes/cm, only a very small sheet is formed which immediately breaks down into a number of rod-like elements (figure 15*f*).

To demonstrate the development of a liquid sheet *having high surface tension, low viscosity with low density*, sodium itself was sprayed at a temperature of 148° C (figure 5) (surface tension 187 dynes/cm, viscosity 0·55 centipoise, density 0·92). The four photographs of figure 16, plate 9, show the form of the liquid sheet at 9, 18, 30 and 50 Lb./in.^{2}. In comparison with other liquids at any pressure, the sheet is disrupted almost as soon as it is formed and consequently does not develop to any extent. The edges of the sheet very quickly contract after leaving the nozzle and, at all corresponding pressures, the spray angle is smaller than with liquids of lower surface tension. (Compare sodium at 50 Lb./in.^{2} figure 16*d*, with 55 % glycerine/water at 50 Lb./in.^{2}, figure 14*e*, or sodium at 19 Lb./in.^{2}, figure 16*b*, with alcohol or water at 20 Lb./in.^{2}, figure 13*c* and *i*.)

At 9 Lb./in.^{2}, figure 16*a*, the liquid sheet contracts into two rims very close to the nozzle, producing two wavy jets. At 19 Lb./in.^{2}, figure 16*b*, the heavy rims of liquid are separated further but still do not have a straight trajectory. The liquid from the centre of the sheet has coalesced into a number of rod-like elements.

At 30 Lb./in.^{2}, figure 16*c*, the sheet shrinks in all directions so that a number of cracks appear in the film and rods or thick filaments are produced which do not disintegrate.

At still higher pressures of 50 Lb./in.^{2}, figure 16*d*, the boundary rims, as well as the centre sheet, disintegrate into a number of filaments which only start to disintegrate after they have moved away a considerable distance from the nozzle.

The effect of liquid properties on the development of the sheet

Surface tension. Two forces come into play on each particle of liquid in the boundary rim as it leaves the orifice. One force results in a velocity in a radial direction (the orifice being the centre) and is proportional to $\sqrt{(2gP/\rho)}$, which, for example, at 20 Lb./in.^{2} with water, corresponds to 54 ft./s and, at 480 Lb./in.^{2} with mercury, equals 72 ft./s. The other force, surface tension, results in a velocity of contraction towards the axis of the sheet and is proportional to the square root of the surface tension. With no surface-tension force each particle of liquid would take a radial path, but with surface tension the path of a particle in the rim will be curved inwards towards the axis.

Figure 17, plate 10, compares the edges of the sheets of four liquids produced at 10 Lb./in.^{2}. Alcohol, figure 17*d*, having the lowest surface tension, shows that the contraction of the edge is much less marked than with sodium or water, figure 17*a* and *b*. The rim is smaller in cross-sectional diameter, the 'antennae' of liquid are very fine and the drops are small. The surface tension being reduced has resulted in longer and finer antennae flowing away from the edge of the sheet before they disintegrate into drops. With sodium, the contraction of the edge has proceeded to such an extent that a jet of liquid is produced. These effects will be more pronounced at low pressure than at high pressure.

The effect of a surface-active agent is somewhat more complex. The surface tension of an aqueous solution of a surface-active agent varies with the age of the surface (Addison 1943). The tension of a freshly formed surface, as measured by dynamic methods, is equal to that of pure liquid, and a definite time interval elapses before it attains an equilibrium value measured by static methods. Since the time interval associated with the life of a liquid sheet at 10 Lb./in.^{2} is of the order of $\frac{1}{250}$ s, the surface tension of the greater part of the sheet is probably that of pure water.

Where the surface is not expanding and, therefore, not changing rapidly, the agent will be more active and the surface tension will be proportionately reduced. Thus the effect of an agent on the formation of a sheet will be more pronounced at low pressure than at high pressure.

Since the velocity is low at low pressures, the surfaces of the rims are not changing rapidly and the agent will reach the surface and reduce the tension there. Rims can be likened to a column of liquid, and since Rayleigh (1879) has shown that the rate of increase of the amplitude of the disturbances on a column of liquid is a function of surface tension the disintegration of the edges is inhibited by a lower tension. Figure 13*d*, distilled water plus a wetting agent, compared with 13*g*, distilled water, shows this quite clearly.

At higher pressures, figures 13*e* and *h*, the surfaces of the rims are changing rapidly. The lower part of the sheet of water plus wetting agent is wider than the pure water sheet (13*h*) and exhibits a more pronounced wave motion, because the concentration of wetting agent on the surface is continually increasing as the liquid moves away from the orifice. Consequently the contraction velocity of the rims is reduced, which accounts for the greater width at the lower part of the sheet, and since the wave motion is caused by air resistance it would be expected to be enhanced in liquids of low surface tension.

The time-interval effect results in the marked difference in the 'antennae' shown in the photographs of figures 17*b* and *c*, plate 10. The contraction velocity is reduced, and thus the sheet is increased in width and more 'antennae' produced.

Viscosity (absolute). A comparison of figures 14 and 13 shows that for equal working pressures the sheet has a greater extent and the region of disintegration occurs at a greater distance from the orifice for the liquid of higher viscosity. The increased viscosity has lowered the radial and contraction velocity and has greatly reduced disturbances caused by air friction. This results in a more placid sheet being formed bounded by undisturbed rims. It was shown by Weber (1931) that the rate of growth of disturbance is reduced by high viscosity. The most marked effect of viscosity is to eliminate the formation of the 'antennae' so that no disintegration occurs at the edge of the sheet.

Density. With normal liquids the variation of density is between 0·7 and 2·0 g/ml. It would be expected, therefore, that the effect of density on the development of the sheet would not be large with liquids of similar surface tension and viscosity.

Liquids metals, however, such as mercury and its amalgams, give a wide range of density increase of 0·9 to 13·6, but this change of density is accompanied with a very big change of surface tension. The two properties, therefore, cannot be dissociated.

Table 3 indicates the photographs which can be compared at approximately equal pressures and the corresponding physical properties. It will be noticed that sodium and an amalgam high in sodium are unique in possessing an exceptionally high ratio of surface tension to density; whereas with mercury, although having both high surface tension and density, the ratio is similar to that of ordinary liquids. This high ratio of surface tension to density must be largely responsible for the anomalous behaviour and breakdown of the sodium sheet. This phenomena is still under investigation.

TABLE 3

plate no.	fig. no.	liquid	pressure (Lb./in.^{2})	surface tension (dynes/cm)	density (g/ml.)	$\frac{\text{surface tension}}{\text{density}}$
9	15 (*b*)	mercury	60	476	13·6	40
9	15 (*e*)	2 % Na, 98 % Hg	50	435	11·5	38
9	15 (*f*)	20 % Na, 80 % Hg	80	320	$<$4·5	$>$71
9	16 (*d*)	sodium	50	187	0·92	203
7	12 (*e*)	15 % soluble oil/tap water	50	35	0·99	35

5. Factors influencing the stability of liquid sheets

The stability of a sheet of liquid may be defined as its resistance to disintegration. A sheet which is the least disturbed by turbulence in the nozzle or air friction can be defined as the most stable. A stable sheet, therefore, will have its region of disintegration farthest from the nozzle, and the largest part of its area will be placid and undisturbed.

When two jets of liquid flowing at low Reynolds number based on hydraulic mean diameter from two opposed nozzles strike each other, a circular sheet of liquid is produced, the rim of which will retain a position of equilibrium when the surface tension or contraction force equals the inertia or expansion force. As the inertia force becomes greater than the surface tension, drops are formed at the leading edge which draw away from the rim as liquid threads. This manner of disintegration is approached in practice with the spinning disk atomizer.

Any disturbance superimposed upon the equilibrium of the two forces will eventually cause disruption. Most of the sheets of liquid produced from nozzles have a relatively high velocity, and turbulent flow conditions exist in the orifice and, because of the velocity in the atmosphere, air resistance plays its part in the disintegration.

(*a*) *The flow through the orifice*

The nature of the flow through an orifice can be characterized by the Reynolds number (Schweitzer 1937). At a relatively low value of the Reynolds number and a relatively high value of sheet velocity, the sheet is greatly affected by air friction. As the Reynolds number is increased, local disturbances in the sheet become more predominant until holes are caused to form near the orifice, giving rise to a perforated sheet. Consequently, the predominant disturbances are a function of both Reynolds number and sheet velocity.

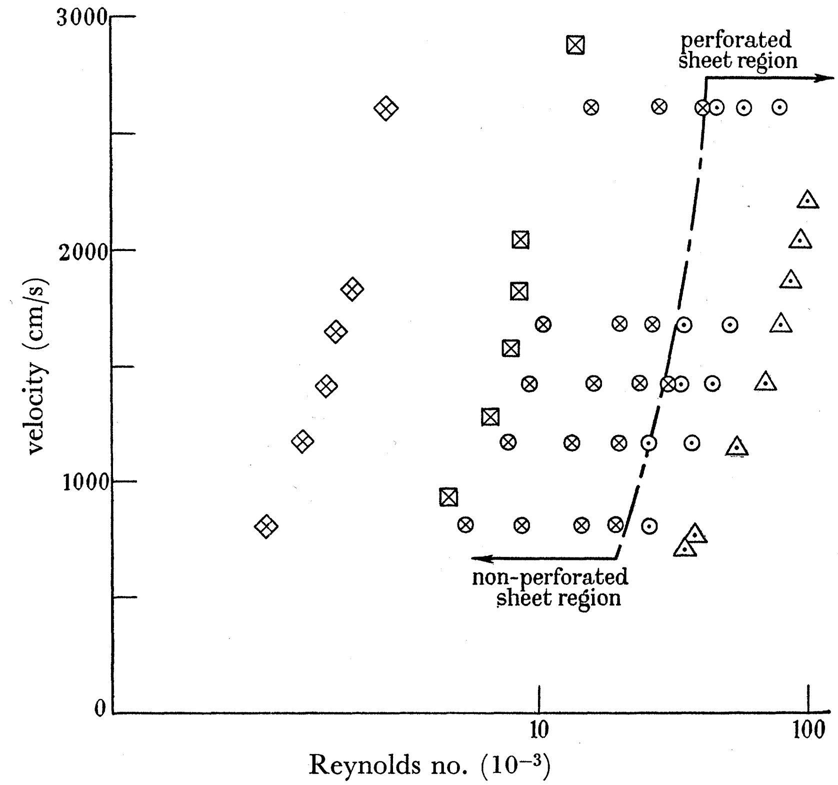

FIGURE 10. Relation between velocity of flow and Reynolds number.
· perforated sheet; × non-perforated sheet; ◇ 55·3 % glycerine/water; ○ water; □ alcohol; △ mercury.

Figure 10 shows the relation between the manner of disintegration with Reynolds number based on hydraulic mean diameter and sheet velocity using the single-hole type of nozzle. It shows that points fall into two groups on either side of a line. Below the Reynolds number of about 20000 and a sheet velocity below 750 cm/s, or of 40000 and a velocity of 2700 cm/s, disintegration is caused mainly by air friction producing waves in the sheet. At a higher number disintegration starts earlier through the formation of perforations in the sheet.

Turbulence in the orifice can cause two types of disturbance in the sheet, either a series of more or less regular circumferential waves with the orifice as a centre, or a number of local point disturbances. Figure 18*b*, plate 10, is of a sheet of mercury taken under a beam of incident light nearly parallel with the sheet to show more clearly the variations in its surface. It shows three distinctly different types of disturbance: at *A*, circumferential waves; *B*, point disturbances which cause craters surrounded by ripples; and *C*, radial folds in the surface. The three black spots *D* are holes in the sheet.

Figure 18*a* is a similar photograph of a sheet of mercury. It shows that the holes in the sheet originate at the centre of the point disturbances or craters. At point *A* a hole has just occurred in the centre of the crater and at *B* a hole has developed.

The shape of the puncture in this particular photograph at point *A* is caused by a slightly longer time of decay of the light flash.

The origin of the point disturbance has been found by making four measurements, namely, the diameter of the first ripple surrounding the point disturbance, the minimum wave-length of the ripples, the velocity of the sheet and its thickness.

The results of the measurements of the thickness of spray sheets produced by single-hole fan-spray nozzles showed that for two dissimilar liquids, such as water and mercury, the thickness of the sheet is always inversely proportional to its distance from the orifice. The following approximate relation was found to be true: thickness of sheet (in microns) multiplied by the distance from the orifice in centimetres is equal to 14.

TABLE 4. ORIGIN OF POINT DISTURBANCES

calculated sheet velocity (cm/s)	minimum wave-length of ripples (cm)	radius of first ripple (cm) x	distance of point disturbance from orifice (cm)	calculated origin of point disturbance (cm) $x=0$
2200	0·01	0·21	3·5	0·06
2200	0·01	0·21	3·5	0·06
2050	0·01	0·24	5·05	0·1
2050	0·01	0·22	5·05	0·35
1420	0·012	0·28	3·03	−0·4

Table 4 gives the results for some of the disturbances that have been analyzed (Dombrowski & Eisenklam 1952). The position of the origin is found to be sufficiently near zero to support the view that the origin is within the orifice at the apex of the sheet.

Where turbulent flow in the orifice is caused by a liquid of high density, the surface of a perforated sheet is comparatively smooth, being disturbed by waves of only small amplitude. In this case the point disturbances predominate.

With a liquid of lower density, where turbulent flow is caused by increasing the orifice size, very marked wave motions and holes occur simultaneously in the sheet.

Figure 19, plate 11, shows three characteristic photographs of nozzles working at Reynolds numbers of 15000, 41000 and 100000 respectively, and velocities of 1430, 1430 and 2200 cm/s.

Figure 19*a* shows the characteristic waves along the leading edge of the sheet enhanced by air resistance. Figure 19*b* shows waves induced by turbulence in the nozzle, and 19*c* shows a smooth but very perforated sheet of mercury.

The mechanism by which the point disturbances break the liquid sheet cannot be likened to the phenomena occurring in a capillary tube where the sheet lies between two concave surfaces and breaks suddenly when they approach one another closely. A sheet of liquid, on the other hand, exposed to disturbances, is stable, and rupture occurs only when large disturbances have reduced the thickness of the sheet to about $10^{-7}\mu$ (as calculated from Fisher 1948). Since the minimum thickness which we have actually obtained in our experiments is of the order of $10^{-4}\mu$, it is concluded that a disturbance which will break the sheet must cause full penetration of its thickness; that is, its depth must be of the order of the thickness of the sheet.

(*b*) *Suspensions in the liquid*

Where solid or liquid particles are suspended in the liquid, the stability of the sheet has been found to depend quite markedly upon the type of suspended particle.

A range of particles of sizes varying from 3 to 60μ was suspended in water or alcohol, as shown in table 5.

TABLE 5. PROPERTIES OF SUSPENSIONS USED (concentration 0·05 % wt/vol.)

type of particle	approx. size range (μ)	liquid	surface tension (dynes/cm)
Bentonite *Lycopodium*	3 25	tap water distilled water distilled water + 1 % Teepol ethyl alcohol	73 73 30 23
micronized glass	3	tap water	73
zircon	8	tap water	73
sillimanite	5–20	tap water	73
fired brick	5–35	tap water	73
copper	10–50	tap water	73
sulphur	10–60	alcohol	24

These mixtures were sprayed to produce a sheet, the thickness of which was measured as 7μ at a distance of 2 cm from the orifice.

It was found that where the particles were wetted by the liquid they had no effect on the manner of disintegration of the sheet. Irrespective of their size, it appears that the particles are held by the sheet through the adsorbed films on their surface.

On the other hand, when suspensions of unwettable particles are used they have a marked effect and cause perforation of the sheet. When, for example, suspensions of sulphur or soluble oil in water were used, the particles of sulphur or oil globules eventually break the sheet when their size is of the order of the thickness of the film. With an oil in water emulsion the size of the suspended particle can be varied during a short time interval by the addition of an electrolyte. By increasing the amount of electrolyte and the time before the sheet is sprayed, larger particles occur in the suspensions, and it was found that holes are formed in the sheet nearer and nearer the orifice.

Figure 20, plate 11, illustrates the changes occurring with the addition of small quantities of sodium chloride to soluble oil/water emulsions.

In these experiments no attempt was made to measure the size of the oil droplets, since the static conditions on the microscope slide would bear very little relation to the dynamic conditions existing in the nozzle.

Figure 20*a* shows no hole formation in a 15 % soluble oil/distilled water emulsion, because the sizes of the oil particles are smaller than the thickness of the sheet.

The similar photographs in figure 12, plate 7, however, of such an emulsion of soluble oil and tap water, show holes; the particle sizes being larger, because of the amount of electrolyte present in tap water.

Figure 20*b* shows the addition of 0·2 % sodium chloride, and perforations are just starting. With 0·4 %, figure 20*c*, the electrolyte acts rapidly and the normal white appearance of the sheet is destroyed and it is completely holed and breaks up near the orifice.

(*c*) *The flow through the atmosphere*

With a single-hole orifice, when the liquid velocity is low and flow in the orifice is of a non-turbulent character, the liquid sheet can remain completely undisturbed by air friction right up to the leading edge. Such placid conditions are more likely to occur and be sustained with liquids having a viscosity higher than water. Figure 24*g*, plate 14, shows a placid sheet of glycerine/water solution of viscosity 5·3 centipoise, travelling at a velocity of 1175 cm/s.

In conical sprays, however, disturbances are always observed in the sheet even at high viscosity (Simons & Goffe 1946), and these disturbances arising from turbulence within the nozzle play an important part in causing distintegration.

When waves are produced disruption can be caused before the formation of the leading edge. The formation of waves increases the frictional drag of the air and the surrounding air is entrained by the sheet. This is illustrated in figure 22*a*, plate 12, where the motion of the air is made visible by smoke trails of titanium tetrachloride. Where the wave motion is most pronounced, air flows into the sheet in a perpendicular direction; whereas nearer the orifice, where the sheet is more placid, the air entrainment is at a more and more oblique angle.

With conical sheets of liquid produced by swirl nozzles the air entrainment has an additional effect. The pressure inside the conical sheet near the nozzle is reduced by continual entrainment and, as a result, the surrounding air moves inwards towards the axis in a direction normal to the surface of the cone. Thus additional air motion sets up disturbances which enhance any wave motion. This action is illustrated in figure 22*b*, plate 12, where the direction of the air flow is indicated by the upper smoke trail. The lower smoke trail shows the turbulent movement of the entrained air.

The phenomenon of waves superimposed on liquid sheets can be compared with waves superimposed on a plain jet. A detailed analysis of the theories of jet disintegration was made in this laboratory (Straus 1950), and it was found that for the break-up by waves the experimental data may be correlated by plotting values of $V\sqrt{\frac{a_J}{\gamma}}$ against values of $\frac{V}{L}\sqrt{\frac{2a_J^3}{\gamma}}$.

This relation was successfully adapted to water sheets by substituting the thickness of the sheet in the region of disintegration for the jet radius.

Whether the air entrained by the sheet is the primary cause of the formation of waves, or whether the initial cause is attributable to turbulence in the flow at the orifice, is still under investigation in this laboratory. Many of our photographs show that the first sign of waves occurs at the edges of the sheet radiating from the thickened rim and vibratory disturbances can be detected right back to the orifice.

To discover the effect of air friction on a flat sheet, photographs are being taken *in vacuo*. Figure 22*c*, plate 12, shows a sheet of soluble oil/water *in vacuo* at a velocity of 3720 cm/s. It shows no wave disturbances and the sheet area is much greater than normal (compare figure 12*f*, plate 7).

(*d*) *The effect of surface tension, viscosity and density on the stability of the sheet*

In order to study the independent effects of surface tension, viscosity and density with a constant air resistance, a selection of liquids was chosen and sprayed in accordance with the plan shown in table 6. In this series the liquids were all sprayed at a constant liquid/air velocity by adjusting the pressure so that the flow quantity was the same. Thus liquids of the highest density were sprayed at the highest pressure.

TABLE 6

(i) increasing surface tension

constant viscosity 0·46 to 0·59 centipoise
constant density 0·87 to 1·0 g/ml.

	dynes/cm	pressure (Lb./in.^{2})
ethyl acetate	24	18·0
toluene	28	17·5
aniline 100° C	38	19·0
water 55° C	68	20·0
liquid sodium	187	19·0

(ii) increasing viscosity

constant surface tension 68 to 73 dynes/cm
constant density 0·99 to 1·22 g/ml.

	centipoise	pressure (Lb./in.^{2})
water 55° C	0·6	20
water 20° C	1·0	20
17 % glycerine/water	1·6	21
37 % glycerine/water	3·3	20
47·5 % glycerine/water	5·3	22
71 % glycerine/water	25·0	24

(iii) increasing density

constant viscosity 0·5 to 0·6 centipoise
constant surface tension 27 to 28 dynes/cm

	density	pressure
toluene	0·87	17
chloroform	1·49	30
methyl iodide	2·28	46

(iv) increasing density and surface tension

constant viscosity 1·55 to 1·7 centipoise

	density	tension	pressure
kerosene	0·8	25·0	16
17 % glycerine/water	1·0	72·5	21
ethylene dibromide	2·1	39·0	42
mercury	13·6	476·0	270

(v) viscosity and surface-tension classification

constant density, 0·81 to 1·1 g/ml.

	surface tension 24 dynes/cm	surface tension 70 dynes/cm
viscosity 0·5	ethyl acetate surface tension 24 viscosity 0·46 density 0·9	water at 55° C surface tension 67 viscosity 0·5 density 0·99
viscosity 5·0	isobutyl alcohol surface tension 23·5 viscosity 5·3 density 0·81	47·5 % glycerine/water surface tension 70 viscosity 5·3 density 1·1

A selection of photographs representative of table 6 is shown in figures 23, 24, plates 13 and 14.

The independent effect of surface tension on disintegration is illustrated in figures 23*a–c*. It is noticed that an increase in surface tension from 20 to 187 dynes/cm produced a reduction in the spray angle, a decrease in sheet area, but a larger placid area.

With the very great increase of surface tension to 187 dynes/cm with sodium, the effect of surface tension is so great that not only is the spray angle greatly reduced but the sheet is hardly formed before it contracts into two or three or more rods of liquid.

The independent effect of viscosity is shown in figures 23*d*,*e*,*f*. It is noticed that with an increase of viscosity from 1 to 5·3 centipoise, the position of disintegration has moved much farther away from the nozzle, the sheet area is much larger and the area of placidity is much greater. Even comparing 23*b*, water at 55° C, with 23*d*, water at 20° C, it is clearly seen that the effect of lower viscosity makes the sheet more unstable.

Comparing figure 23*g* of toluene with figure 24*a* of kerosene, the effect of increasing the viscosity from 0·59 to 1·6 centipoise is to improve the stability.

The independent effect of density is shown in figures 23 *g*, *h* and *i*, from which it will be noticed that an increase of density from 0·87 to 2·28 results in only a small increase in the area of the sheet. The area of disintegration at the high density has moved somewhat farther away from the nozzle, but because of low viscosity and low surface tension the stability of the sheet is poor and early disintegration ensues.

The combined effect of density and surface tension increase at a constant viscosity is shown in figures 24*a*, *b* and *c*. These photographs show that the combined effect of a large increase in density and surface tension produce a sheet (i.e. mercury) highly resistant to turbulence by air friction and, therefore, devoid of major waves. The area of disintegration is at a greater distance from the nozzle.

The combined effect of viscosity and surface tension with an approximately constant density is clearly illustrated in figures 24*d* and *f*, and *e* and *g*. We have seen that the effect of changing the density as much as 2·6 times is small. Thus the small variation of density in these photographs can be ignored.

The photographs show the marked effect of increasing the viscosity approximately ten times at two levels of surface tension, and also the effect of increasing the surface tension approximately three times at two levels of viscosity.

Ethyl acetate (*d*), isobutyl alcohol (*f*), or water (*e*) and glycerine (*g*), illustrate the greatly increased stability caused by increased viscosity. Three different effects can be noted: first, the wave motion (if any) at the higher viscosity occurs much farther from the orifice; secondly, that the actual wave motion itself is very much more regular; and thirdly, that the high viscosity inhibits disintegration of the rims of the sheet.

The isobutyl alcohol (*f*) compared with glycerine (*g*) shows the effect at the high viscosity of increasing the surface tension. It is observed that the sheet is even more placid and completely devoid of waves. Surface tension has caused it to contract very considerably, the rims have become much thicker and carry a much greater proportion of the liquid.

Glycerine (*g*) compared with water (*e*) illustrates the effect of reducing the viscosity again at this high surface tension. It shows that the sheet is still contracted to the same degree, but it is now more disturbed by waves and disintegration of the rims occurs very early.

The factors influencing the stability of a liquid sheet may be summarized as follows:

The disintegration of a liquid sheet is controlled by the surface tension, viscosity and density of the liquid, the nature of the fluid flow through the orifice and through the air, and the presence of suspended particles.

The liquid sheet with the highest viscosity and surface tension will be the most resistant to disruption, so that the region of disintegration will be a greater distance from the nozzle. On the other hand, the easiest liquid to disintegrate will be one having a low viscosity and low surface tension, and the region of break-up will occur near the nozzle.

With liquids of low surface tension and viscosity a change of density has little effect.

Under flow conditions in the orifice of low turbulence a sheet of low viscosity and low surface tension is disintegrated by means of waves blown in the sheet by air friction. This manner of break-down is enhanced at high velocity but is hindered by high viscosity and high surface tension. Thus at low velocities and non-turbulent flow conditions in the orifice, a viscous liquid sheet remains completely placid.

Under flow conditions in the orifice of high turbulence the sheet becomes punctured at a number of point disturbances which originate in the orifice, and a perforated sheet is produced. This condition may be realized with a liquid of high density such as mercury, or by the use of a large orifice.

The use of a wetting agent does not affect disintegration because the agent is not effective in changing the surface tension during the short life of the sheet.

Whereas small quantities of wettable particles have no effect on the sheet, unwettable particles puncture and perforate it.

6. The mechanisms of the formation of liquid threads

In the disintegration of a sheet of liquid the formation of ligaments or threads is a necessary stage before the production of drops. The process of breakdown is similar in flat sheets produced from either single-hole fan-spray nozzles or spinning disks, and in conical sheets from swirl-spray nozzles. Threads can be formed either directly from any free edge or from any new boundary, such as the periphery of a hole, produced by the disruption of the sheet.

(*a*) *Threads formed at the free edges of stable sheets*

A free edge is formed when equilibrium exists between surface tension and inertia forces. When a free edge of liquid is formed at the rim of a spinning disk or cup it can be controlled in thickness and uniformity by controlling the liquid flow rate, the speed of the disk and thus the centrifugal force. Because the sheet is in contact with a surface, the effect of wind is reduced and the diameters of the threads and the drops formed under these conditions are most uniform.

Figures 25*a* and *c*, plate 15, illustrates a typical example of pendant drops at the ends of threads which occur at low speed and low rates of flow from a spinning disk (flow rate 2·3 ml./s; peripheral speed 210 cm/s). The particles formed under these conditions are of a limited number of sizes, consisting of the major and satellite drops only.

As the liquid leaves the centre of the disk it is spread out towards the periphery and collects there as a thick rim. Disturbances appear in the rim which result in drops being formed which become centrifuged off. At A a swelling appears at the rim; at B under centrifugal force it has grown and the front starts to draw itself into a spherical globule C; at D the drop is held to the disk by a fine thread which attenuates as the drop moves away from the edge until it finally becomes detached as at E. At F and G the major drop has left the disk and the thread has broken into a train of satellite drops; at H the liquid is drawn back into the rim which thus still retains the swelling. This swelling will then cause the process to be repeated. The process is therefore essentially intermittent.

When the rate of flow on to the disk is increased to 15 ml./s at the same peripheral speed, the pendant drops draw out much thicker and longer threads of liquid, and these threads break down into a wider spectrum of drops (figure 25*b*).

Figure 26*a*, plate 15 shows the atomization occurring from a spinning disk atomizer commonly used for the purposes of spray drying. In this device the length of the leading edge is greatly increased by using slots or windows on the rim of a wheel. The photograph shows atomization at a flow rate of 22 ml./s and a peripheral velocity of 3400 cm/s. The drops and threads are seen to be leaving the controlling edges of the slots and breaking up into long strings of particles giving a narrow spectrum of drop sizes. This is a similar process to that shown in figure 25*b*.

When the rate of flow is increased at the same peripheral speed, the liquid boundary is eventually forced away from the rim of the disk and thus a free sheet of liquid is produced having no controlling surface. Threads are again thrown out from the liquid edge but now in a much more disorderly manner.

Figure 27*a*, plate 16, shows an area of the free edge of the liquid sheet displaced from the disk. In this picture the irregular thickness of the edge is clearly seen, resulting in a much more irregular formation and size of the threads, causing a still wider spectrum of drops.

The series of waves in the liquid sheet behind the rim and parallel to it shown in this picture is of great interest. These ripples are caused by the rebound of the root of the thread back into the rim after the drop has broken off. This occurrence is more clearly seen in this picture because the liquid has a higher surface tension than that in figure 25.

Similar free-edge disintegration is observed in the sheets of liquid produced from nozzles where the sheet is undisturbed. If there are no air disturbances in the sheet drops will be formed freely from the leading edge in a manner similar to figure 27*a*. This is also illustrated in the vacuum photograph, figure 22*c*, plate 12.

With a placid sheet of high viscosity, threads produced at the leading edge are formed by another process. They are formed between the thick boundary rims and the leading edge which is spasmodically retracting backwards from each rim.

Figure 21*a*, plate 12, which is of a sheet of 71 % glycerine/water travelling at 1160 cm/s, clearly shows these successive events. The point at which breakaway from the rims has occurred is indicated by successive notches therein. Near the leading edge there are a number of threads not yet extended to disruption point.

Immediately waves are caused in the earlier life of the sheet, figure 21*b* (84 % glycerine/water at 1630 cm/s), the above process is interfered with and a much more rapid disintegration is effected by drawing a larger number of fine threads.

Figures 17*b*, *c* and *d*, plate 10, illustrate the threads formed on the curved side of the sheet. Drops formed at the curved boundaries of a flat sheet are always found to be larger than all others, indicating that they are not formed by the normal mechanism of the liquid flowing through the sheet towards the leading edge.

If there were no surface-tension force the boundary of the sheet would be straight and the sheet would be a sector of a circle. Because of surface tension the boundaries are continually rolling back and the edges of the sheet become curved. As the liquid moves away from the orifice the rims become thicker and unstable so that drops leave them. As the rims are traversing a curved path, threads are drawn out behind the drop in much the same way as occurs from a spinning disk. As the drops leave the rim it becomes unstable and has the appearance of a serrated edge which changes its form from instant to instant. Figure 17, plate 10, shows this process clearly.

(*b*) *Threads formed during the disruption of sheets*

It has already been mentioned that the stability of the sheet is greatly influenced by local vibratory disturbances in its surface, caused by turbulence in the nozzle or by the presence of unwettable particles of size about equal to its thickness.

If a sheet with a free edge is produced from a spinning disk using water containing unwettable particles of soluble oil, the sheet is immediately unstable and the free edge is no longer a uniform distance from the disk. Although the liquid leaves the disk uniformly in an involute direction, holes appear in the sheet and the liquid rolls back in all directions from the point of perforation generating a progressively thicker rim as it moves back towards the disk against the flow of the liquid.

Comparing figures 27*a* and *b*, plate 16, the very considerable effect of this process is evident. In *b* the liquid containing unwettable particles has a surface tension of 35 dynes/cm, while *a* is 56 dynes/cm. Thus the distance from the disk at which the sheet would normally become stabilized is much greater in *b*.

Whereas with normal conditions the threads are formed fairly uniformly from a rim of irregular cross-section, as in figure 27*a*, the part indicated at *A* in figure 27*b* represents the true edge where two drops are about to leave. Because of surface tension, the rest of the boundary has contracted and the edges have become considerably thickened.

When the same process occurs in fan-shaped sheets with soluble oil and water (figures 28 and 22*c*), or with mercury (figure 15), the perforations can be seen to develop quite early near the nozzle, and development of the hole by contraction of the edge occurs very regularly so that the holes remain sensibly circular until they coalesce with each other forming threads or long ligaments.

In a steadily expanding sheet the contraction of the liquid at the rims of the holes is a regular process, and no disintegration of the rims occurs until two holes meet and the coalescence of their rims produces the thread of liquid. At the instant before coalescence of the two rims the ribbon of liquid between them may twist. This imparts vibration to the thread. Further expansion of the adjacent holes stretches the thread and it breaks down uniformly.

Figures 28*b* and *c*, plate 17, show at points *K*, *L*, *M* and *N*, some of the stages of the growth of a rotational symmetrical disturbance on a thread. At *K* a thread has recently formed and only small disturbances can be observed. At *L* the thread has existed for a longer period and pronounced disturbances are seen. At *M* and *N* the threads are in the last stages of break-up and a number of uniform drops are being produced.

Figure 26*b*, plate 15, consists of two superimposed photographs taken at a 250 μs interval. The two holes at *A* have increased in diameter and joined together forming a thread. At *B* a thread already formed has stretched further. At *C* the thread is just in the final stages of disintegration into drops.

The velocity of the sheet can be calculated from the movement of the holes, in the $250\,\mu s$ interval. The sheet velocity calculated thus is 1030 cm/s. Similarly, the velocity of the contraction due to surface tension can be calculated from the enlargement of the holes. This is 337 cm/s. It can also be observed in this photograph that the leading edge of the sheet moves a shorter distance. It has, in fact, only the resultant velocity of the forward velocity minus the contraction velocity, namely, 693 cm/s. It is also seen that once the particles have left the sheet and are no longer influenced by the contraction velocity, they have a greater forward velocity, namely, 915 cm/s.

Approximate calculations show that the break-up of the threads in our photographs conforms to Rayleigh's theory of the stability of liquid columns. The theory says that a free column of liquid is unstable if its length is greater than its circumference. For a non-viscous liquid the wave-length of that disturbance which will grow most rapidly in amplitude is 4·5 times the diameter. The results of some of our calculations are given in table 7 and show a fair agreement between the theoretical values and those calculated from figures 28*b* and *c* (position 3, 4, 5) and others.

TABLE 7. WAVE-LENGTH/DIAMETER RATIO OF THREADS

pressure (Lb./in.^{2})	calculated diameter (cm)	wave-length (cm)	$\frac{\text{wave-length}}{\text{diameter}}$
40	0·015	0·059	3·9
3	0·018	0·080	4·4
7	0·008	0·050	6·3
7	0·015	0·070	4·7
8	0·013	0·047	3·6
10	0·024	0·097	4·0

Where a number of holes approach each other, irregular areas of sheet or 'islands' of liquid remain. Figure 28*a* shows a large number of holes approaching the leading edge of the sheet causing a curtain of threads. These threads may be connected in threes and fours or an even greater number. The threads, being approximately uniform in diameter, will produce uniform drops, whereas the irregular areas or 'islands' of liquid will disintegrate into a wide spectrum of drops. The photograph also shows that the disposition of the drops, after they have left the sheet, is patterned on the arrangement of the threads in the sheet. The holes are thus finally reproduced as voids in the spray curtain.

When the velocity of the sheet in the atmosphere is great enough, air friction will cause slight variations in the sheet to develop rapidly into major wave disturbances so that areas of the sheet will be moving inclined to the direction of motion. This will result in holes being blown through the sheet causing disruption to start before the formation of the leading edge.

When the peripheral velocity of a spinning disk is increased and the flow rate is such that a free edge of liquid will be formed outside the disk, the sheet can be extremely irregular and disruption can occur quite close to the disk causing ripples to develop very quickly into waves. (Compare figures 27*a* and *c* where the flow rates are the same but the velocity in *c* is four times that of *a*.) In sheets produced from pressure atomizers, a similar process can take place.

When a placid sheet is disturbed by waves, threads are torn from numerous points in the wave crests and holes may be blown in the sheet between the waves (figure 21*c*, plate 12, 78 % glycerine/water at 630 cm/s).

Where the velocity of the sheet is high and the wave amplitude is sufficiently great, particles are formed and torn off from the inner edges of the holes and the wave crests are curled back (figure 21*a*, plate 12, 50 % glycerine/water at 2440 cm/s). The holes formed in this manner are, in fact, characterized by drops being formed around their periphery. On the other hand, holes produced by perforation of the sheet, as already described, have drops formed at their periphery only when the life of the holes is prolonged, i.e. mercury and liquids *in vacuo*.

With liquids having visco-elastic properties, where the viscosity is reduced with increase of rate of shear, the sheet is similarly disintegrated through the formation of waves. By reason of the rapid reduction of inertia forces, however, the viscosity increases rapidly and inhibits a further break-up of the thread into drops. A gossamer-like spray is formed consisting of a web of fine threads. This is shown in figure 29*a*, plate 16.

In a twin-fluid atomizer of the type using a vortex cup, where the liquid is made to spread out from a central orifice to the edge by the formation of a vortex ring (as in figure 3), the sheet of liquid leaving the edge of the cup is immediately disintegrated by air passing over its edge. Figure 29*b* shows the process of disintegration in such a device when the air is greatly reduced in velocity.* The liquid is entering at the centre of the cup and is uniformly spread out around the rim. It is then blown out into threads of varying diameters which are subsequently shattered by air action into a wide spectrum of drop sizes.

In conclusion, we wish gratefully to acknowledge the provision of an extra-mural research grant from H.M. Colonial Office to enable this work to be carried out at the High Speed Fluid Kinetics Laboratory, Chemical Engineering Department, Imperial College of Science and Technology, during the years 1947 to 1950, and for the continuation of the grant since 1950 by the Agricultural Research Council. We also wish to express our indebtedness to Professor D. M. Newitt, F.R.S., for his interest and encouragement during the course of the work.

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* This photograph had to be taken at a pressure much below the proper operating pressure to enable the process to be clearly seen.

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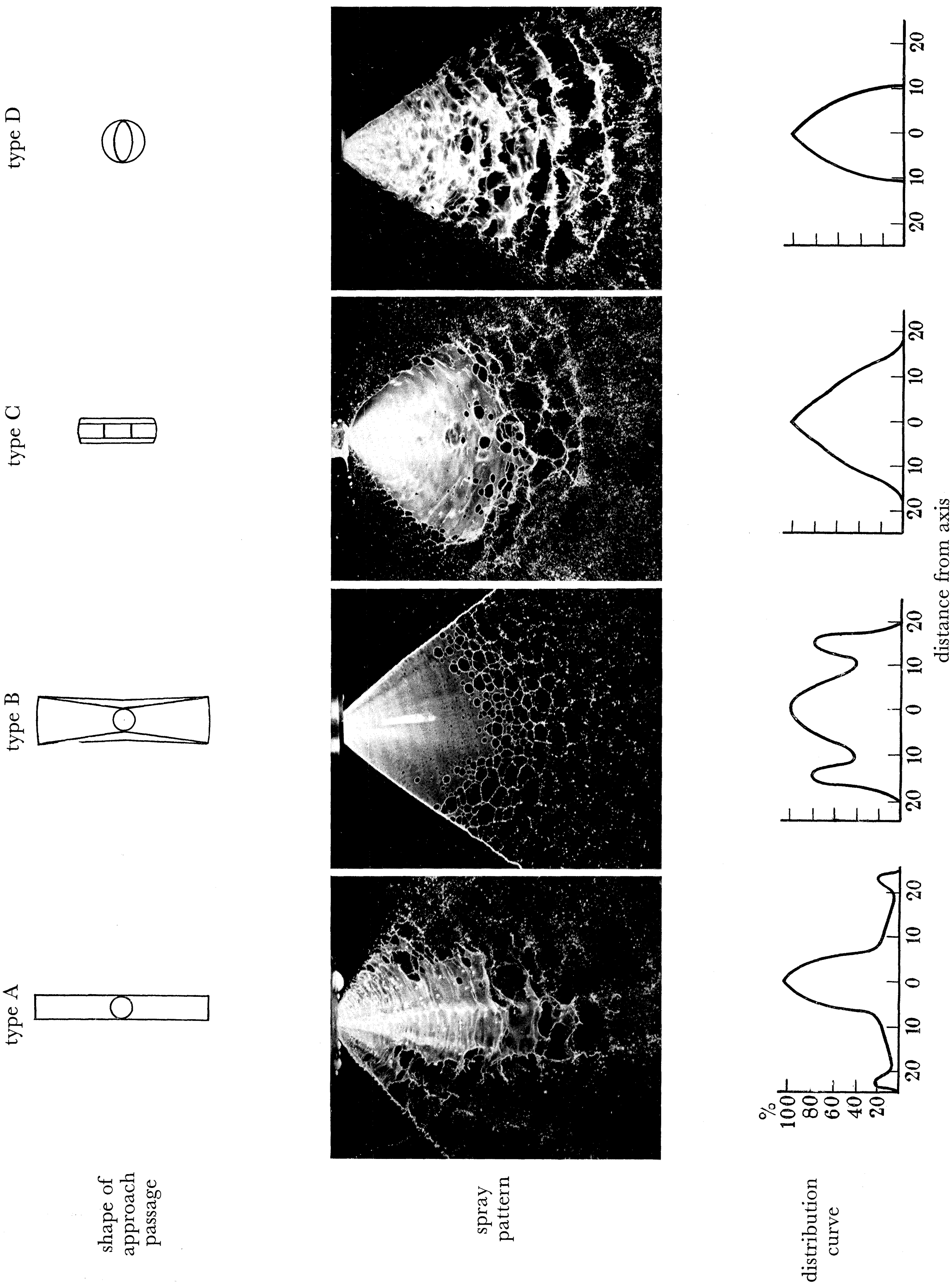
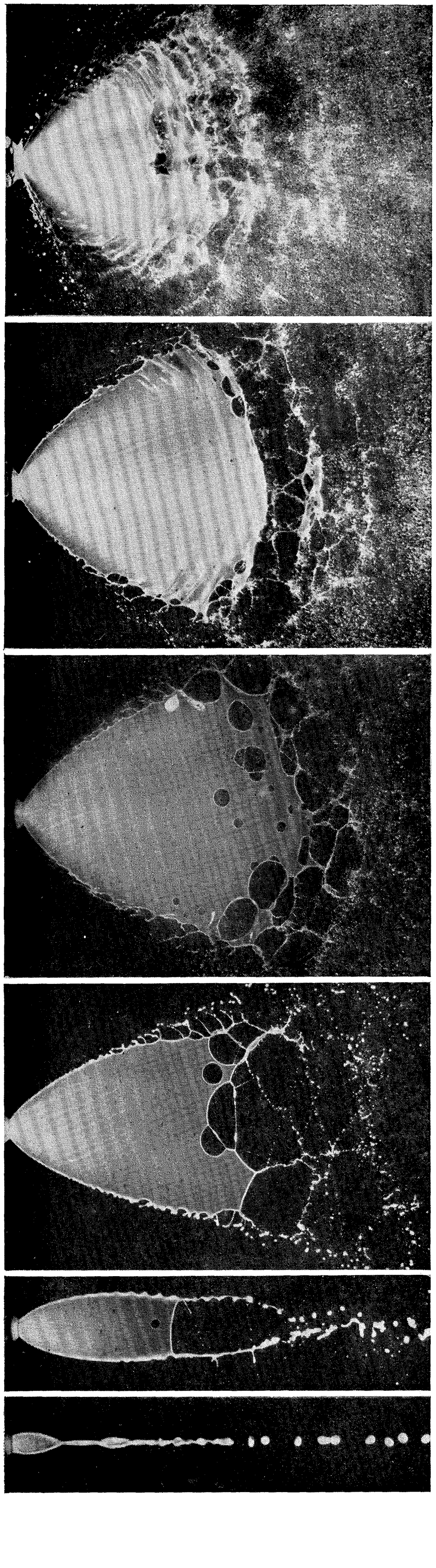
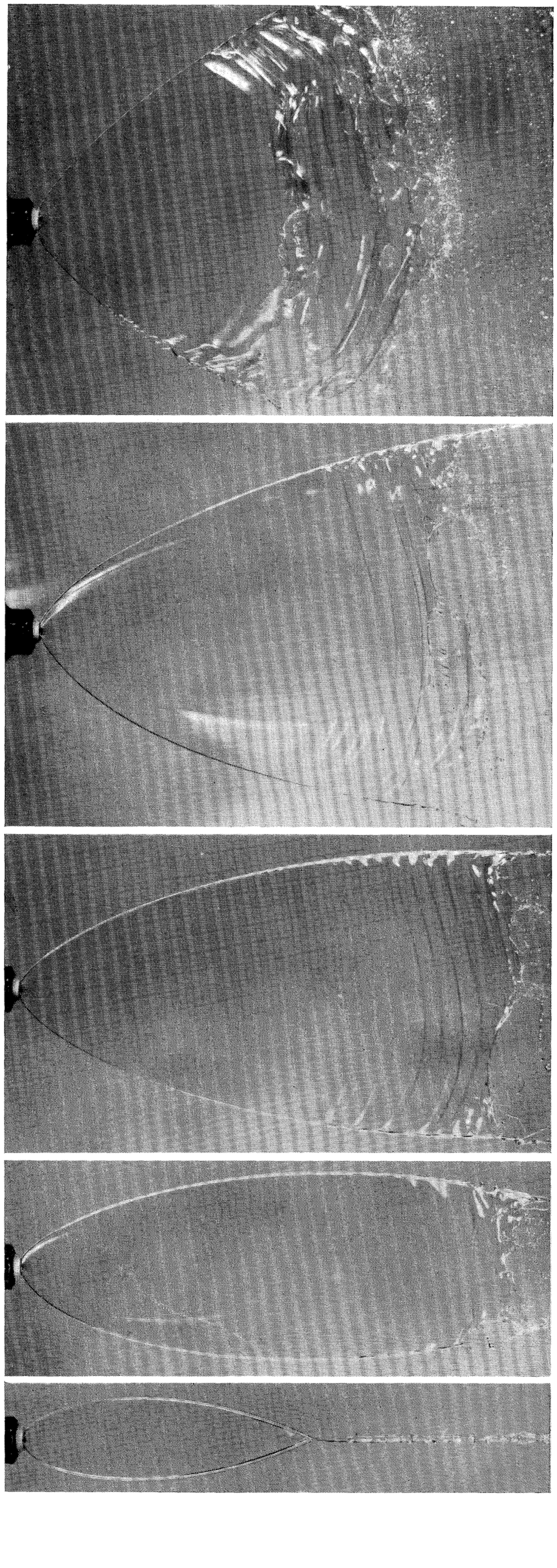


FIGURE 11. Influence of design on spray pattern in single-hole nozzles.



a (1) *b* (3) *c* (8) *d* (25) *e* (50) *f* (185)

FIGURE 12. Characteristic development of a liquid sheet with increase of pressure (15 % soluble oil/tap water). Pressures in Lb./in.^{2} as shown by figures in brackets. (Nat. size.)



a (5) *b* (10) *c* (15) *d* (20) *e* (50)

FIGURE 14. The development of sheets of liquid having low surface tension, high viscosity and low density (55·3 % glycerine/water). Pressures in Lb./in.^{2} shown by figures in brackets. (Nat. size.)

5 Lb./in.^{2} 15 Lb./in.^{2} 20 Lb./in.^{2}

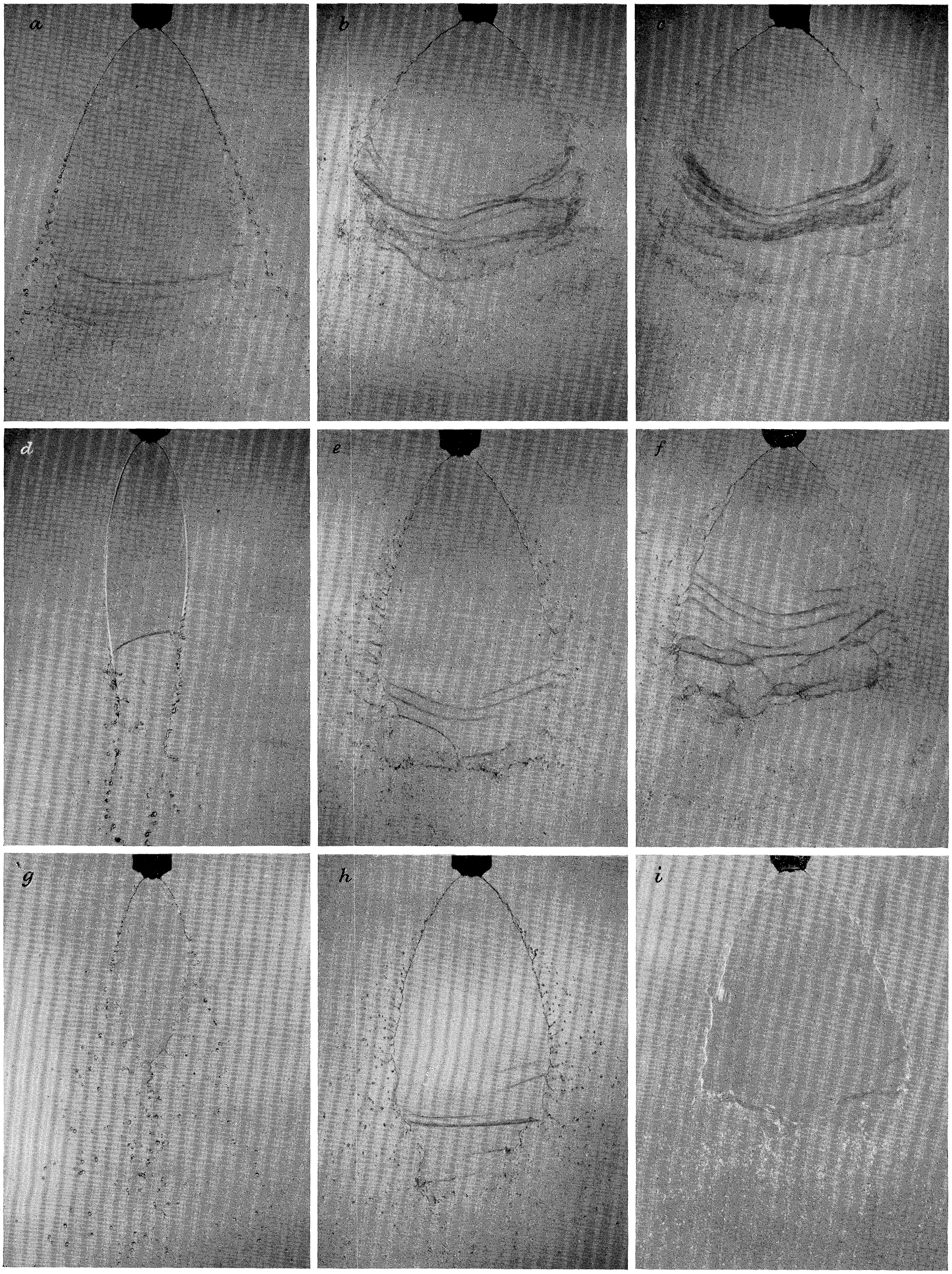
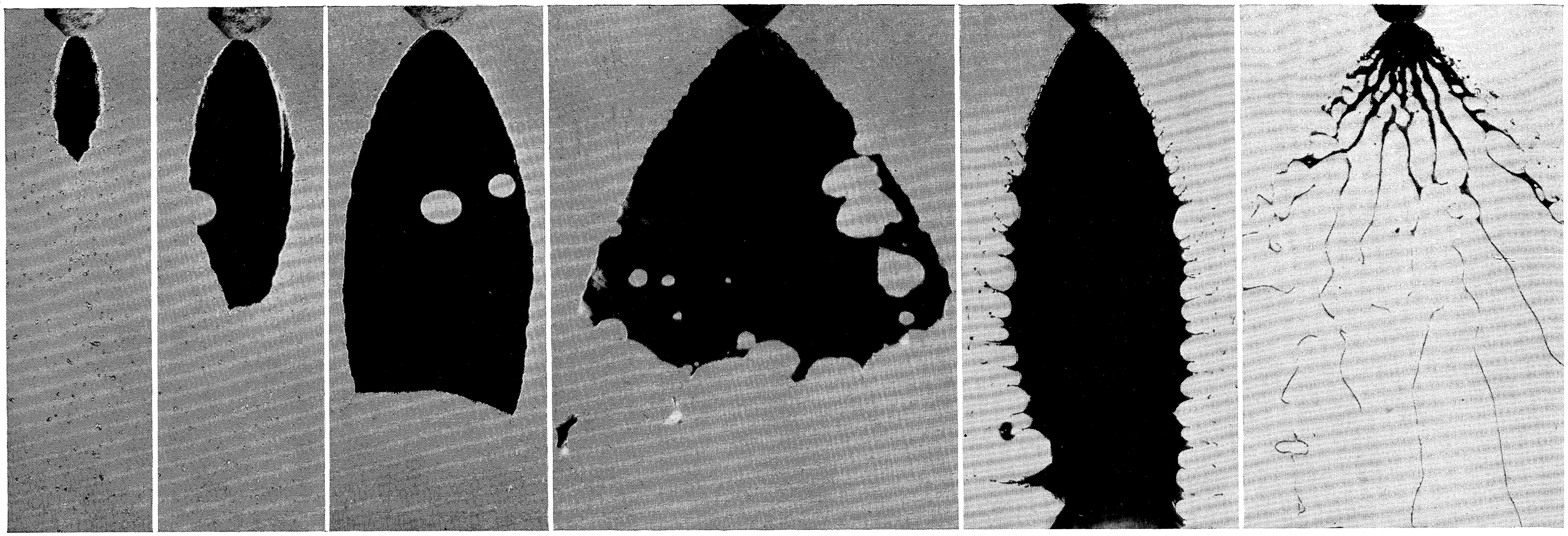
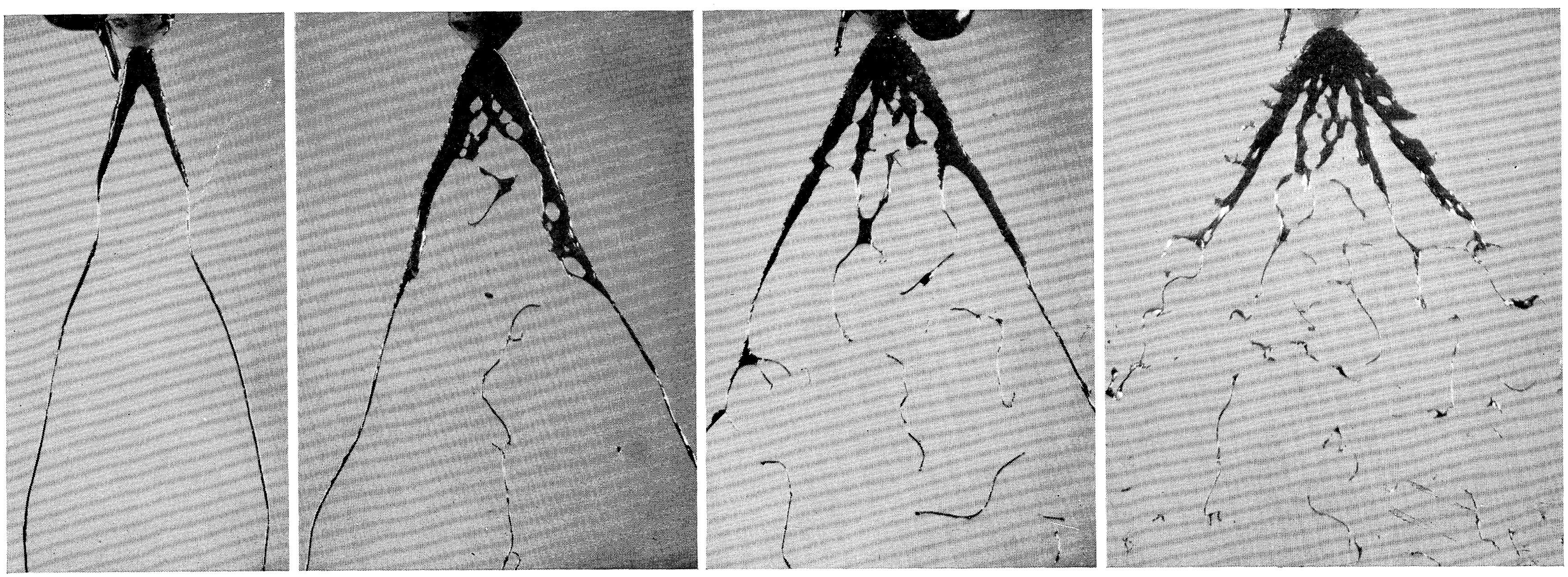


FIGURE 13. The development of sheets of liquid having low viscosity, surface tension and density. *a* to *c*, ethyl alcohol: surface tension 24 dynes/cm. *d* to *f*, distilled water plus a wetting agent: surface tension 30 dynes/cm. *g* to *i*, distilled water: surface tension 73 dynes/cm. (Nat. size.)



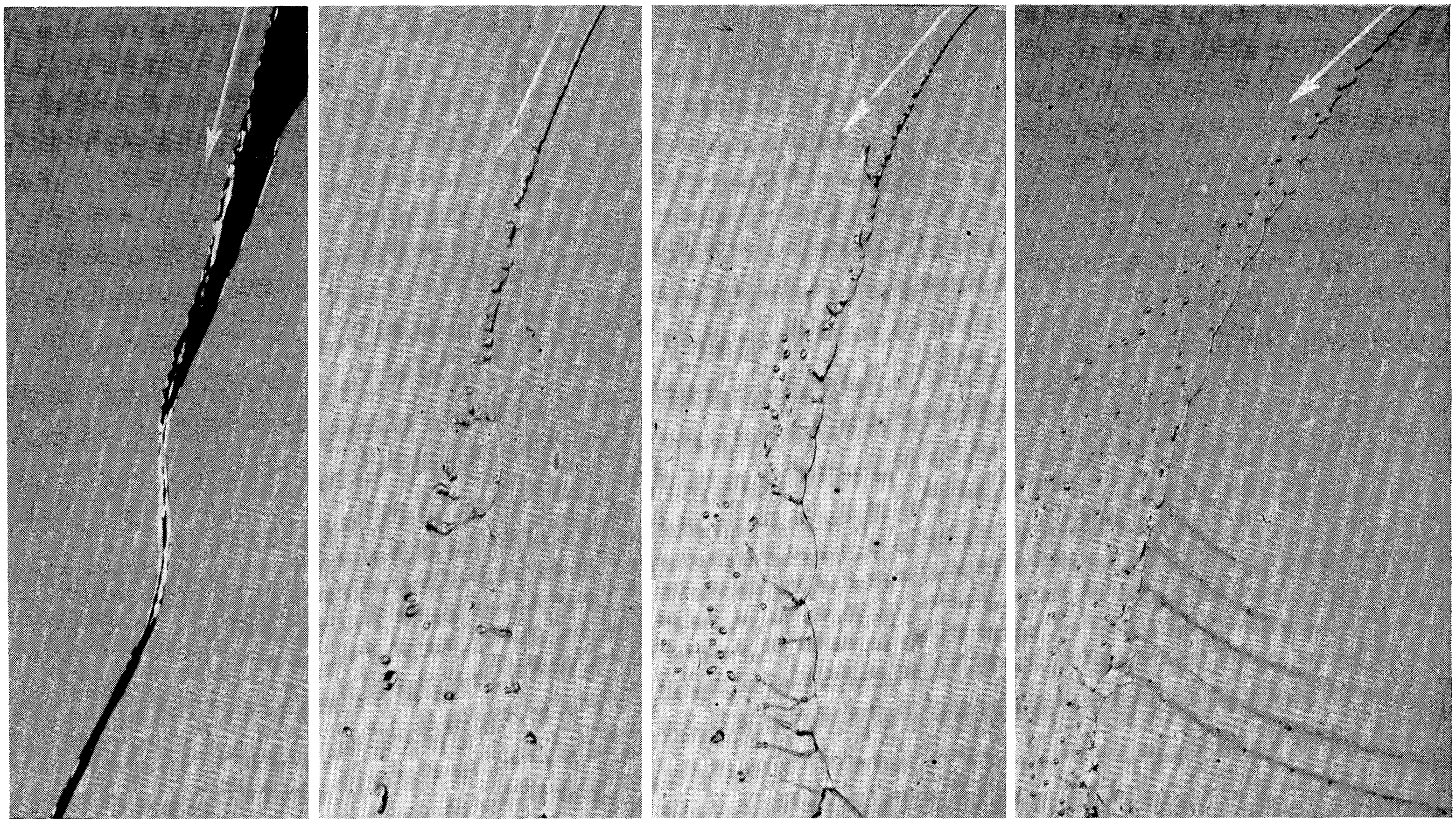
a (25) Hg *b* (60) Hg *c* (130) Hg *d* (480) Hg *e* (50) 2 % Na/Hg *f* (80) 20 % Na/Hg

FIGURE 15. The development of sheets of liquid having high surface tension, low viscosity and high density. Pressures in Lb./in.^{2} shown by figures in brackets. (Nat. size.)



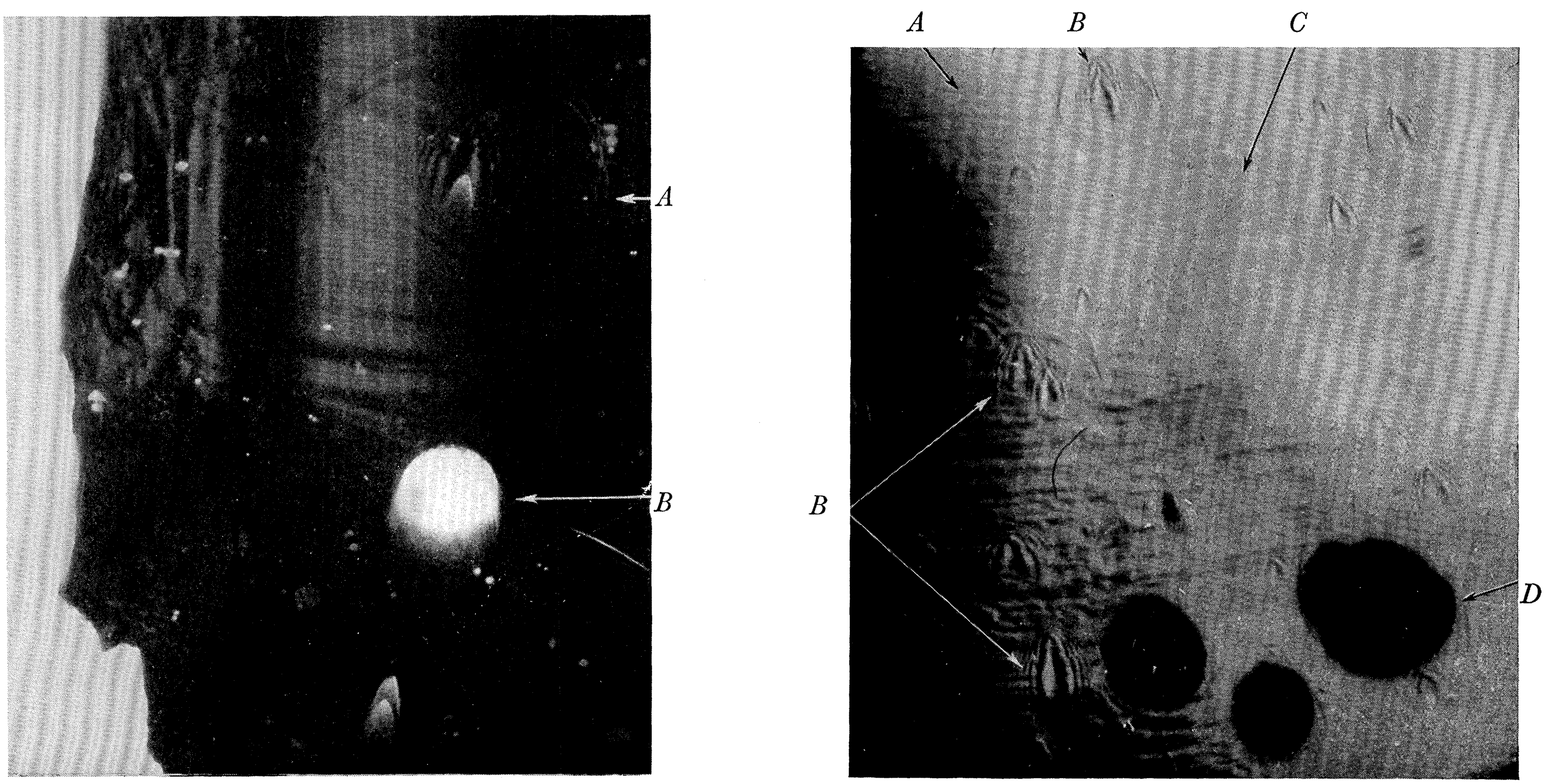
a (9) Na *b* (19) Na *c* (30) Na *d* (50) Na

FIGURE 16. The development of sheets of liquid having high surface tension, low viscosity and low density. Pressures in Lb./in.^{2} shown by figures in brackets. (Nat. size.)



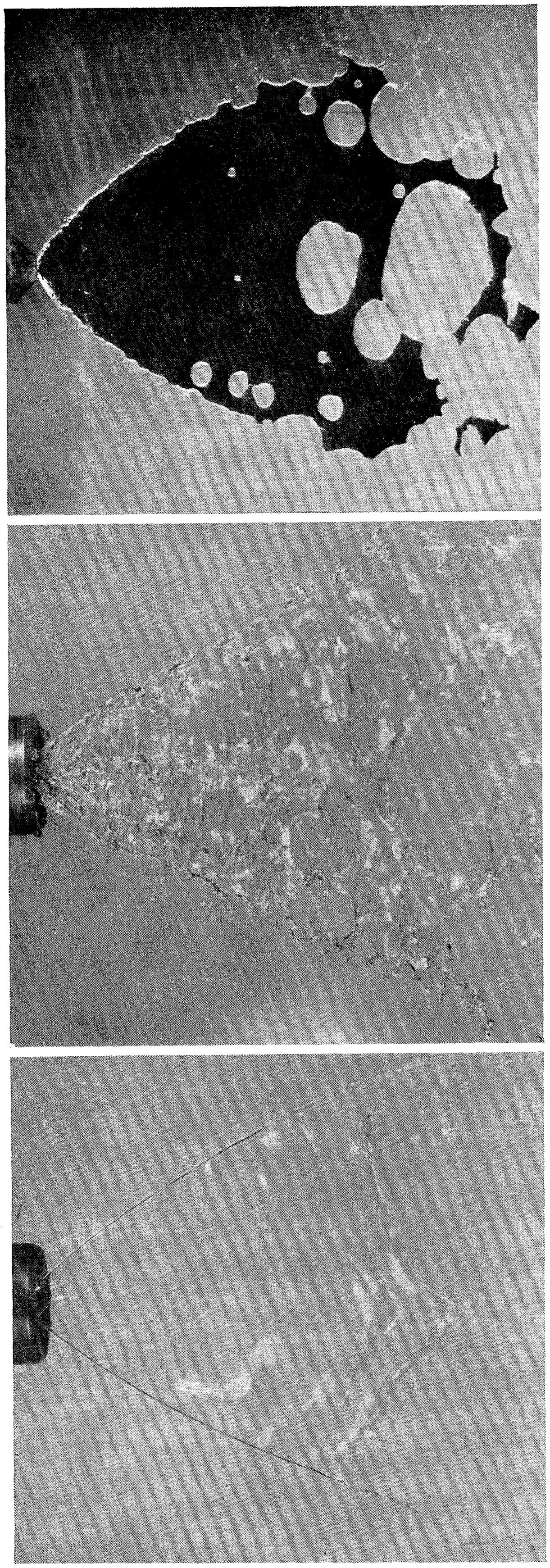
a, sodium *b*, water *c*, water + wetting agent *d*, ethyl alcohol

FIGURE 17. The formation of drops from the edge of a sheet. (Magn. × 3.)



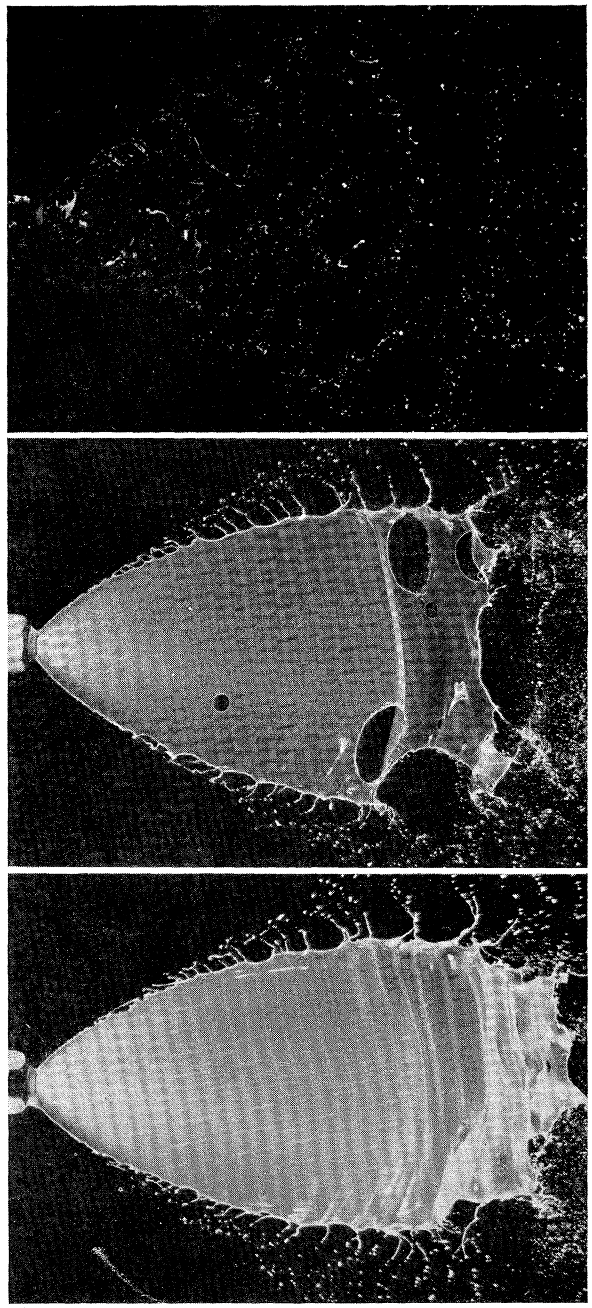
a *b*

FIGURE 18. Disturbances on a mercury sheet. (Magn. *a*, × 6·6; *b*, × 5·7.)



a, $R = 15000$ *b*, $R = 41000$ *c*, $R = 100000$

FIGURE 19. Influence of the Reynolds number on sheet disintegration.
a, water, 1430 cm/s; *b*, water, 1430 cm/s; *c*, mercury, 2200 cm/s. (Nat. size.)



a *b* *c*

FIGURE 20. Perforations produced in a sheet of soluble oil in water. (Nat. size.)

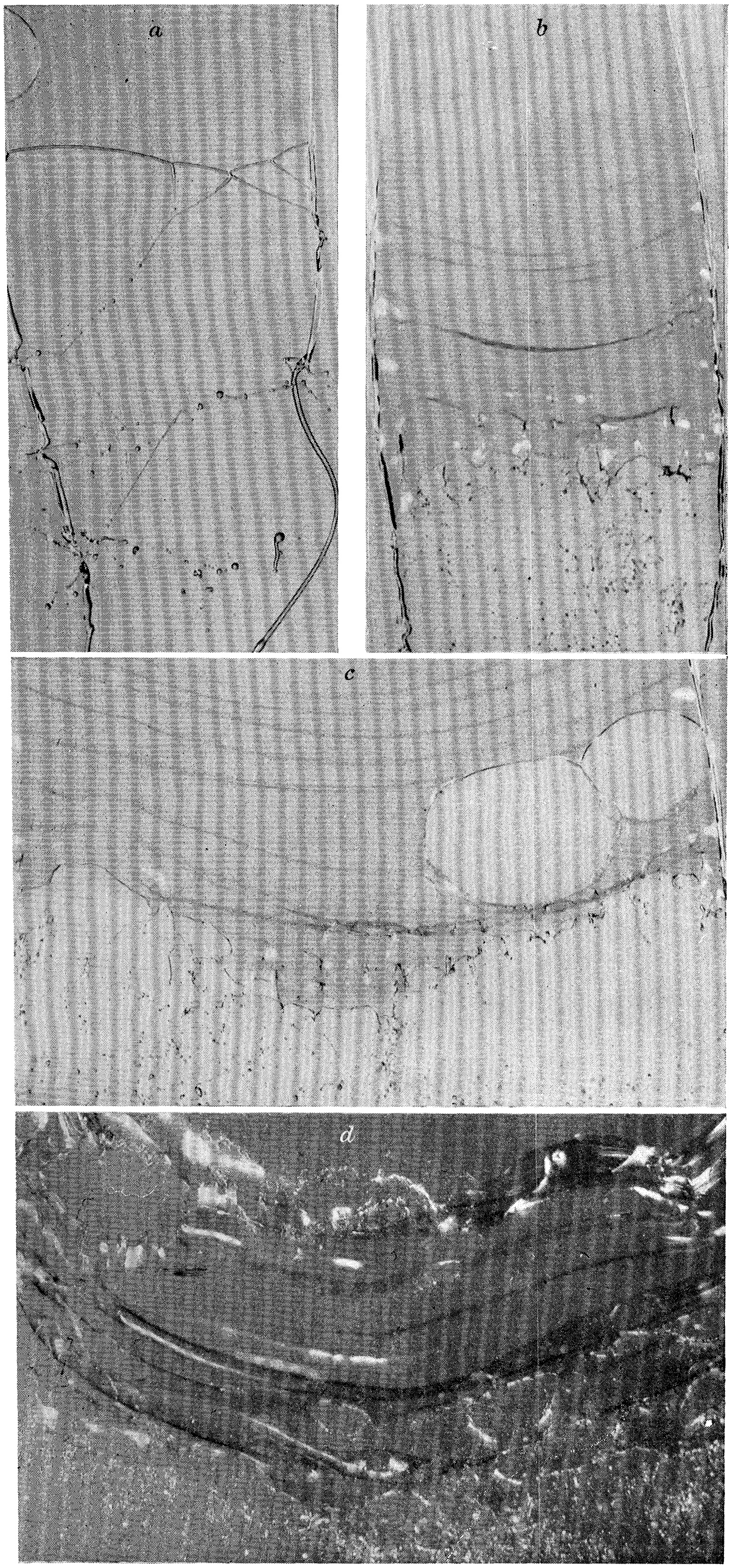


FIGURE 21. Disintegration in the leading edge and the effect of the atmosphere.
Velocities in ft/s. *a*, 38; *b*, 54; *c*, 54; *d*, 80. (Magn. × 2.)

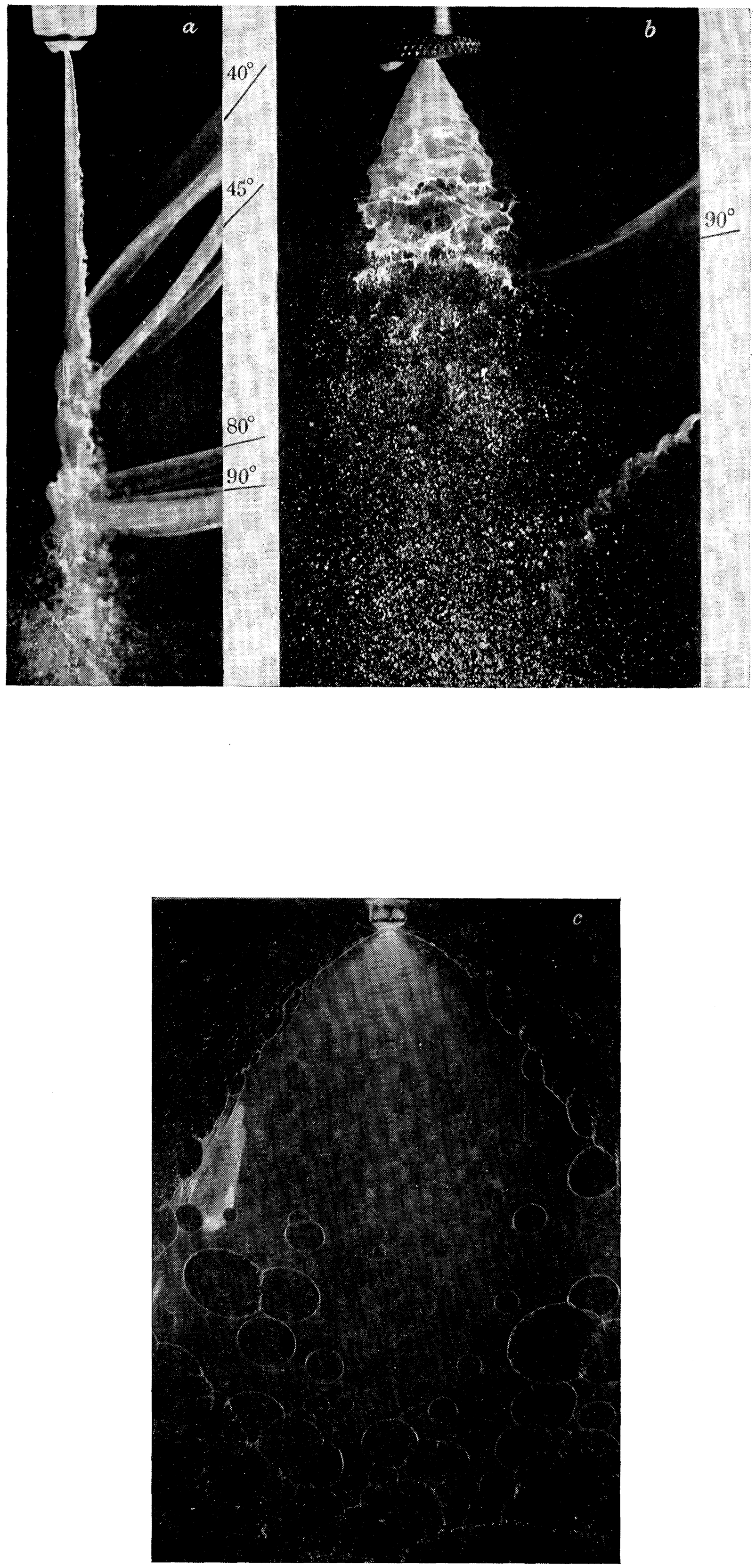


FIGURE 22. Entrainment of air by the sheet.
a, flat sheet (magn. × 1·3); *b*, conical sheet (magn. × 0·83); *c*, fan spray *in vacuo* (magn. × 0·66).

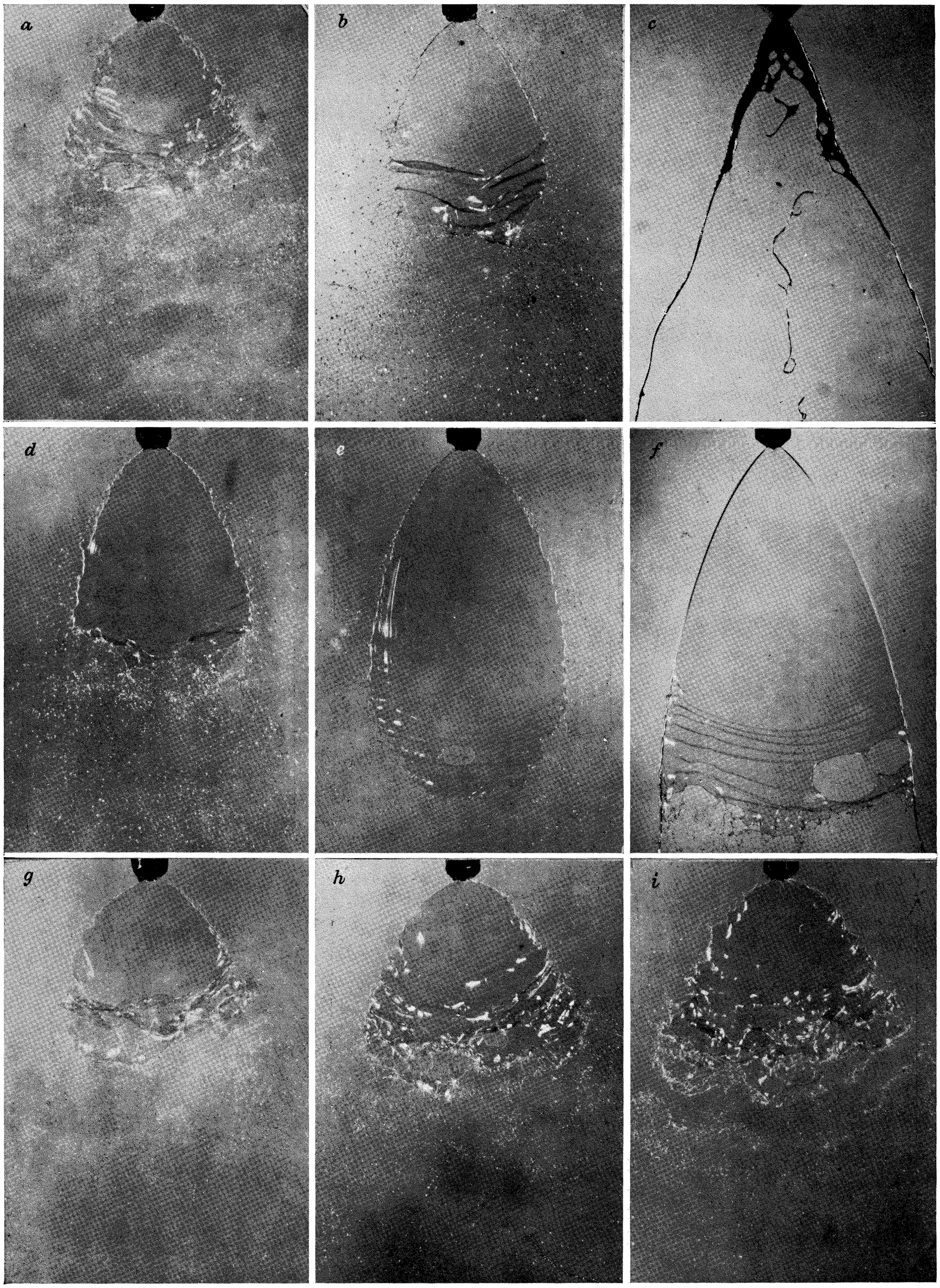
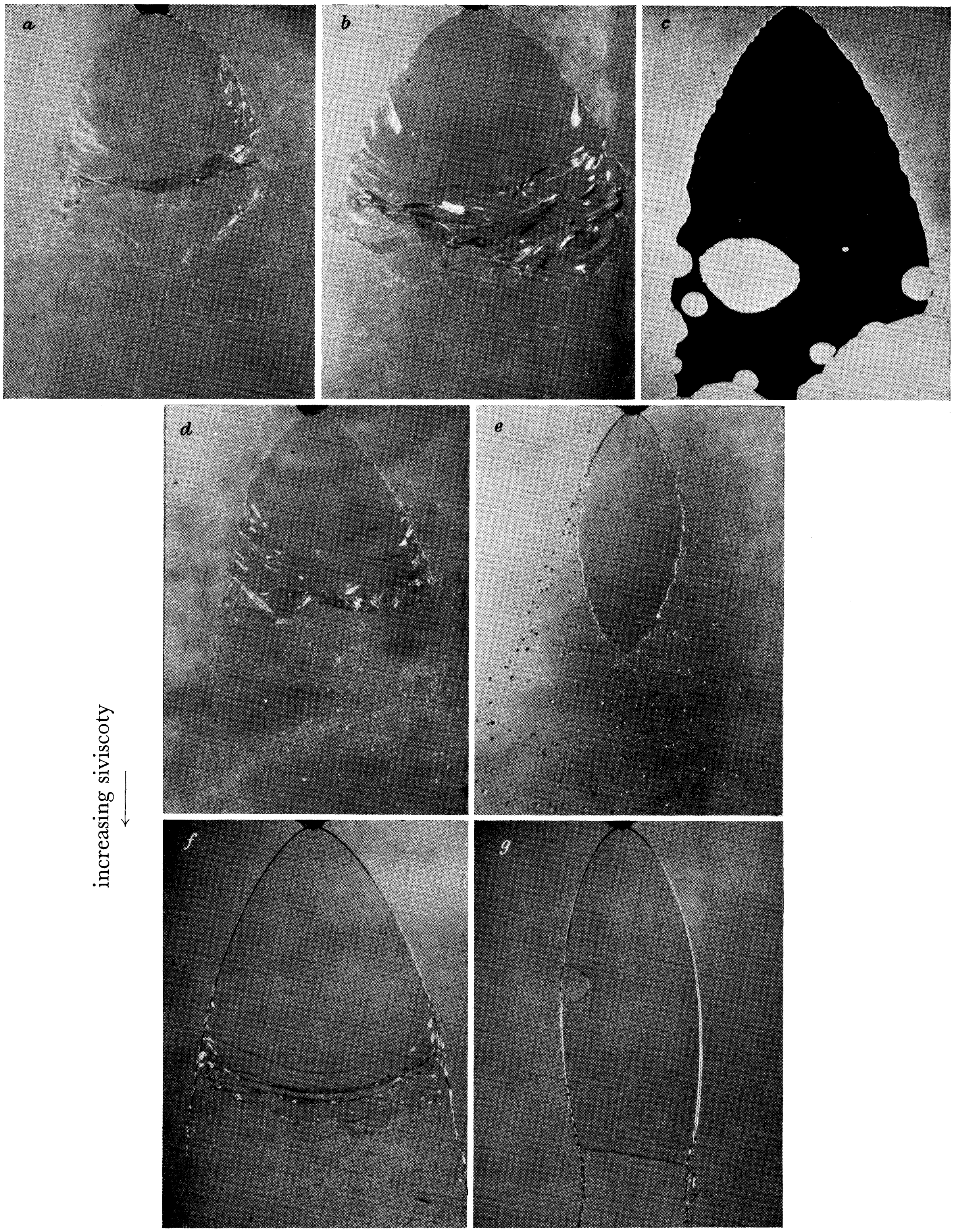


FIGURE 23. The independent effects of surface tension, viscosity and density on the stability of the liquid sheet. (Magn. × 0·8.)

substance	pressure (Lb./in.^{2})	viscosity (cp)	surface tension (dynes/cm)	density (g/ml.)	
a, ethyl acetate	18	0·46	24	0·9	increasing surface tension
b, water (55° C)	20	0·5	67	0·99	
c, sodium	19	0·55	204	0·92	
d, water (20° C)	20	1·0	73	1·0	increasing viscosity
e, 37 % glycerine/water	20	3·3	72	1·1	
f, 47·5 % glycerine/water	22	5·3	70	1·12	
g, toluene	17	0·59	28	0·87	increasing density
h, chloroform	30	0·54	27	1·49	
i, methyl iodide	46	0·5	27	2·28	

increasing surface tension and density
⟶



increasing siviscoty ⟵

⟶
increasing surface tension

FIGURE 24. *a* to *c*, the combined effects of density and surface tension. *d* to *g*, the combined effects of viscosity and surface tension with constant density. (Magn. × 0·8.)

substance	pressure (Lb./in.^{2})	viscosity (cp)	surface tension (dynes/cm)	density (g/ml.)
a, kerosene	16	1·6	25	0·8
b, ethyl dibromide	42	1·6	39	2·1
c, mercury	270	1·55	540	13·6
d, ethyl acetate	9	0·46	24	0·9
e, water (55° C)	10	0·5	67	0·99
f, *iso*butyl alcohol	9	5·3	23·5	0·81
g, 47·5 % glycerine/water	11	5·3	70	1·1

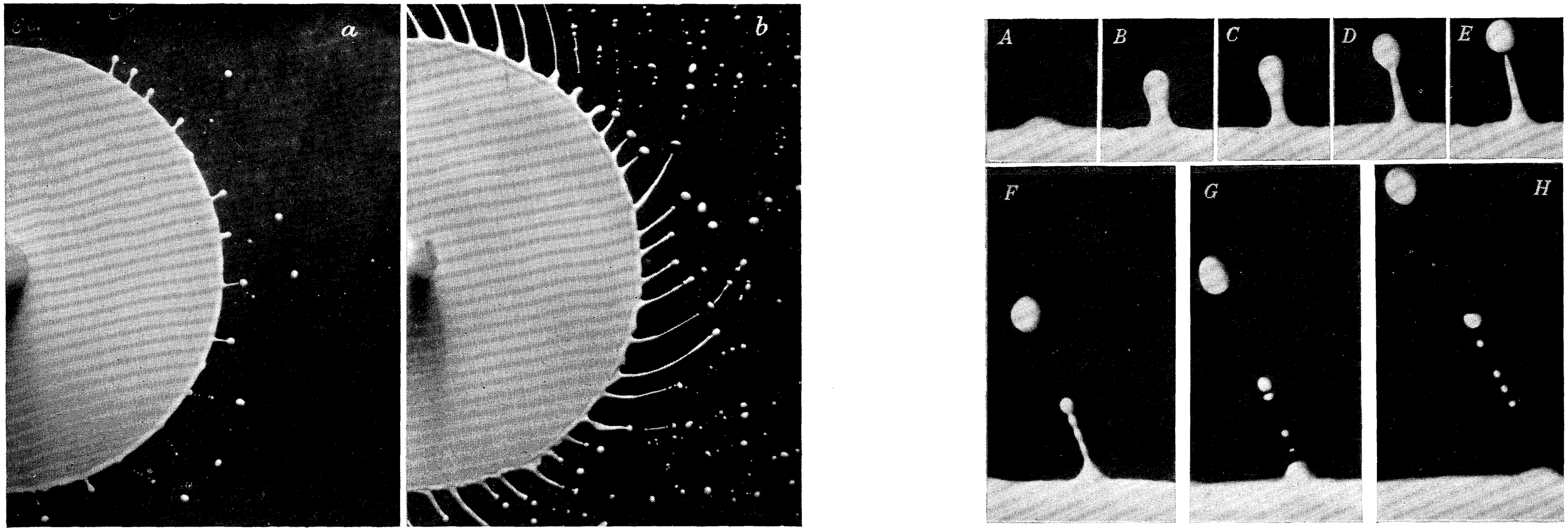


FIGURE 25. Drop formation from the edge of a spinning disk.
a, velocity 210 cm/s, quantity 2·3 ml./s (magn. ×0·8). *b*, velocity 210 cm/s, quantity 15 ml./s (magn. ×0·8). *A* to *H*, magn. ×4.

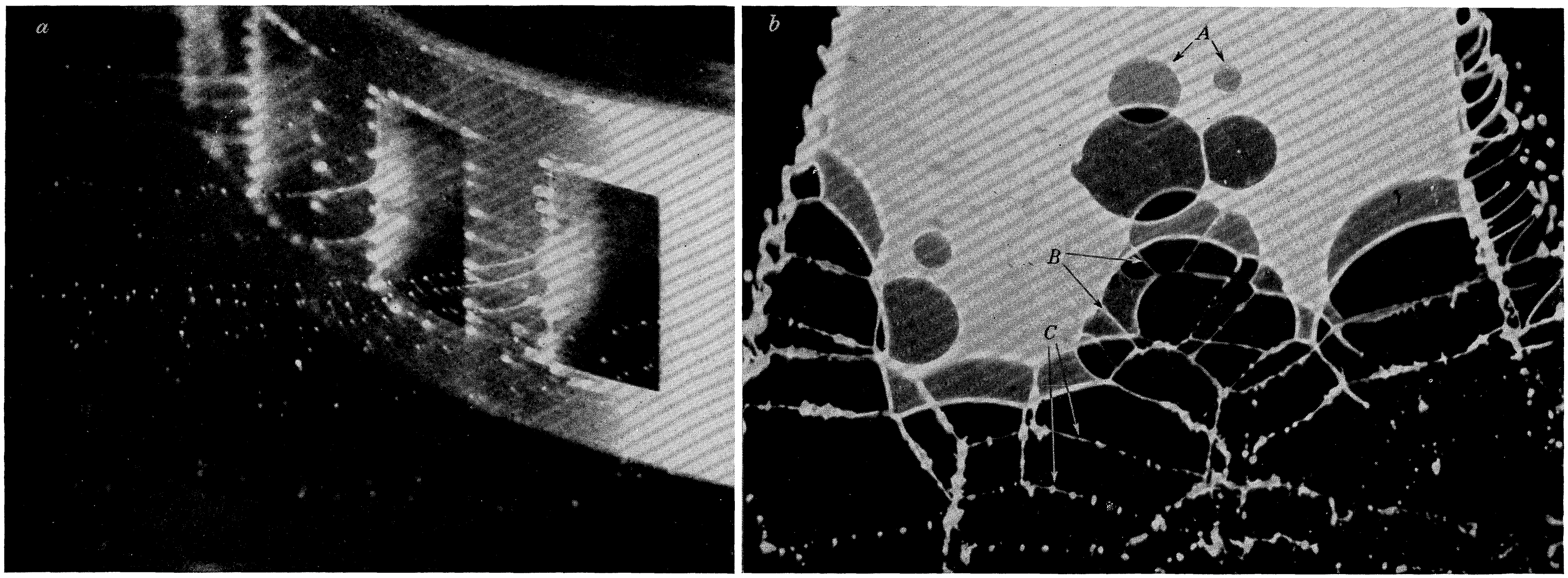


FIGURE 26. *a*, drop formation from a slotted spinning disk (magn. ×5·66). *b*, superimposed photograph, 250 μs interval (magn. ×3·83).

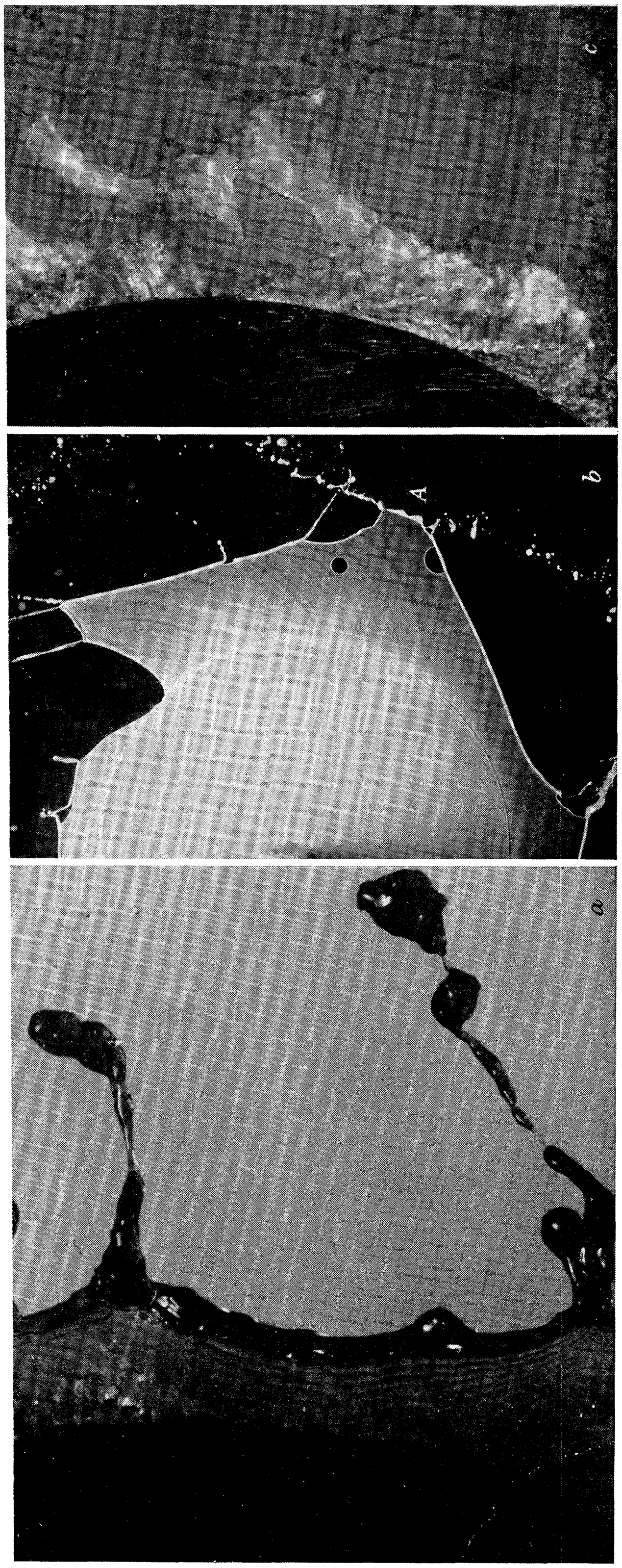


FIGURE 27. Drop formation from the edge of a spinning disk at high outputs.
a, velocity 210 cm/s, quantity 27 ml./s (magn. × 3·3). *b*, velocity 210 cm/s, quantity 27 ml./s (magn. × 0·66).
c, velocity 840 cm/s, quantity 27 ml./s (magn. × 2).

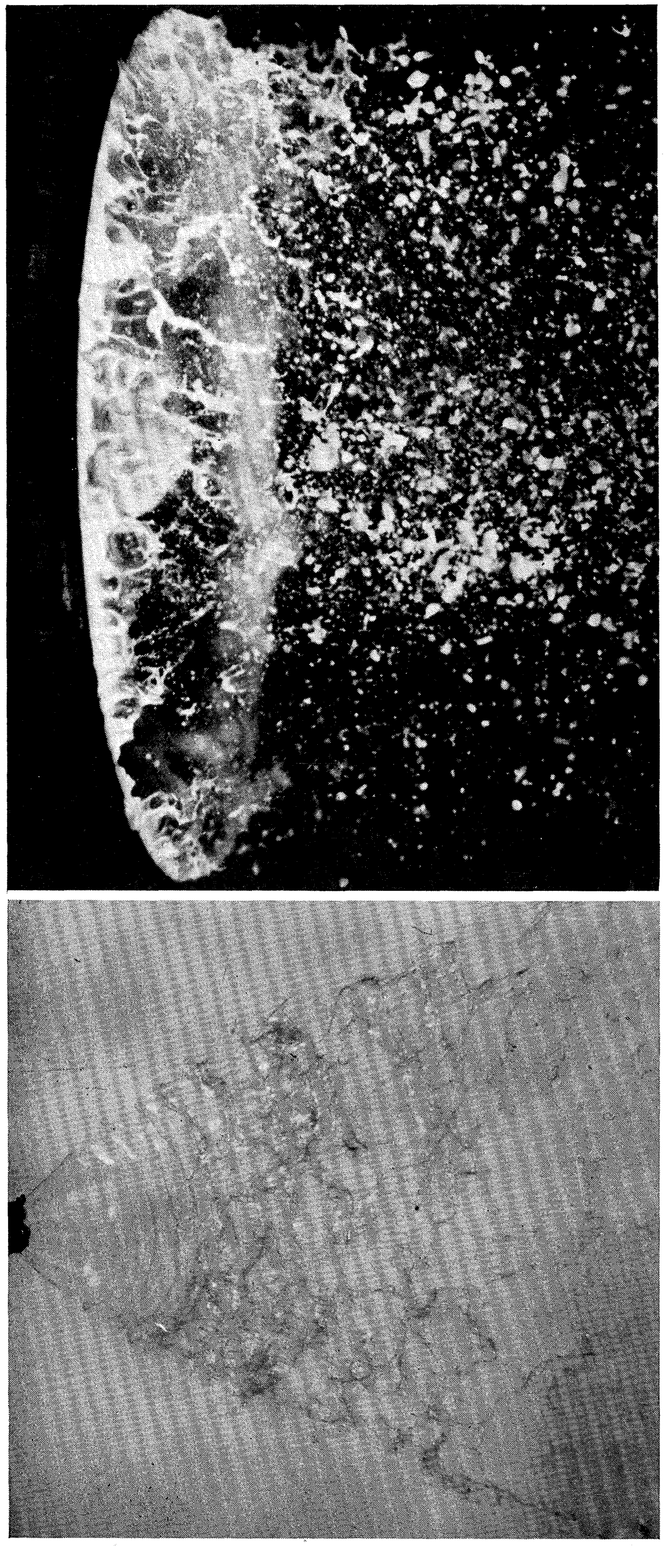


FIGURE 29. *a*, disintegration of a sheet of liquid having visco-elastic properties (magn. × 1·33).
b, disintegration of a liquid in a twin-fluid atomizer (magn. × 3·3).

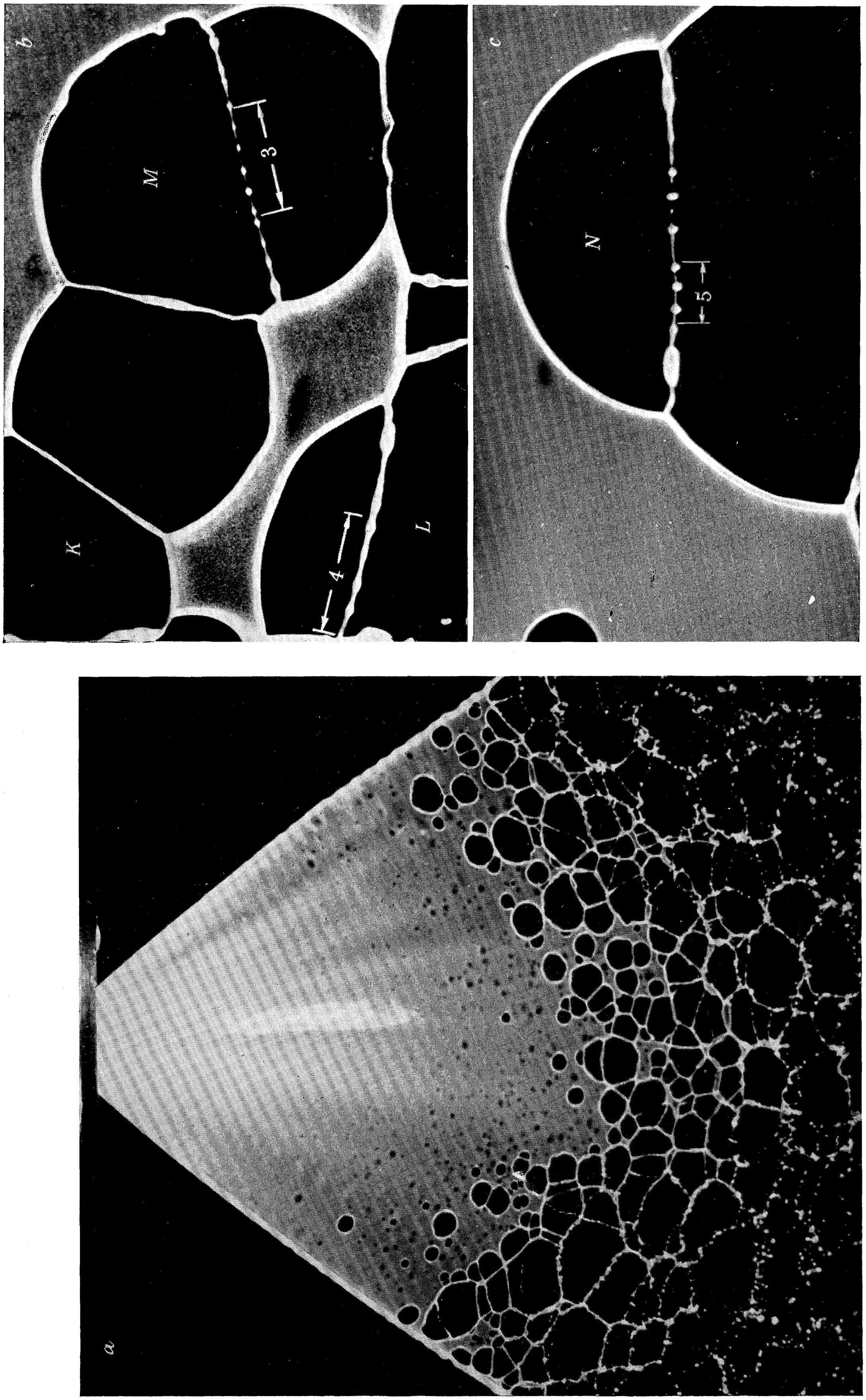


FIGURE 28. Disintegration through perforation with a soluble oil/water emulsion. (Magn. *a*, $\times 2{\cdot}5$; *b*, $\times 3{\cdot}75$; *c*, $\times 7{\cdot}5$.)

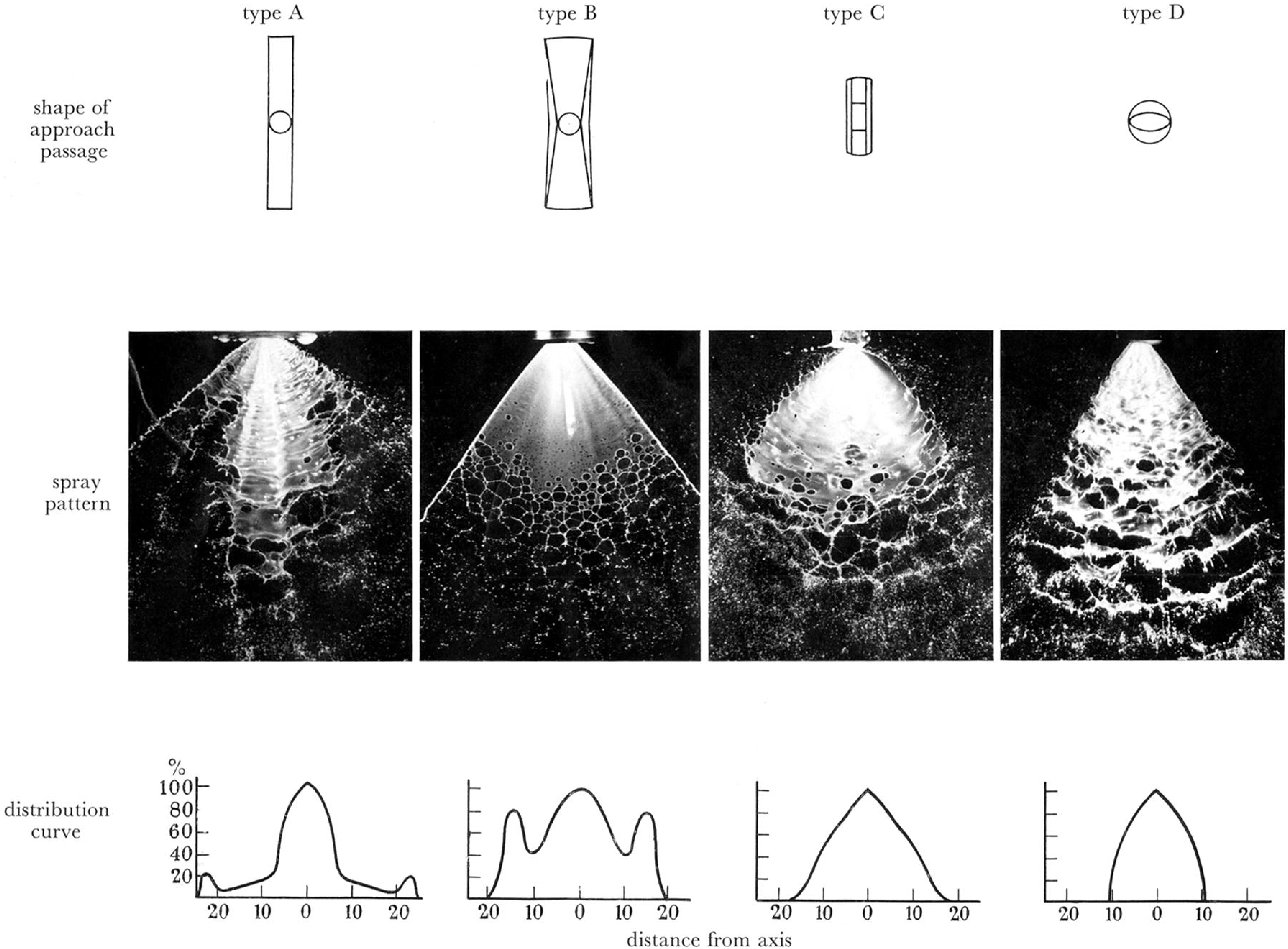


FIGURE 11. Influence of design on spray pattern in single-hole nozzles.

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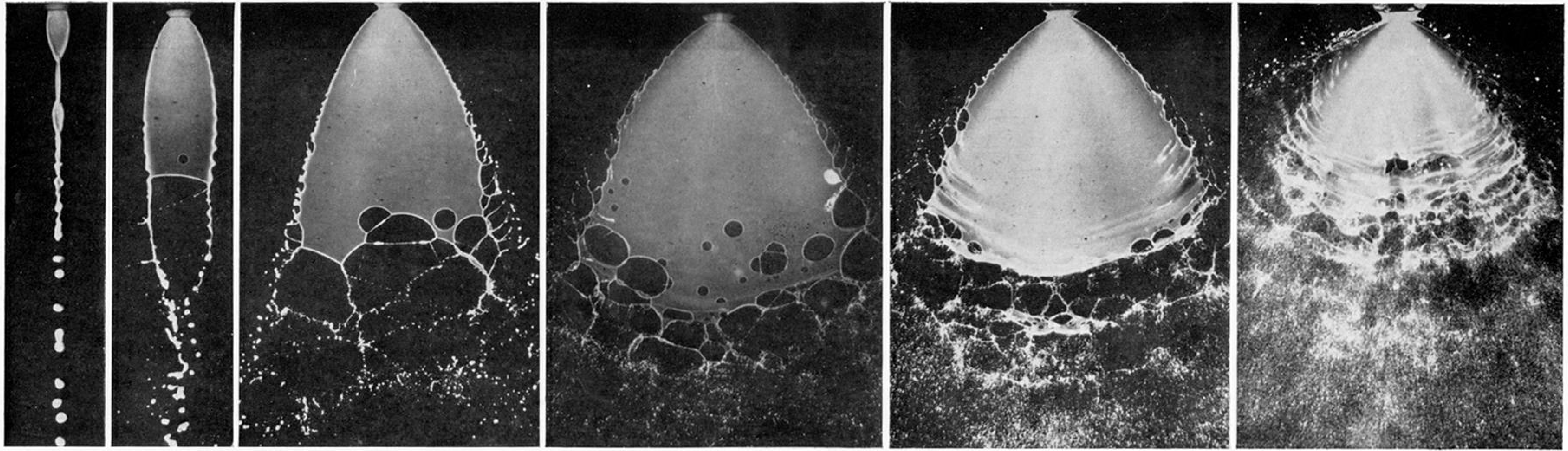
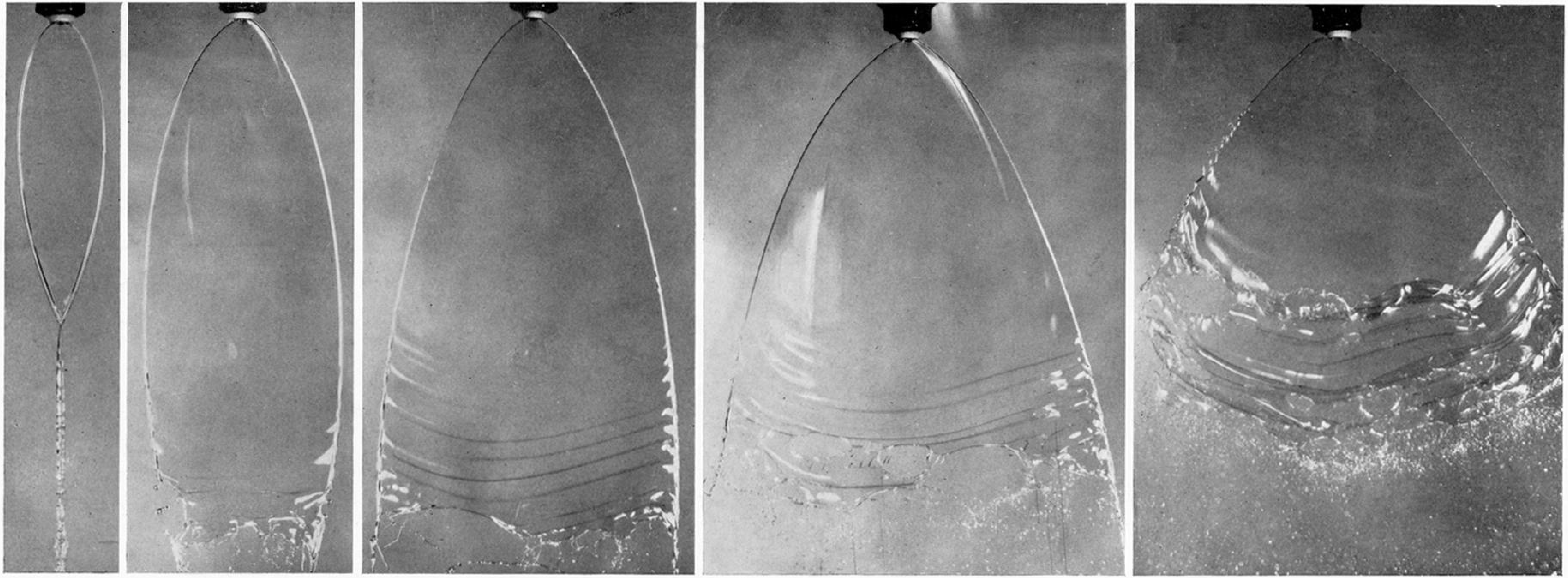


a (1) *b* (3) *c* (8) *d* (25) *e* (50) *f* (185)

FIGURE 12. Characteristic development of a liquid sheet with increase of pressure (15 % soluble oil/tap water). Pressures in Lb./in.^{2} as shown by figures in brackets. (Nat. size.)



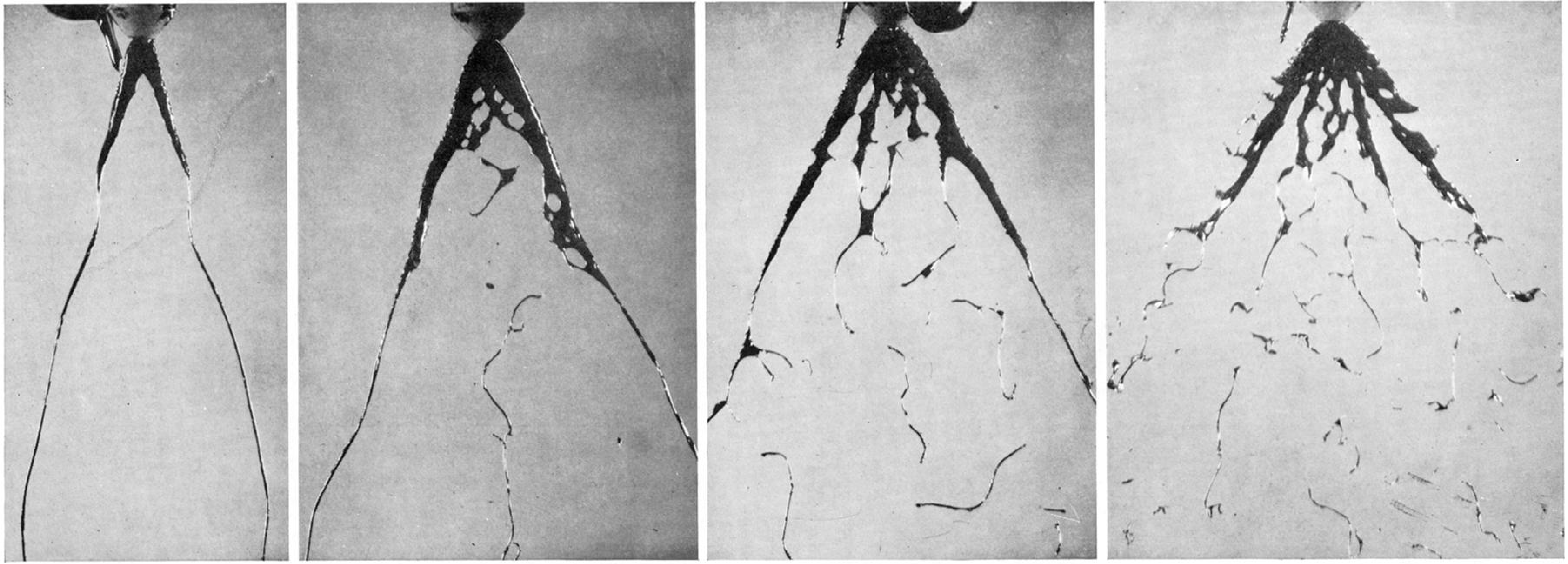
a (5) *b* (10) *c* (15) *d* (20) *e* (50)

FIGURE 14. The development of sheets of liquid having low surface tension, high viscosity and low density (55·3 % glycerine/water). Pressures in Lb./in.^{2} shown by figures in brackets. (Nat. size.)

FIGURE 13. The development of sheets of liquid having low viscosity, surface tension and density. *a* to *c*, ethyl alcohol: surface tension 24 dynes/cm. *d* to *f*, distilled water plus a wetting agent: surface tension 30 dynes/cm. *g* to *i*, distilled water: surface tension 73 dynes/cm. (Nat. size.)

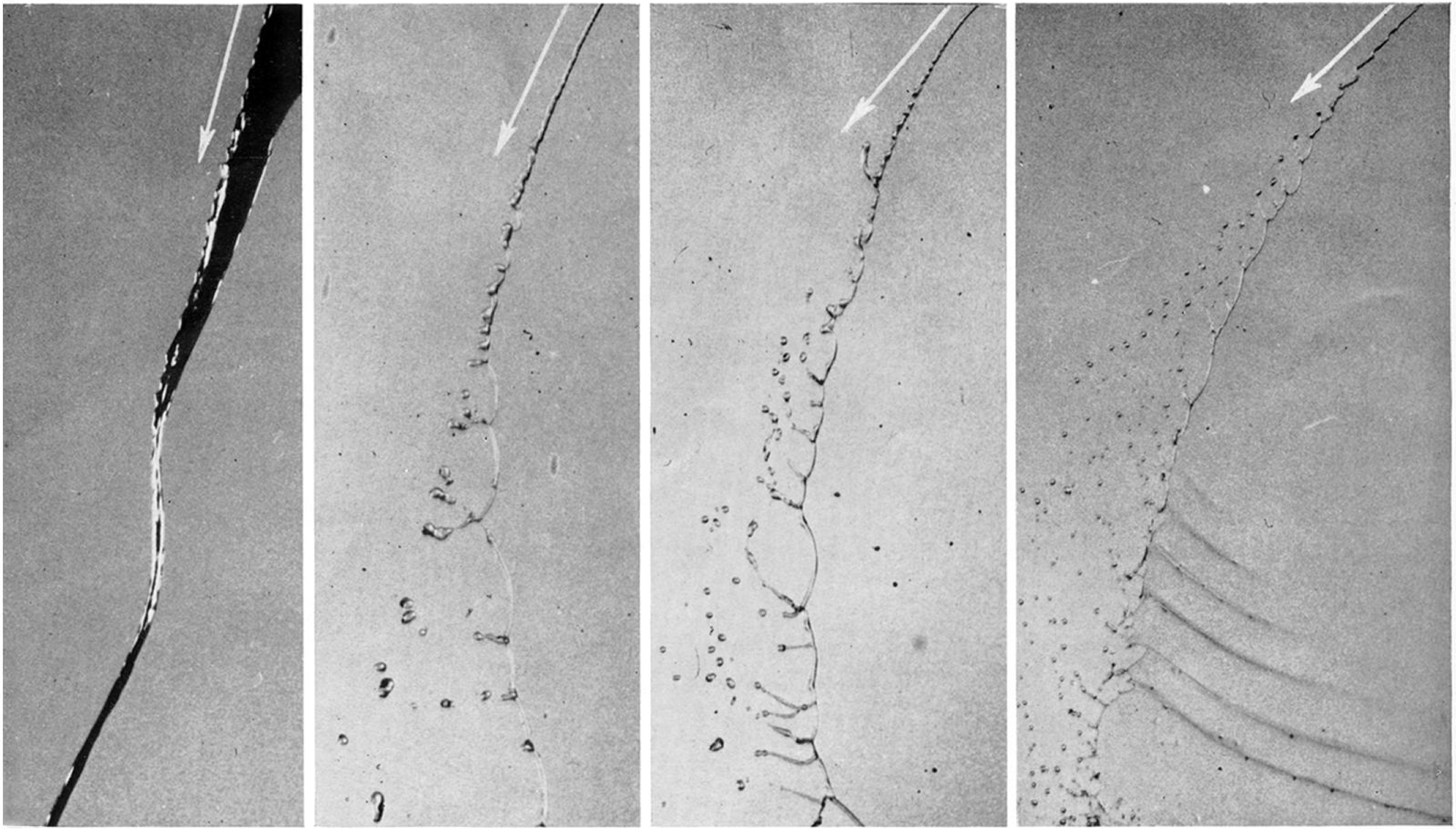
a (25) Hg *b* (60) Hg *c* (130) Hg *d* (480) Hg *e* (50) 2 % Na/Hg *f* (80) 20 % Na/Hg

FIGURE 15. The development of sheets of liquid having high surface tension, low viscosity and high density. Pressures in Lb./in.^{2} shown by figures in brackets. (Nat. size.)



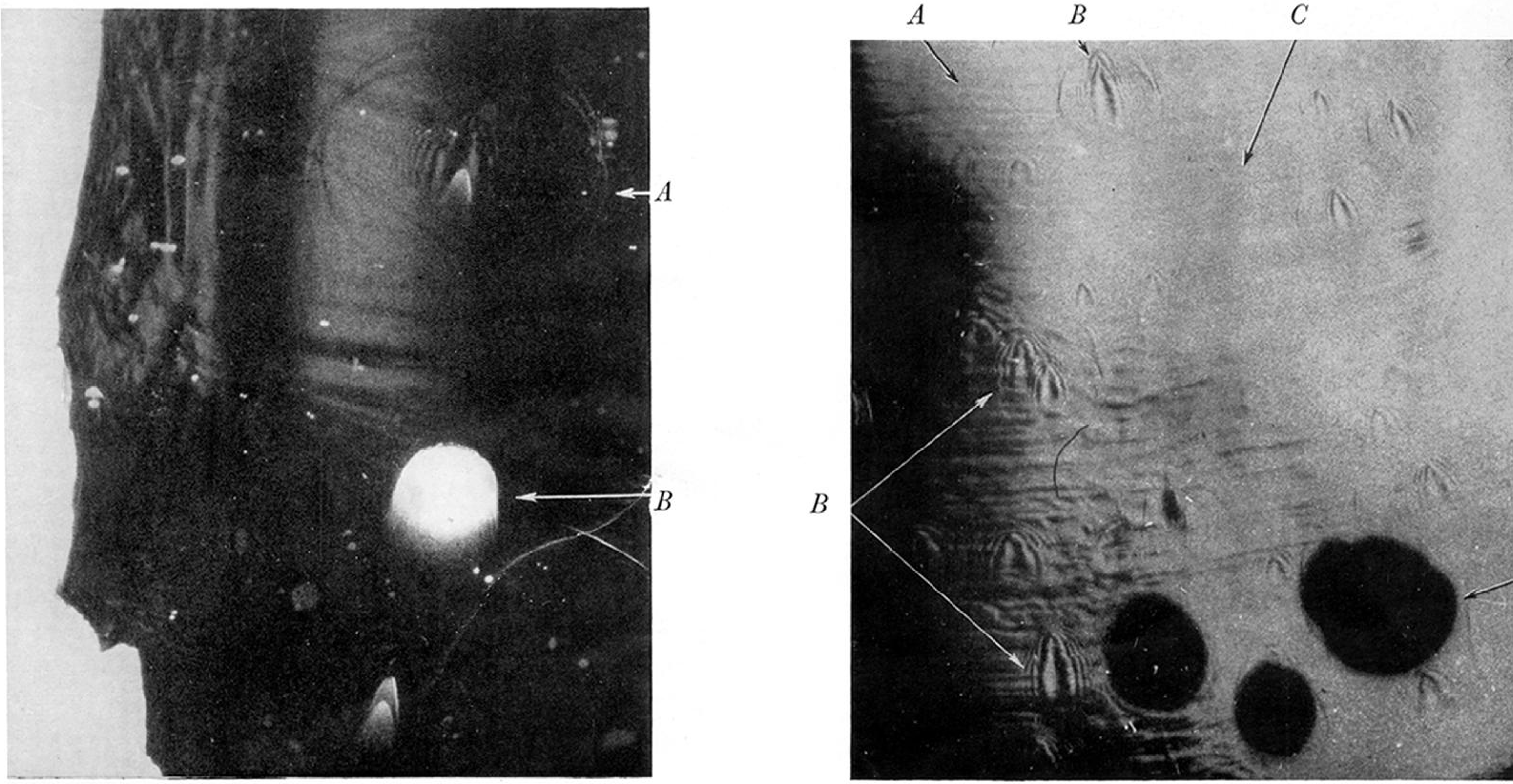
a (9) Na b (19) Na c (30) Na d (50) Na

FIGURE 16. The development of sheets of liquid having high surface tension, low viscosity and low density. Pressures in Lb./in.^{2} shown by figures in brackets. (Nat. size.)



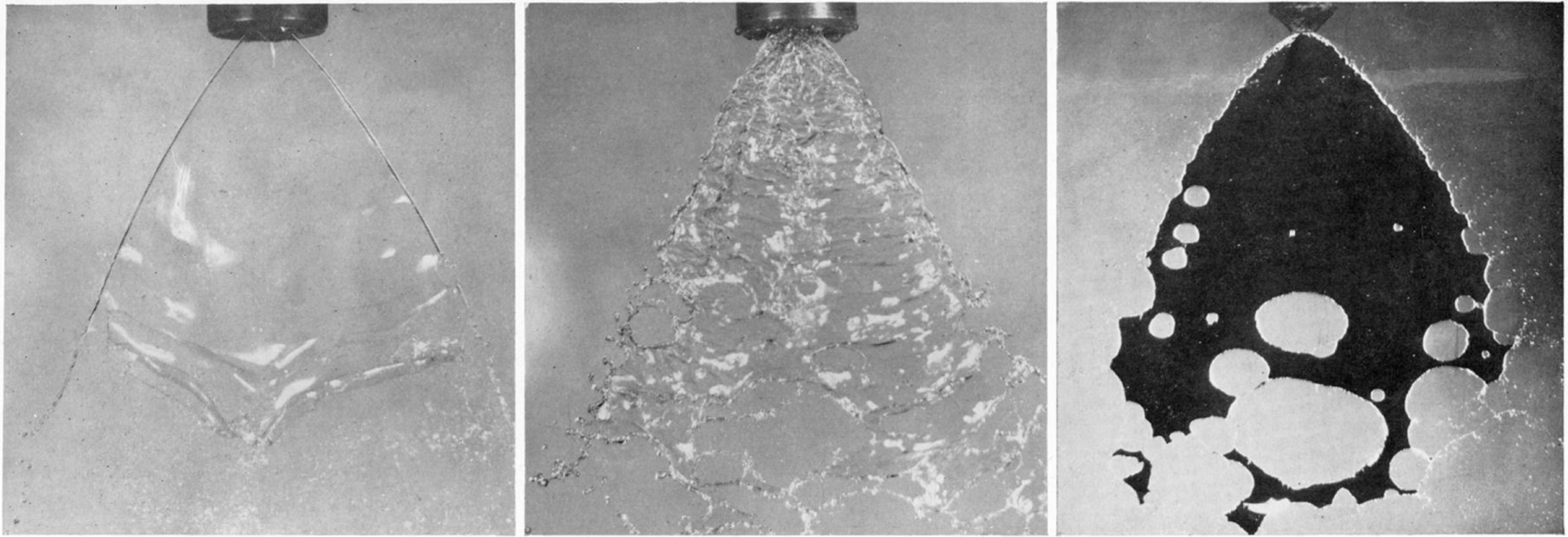
a, sodium　　*b*, water　　*c*, water + wetting agent　　*d*, ethyl alcohol

FIGURE 17. The formation of drops from the edge of a sheet. (Magn. ×3.)



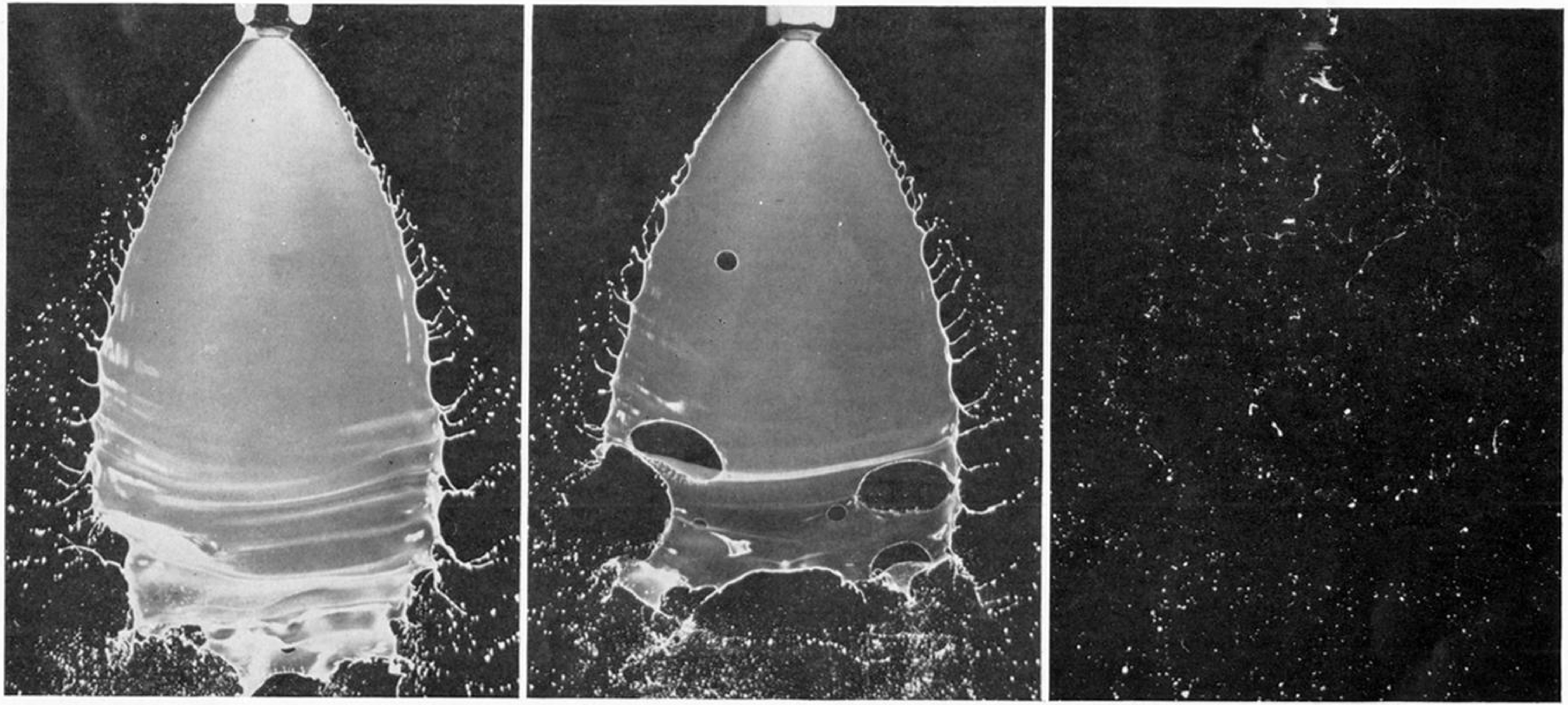
a *b*

FIGURE 18. Disturbances on a mercury sheet. (Magn. *a*, ×6·6; *b*, ×5·7.)



a, $R = 15\,000$ *b*, $R = 41\,000$ *c*, $R = 100\,000$

FIGURE 19. Influence of the Reynolds number on sheet disintegration.
a, water, 1430 cm/s; *b*, water, 1430 cm/s; *c*, mercury, 2200 cm/s. (Nat. size.)



a *b* *c*

FIGURE 20. Perforations produced in a sheet of soluble oil in water. (Nat. size.)

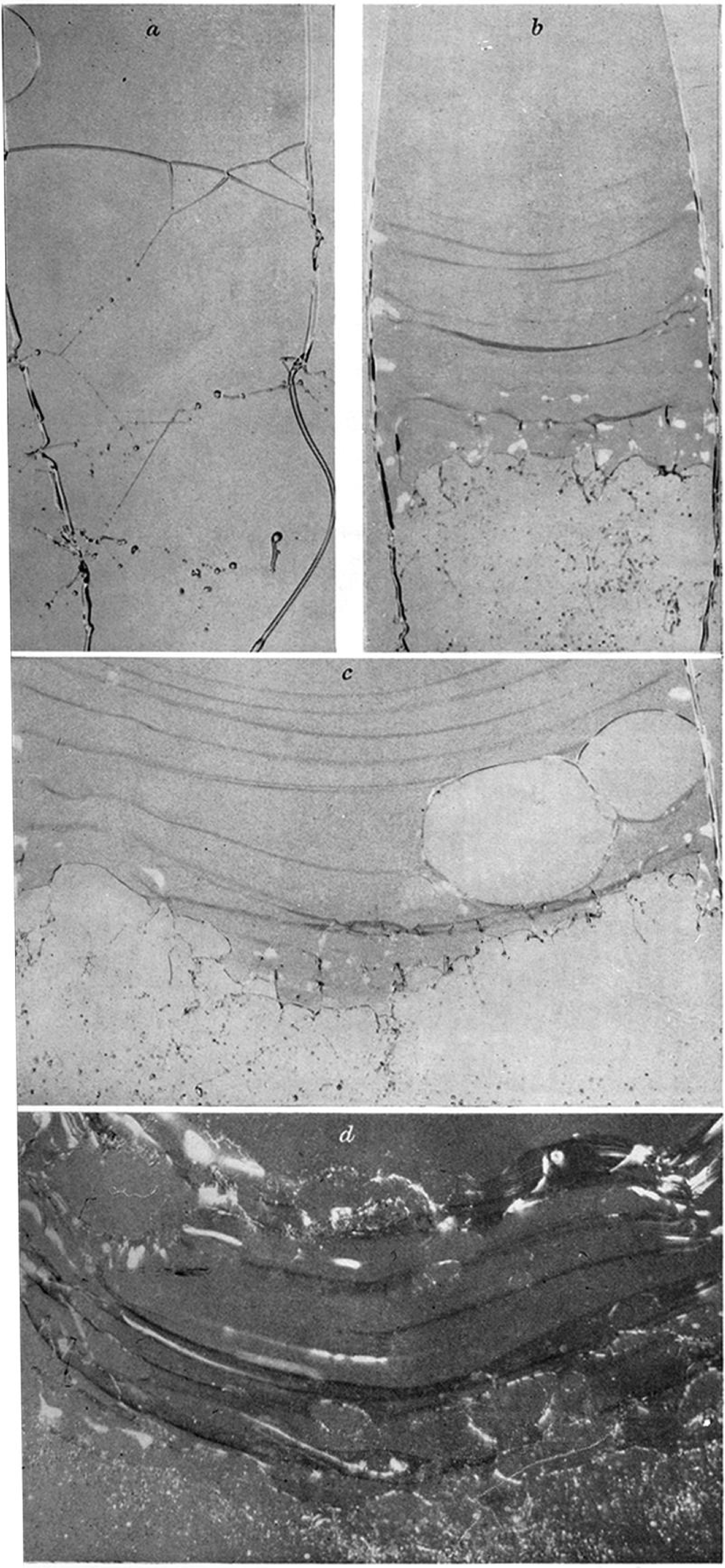


FIGURE 21. Disintegration in the leading edge and the effect of the atmosphere.

Velocities in ft/s. *a*, 38; *b*, 54; *c*, 54; *d*, 80. (Magn. × 2.)

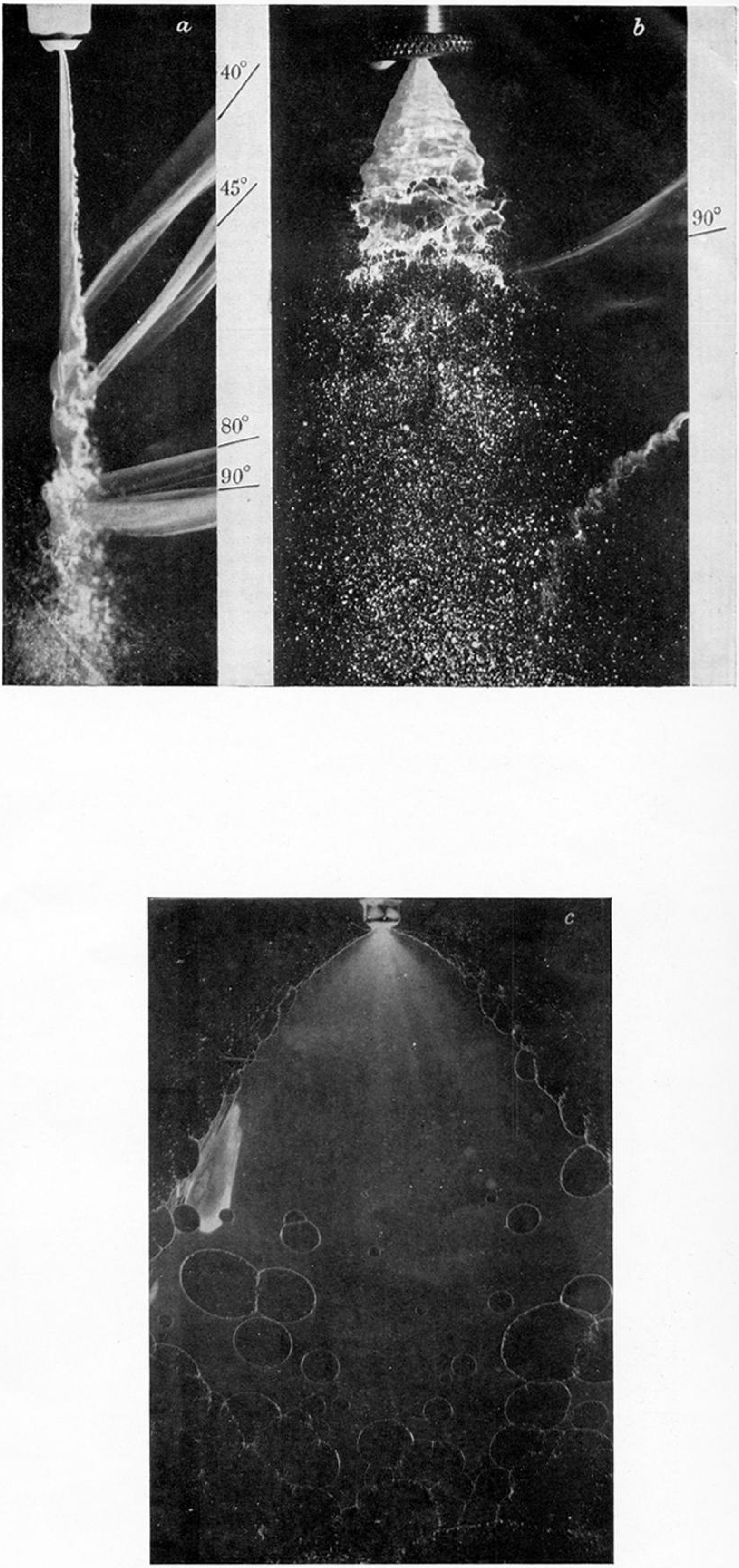


FIGURE 22. Entrainment of air by the sheet.
a, flat sheet (magn. × 1·3); *b*, conical sheet (magn. × 0·83); *c*, fan spray *in vacuo* (magn. × 0·66).

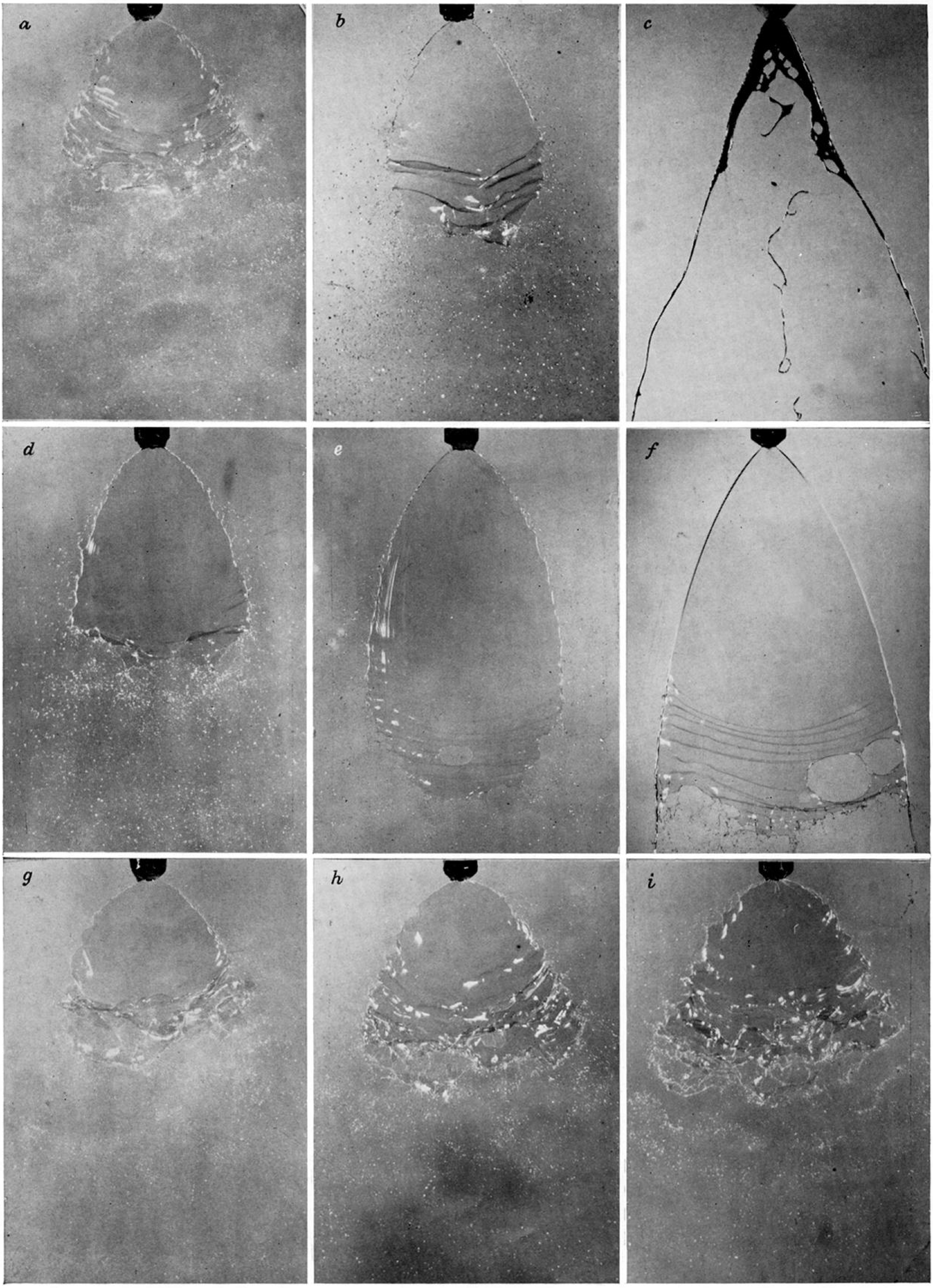


FIGURE 23. The independent effects of surface tension, viscosity and density on the stability of the liquid sheet. (Magn. ×0·8.)

substance	pressure (Lb./in.^{2})	viscosity (cp)	surface tension (dynes/cm)	density (g/ml.)	
a, ethyl acetate	18	0·46	24	0·9	increasing surface tension
b, water (55° C)	20	0·5	67	0·99	
c, sodium	19	0·55	204	0·92	
d, water (20° C)	20	1·0	73	1·0	increasing viscosity
e, 37 % glycerine/water	20	3·3	72	1·1	
f, 47·5 % glycerine/water	22	5·3	70	1·12	
g, toluene	17	0·59	28	0·87	increasing density
h, chloroform	30	0·54	27	1·49	
i, methyl iodide	46	0·5	27	2·28	

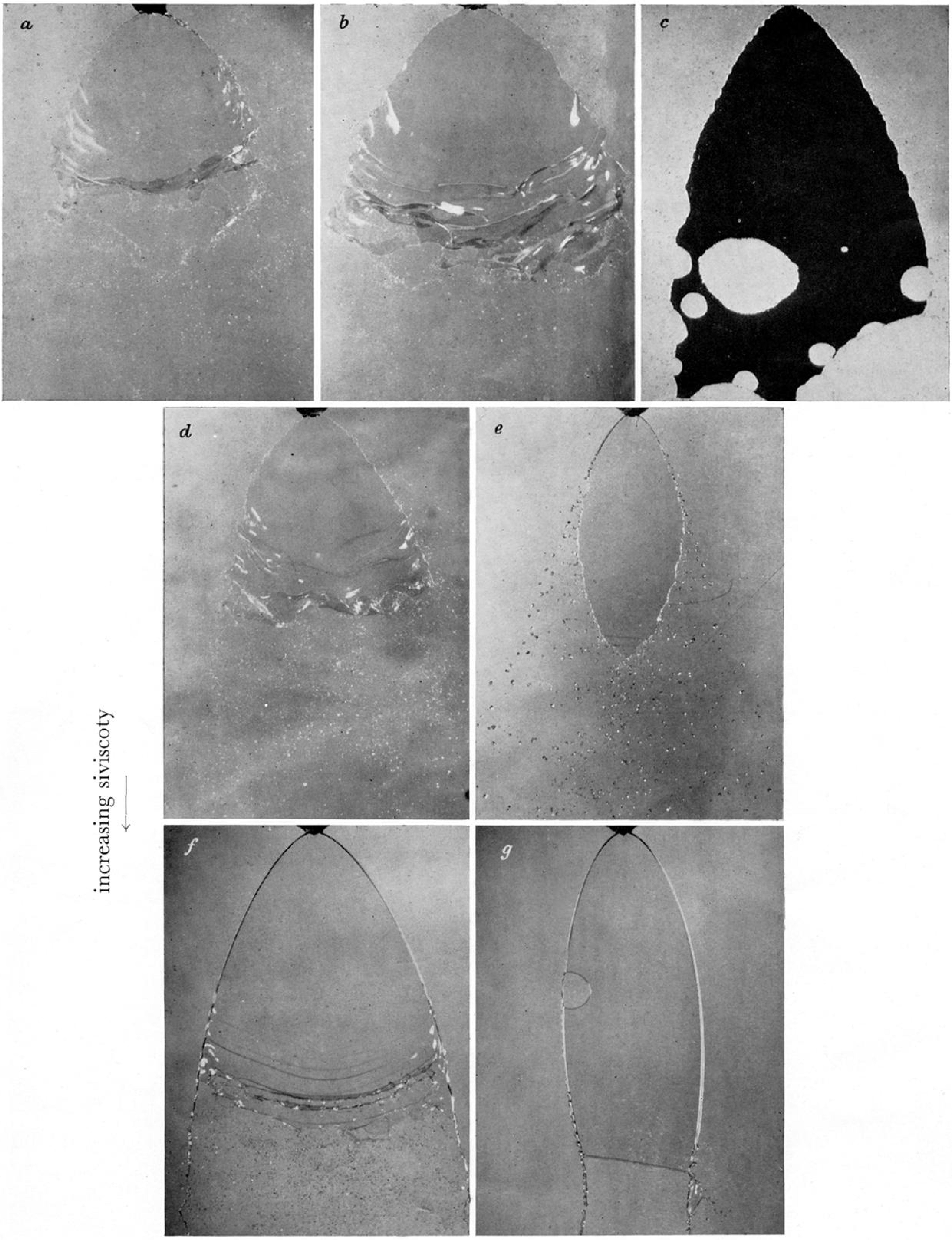


FIGURE 24. *a* to *c*, the combined effects of density and surface tension. *d* to *g*, the combined effects of viscosity and surface tension with constant density. (Magn. × 0·8.)

substance	pressure (Lb./in.^{2})	viscosity (cp)	surface tension (dynes/cm)	density (g/ml.)
a, kerosene	16	1·6	25	0·8
b, ethyl dibromide	42	1·6	39	2·1
c, mercury	270	1·55	540	13·6
d, ethyl acetate	9	0·46	24	0·9
e, water (55° C)	10	0·5	67	0·99
f, *iso*butyl alcohol	9	5·3	23·5	0·81
g, 47·5 % glycerine/water	11	5·3	70	1·1

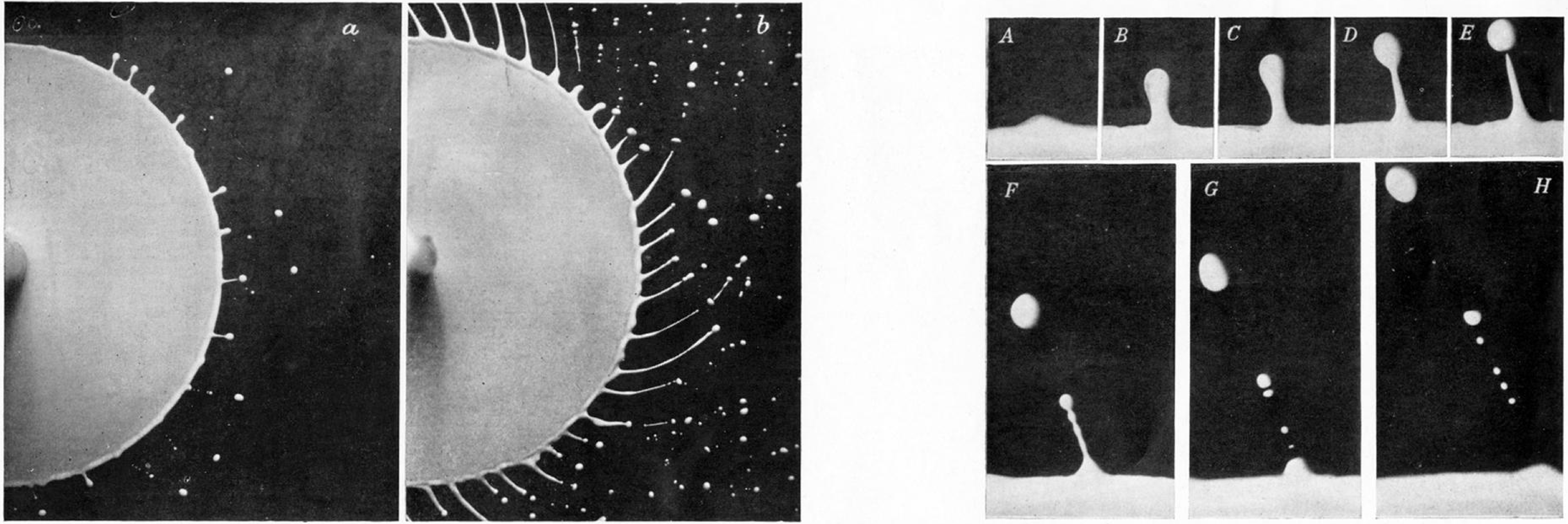


FIGURE 25. Drop formation from the edge of a spinning disk.
a, velocity 210 cm/s, quantity 2·3 ml./s (magn. ×0·8). *b*, velocity 210 cm/s, quantity 15 ml./s (magn. ×0·8). *A* to *H*, magn. ×4.

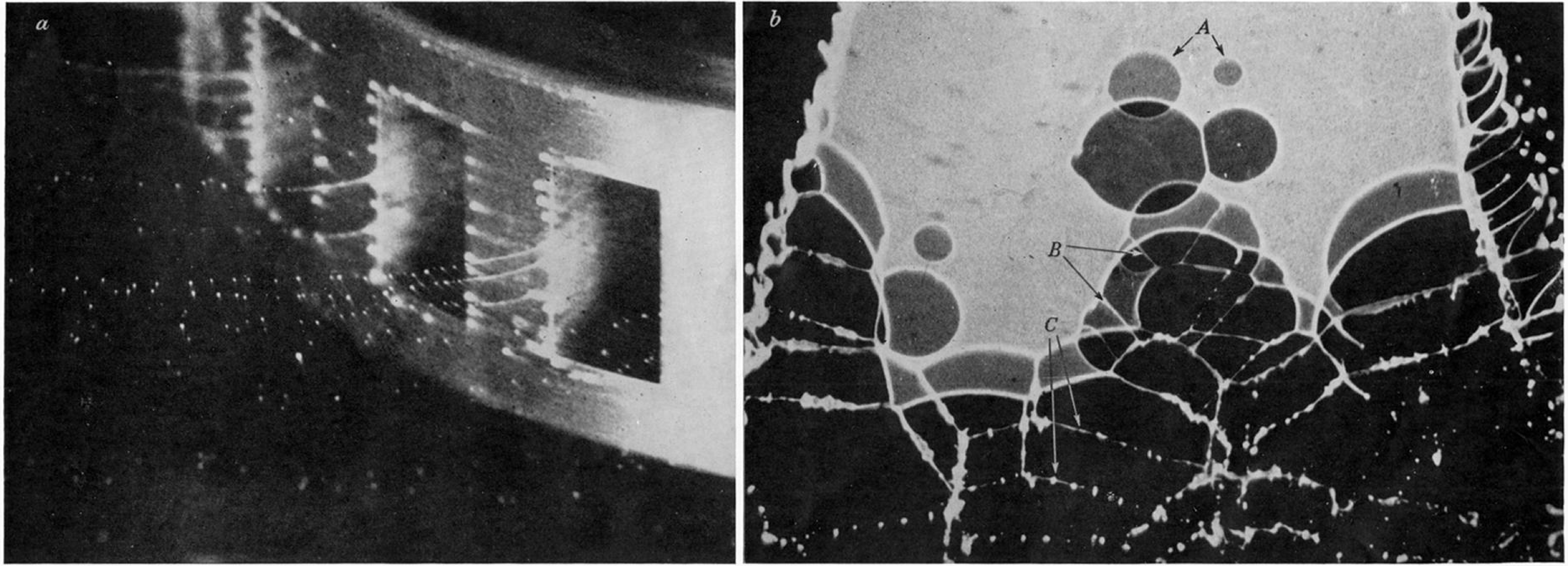


FIGURE 26. a, drop formation from a slotted spinning disk (magn. $\times 5{\cdot}66$). b, superimposed photograph, $250\,\mu s$ interval (magn. $\times 3{\cdot}83$).

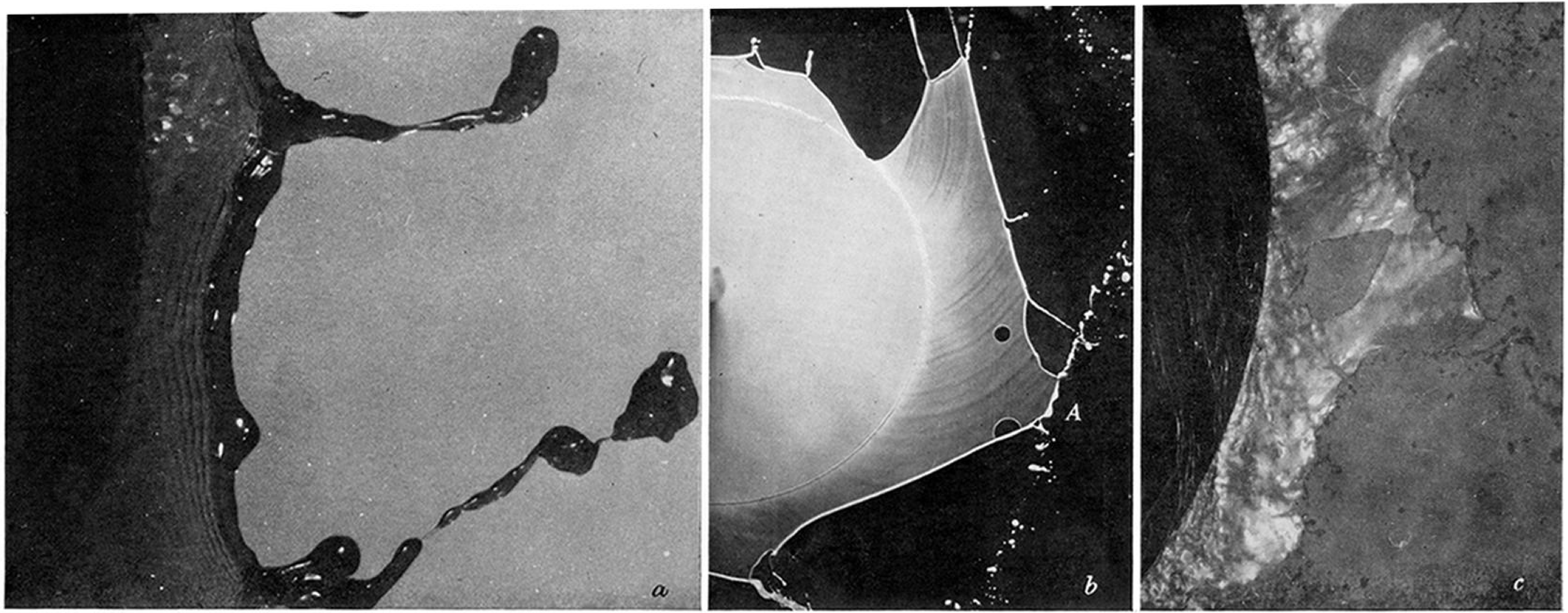


FIGURE 27. Drop formation from the edge of a spinning disk at high outputs.
a, velocity 210 cm/s, quantity 27 ml./s (magn. ×3·3). *b*, velocity 210 cm/s, quantity 27 ml./s (magn. ×0·66).
c, velocity 840 cm/s, quantity 27 ml./s (magn. ×2).

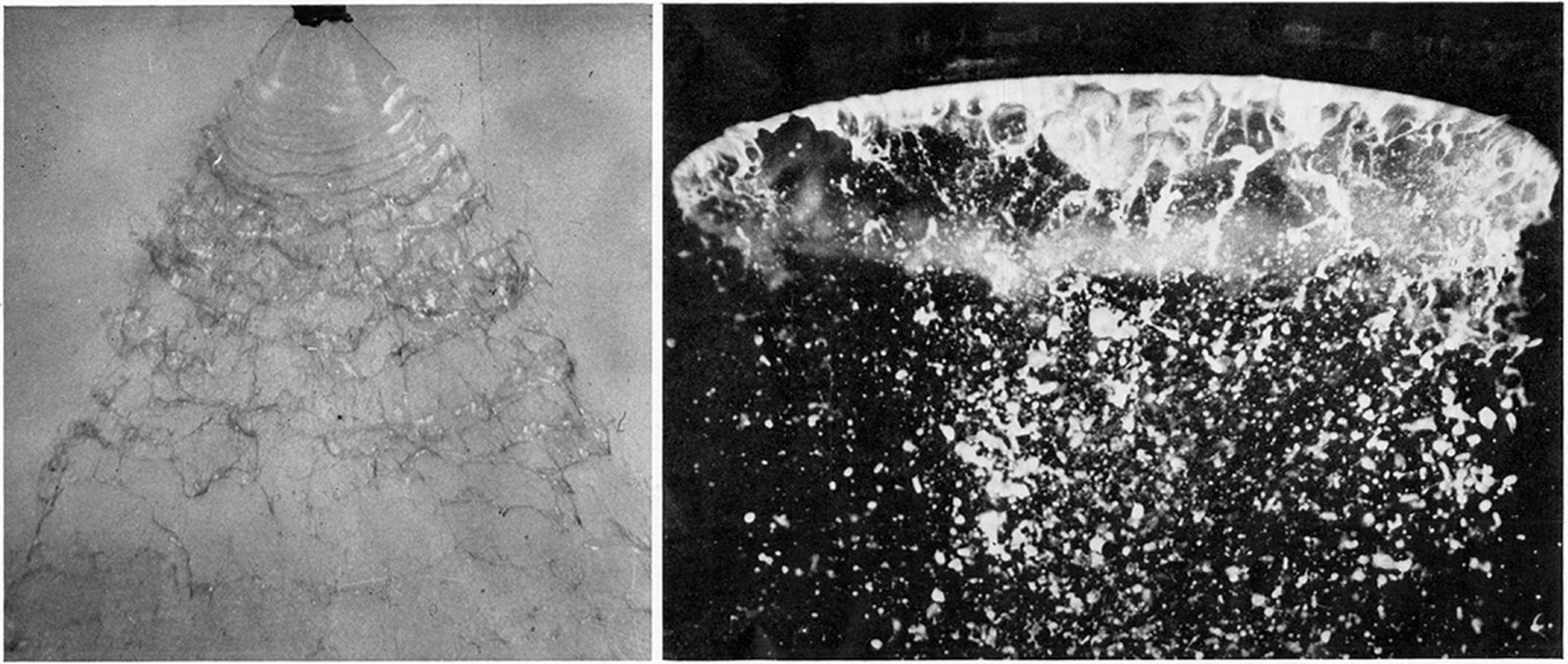


FIGURE 29. *a*, disintegration of a sheet of liquid having visco-elastic properties (magn. ×1·33).
b, disintegration of a liquid in a twin-fluid atomizer (magn. ×3·3).

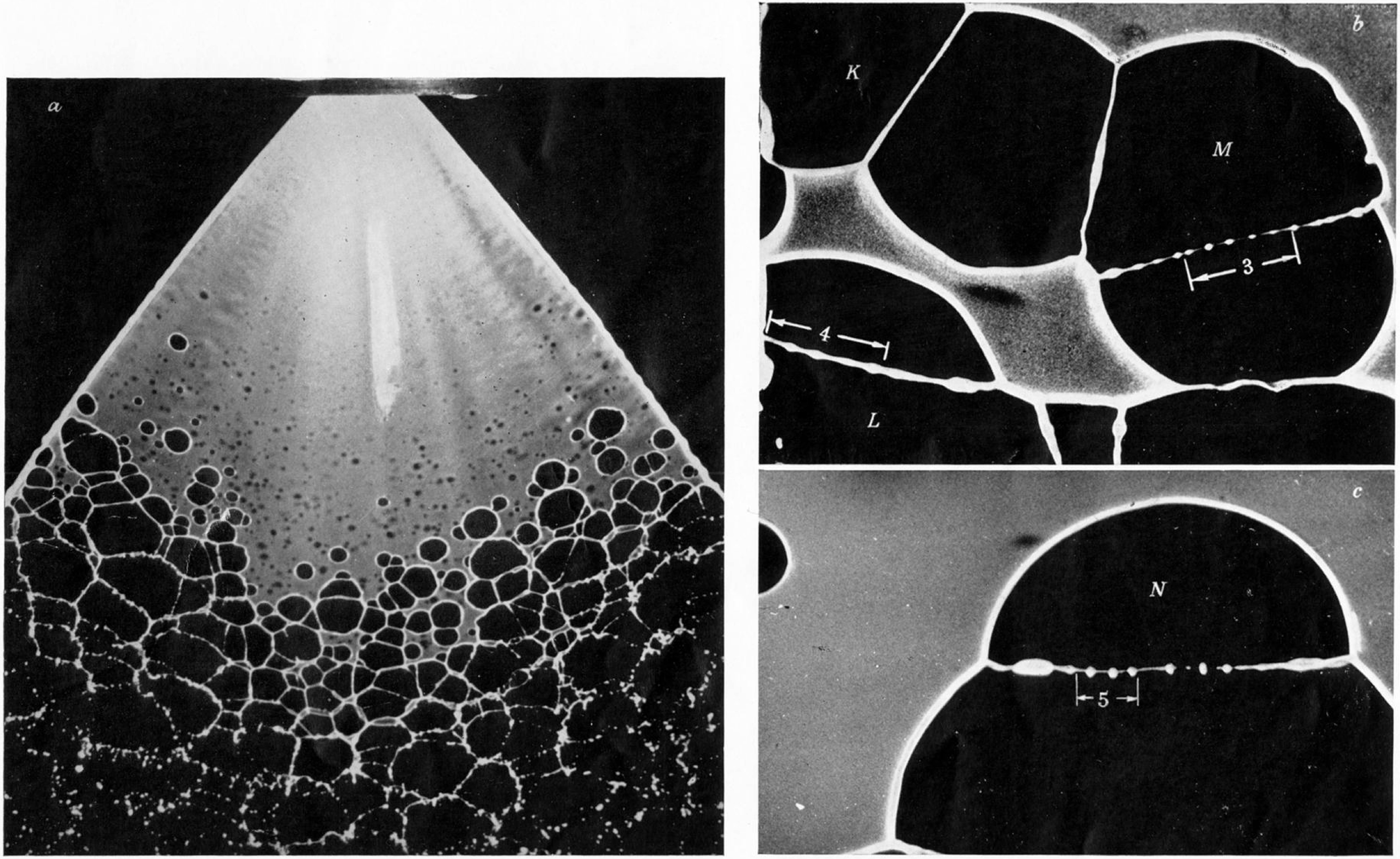


FIGURE 28. Disintegration through perforation with a soluble oil/water emulsion. (Magn. a, $\times 2{\cdot}5$; b, $\times 3{\cdot}75$; c, $\times 7{\cdot}5$.)