V. *Impact with a Liquid Surface, Studied by the Aid of Instantaneous Photography.*

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Received September 25, 1895,—Read February 6, 1896.

[PLATES 1–8.]

Preliminary Statement by Professor WORTHINGTON.

IN three papers, published in the 'Proceedings'* of the Society, in 1877 and 1882, I had the honour to communicate to the Society the results of experiments on various classes of impact with a liquid surface which may all be conveniently referred to as "splashes." The splashes studied were those produced (i.) by a liquid sphere falling on a horizontal solid plate, (ii.) by a liquid sphere falling into a liquid, (iii.) by a solid sphere falling into a liquid.

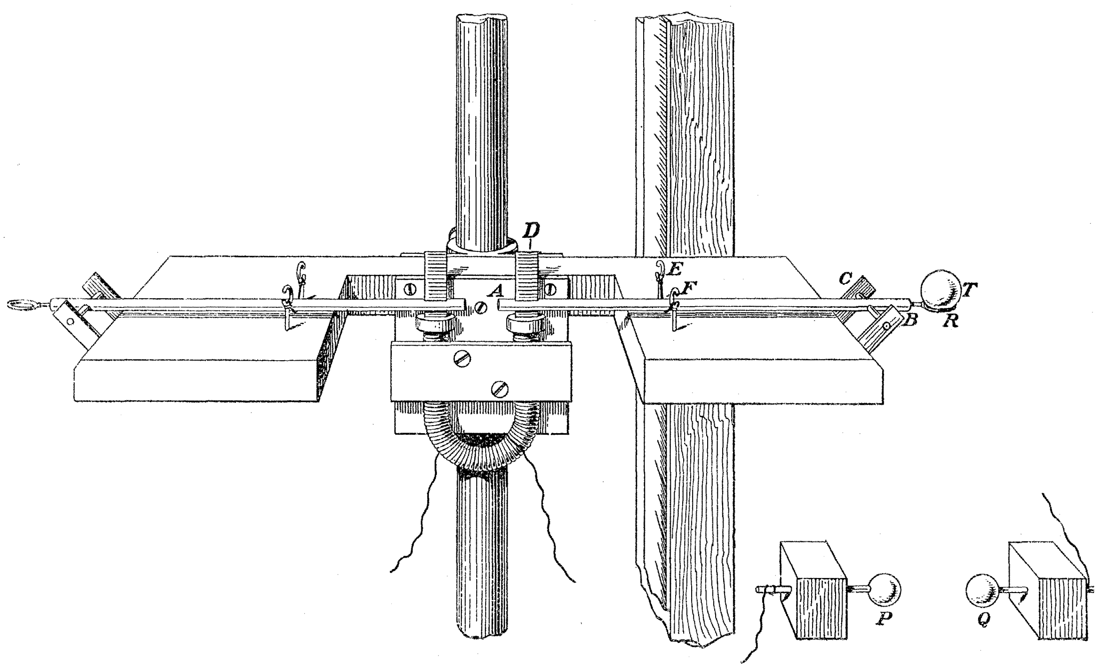
The phenomena were examined by means of an electric flash of very short duration, which by a suitable mechanism could be so timed as to illuminate the splash at any stage which it was desired to observe, within three or four thousandths of a second. After a sufficient number of repetitions to secure accuracy, a drawing was made of the configuration thus revealed, and when one stage had been sufficiently studied, the observer passed on to a later stage. Since, however, each drawing was made from a separate, though similar splash, it was not possible to obtain accurate information about those details which were at once too minute to be seized in such single, momentary glimpses, and too unstable to be capable of exact reproduction in another splash.

A photograph, which can be studied at leisure, is under such circumstances indefinitely more valuable than a drawing, and produces that confidence in one's knowledge of the facts without which speculation as to the causes can hardly proceed. But, at the date when the observations were made, photographic plates, sufficiently sensitive to respond to such extremely short exposures were not obtainable, and my efforts to secure photographs were unsuccessful. A year and a half ago, encouraged by Professor BOYS's success in the photography of flying bullets, I returned to the attempt, being also so fortunate as to obtain the co-operation of my colleague at

* 'Proc. Roy. Soc.,' 1877, vol. 25, pp. 261 and 498, and 1882, vol. 34, p. 217.

Devonport, Mr. COLE, and after taking advice from Professor BOYS, and exchanging my old self-induction spark for the much shorter Leyden-jar spark that had been employed by Lord RAYLEIGH* for a similar purpose, we obtained after a few weeks of failure, some preliminary photographs which were shown at the Royal Institution, May 18, 1894.† These photographs, while amply confirming the old drawings, gave so much new and detailed information as to make it seem worth while to go over the whole ground again. Of this review, which is our joint work, the following communication is the first instalment.—A. M. W.

Fig. 1.



Method of Taking the Photographs.—The method consists in letting fall, simultaneously with the drop, a metal timing-sphere. This in its fall passes between two other insulated spheres connected to the inner coats of two large, oppositely-charged Leyden-jars that stand on the same badly-conducting table. From the outer coats of these jars wires are led into the dark room, and there terminate in a spark-gap between magnesium terminals at the focus of a small concave mirror. The timing-sphere, in its fall, discharges the inner coatings of the two Leyden-jars, and this produces a simultaneous discharge at the spark-gap between the outer coatings, and it is this that illuminates the splash.

Fig. 1 is a magnetic releasing key, of which two were used on the same electric

* See 'Nature,' July 16, 1891, p. 249.

† 'On the Splash of a Drop and Allied Phenomena'—a Friday Evening Discourse. This will be found to contain a *résumé* of all previous papers. See also in 'Nature,' July 5, 1894, a paper by Mr. COLE.

circuit, one in the dark room for releasing the drop or sphere whose splash is to be photographed, and the other in the laboratory for releasing simultaneously the timing-sphere.

A B is a light wooden rod, about 20 centims. in length, and rather stouter than a lead pencil; this is pivoted at C. At the end B is fixed a metal ring (R), on which the timing-sphere (T) can be placed. At the other end (A) is fixed a thin strip of tinned iron plate (D), which is held down by the electromagnet beneath it against the pressure of a catapult made of an indiarubber ring stretched between the two hooks E and F. On cutting off the current of the electromagnet, the end A is tossed up by the catapult, and thus T is left in mid-air free to fall from rest. The end B is prevented from rebounding, and thus possibly interfering with the fall of T, by impaling itself on a suitably placed pin, which is hidden from view in this diagram, but is seen at H in fig. 2.

The releasing key in the dark room is precisely similar to this, with the exception that when a liquid drop is to be let fall it carries, instead of the ring R, a small and deeply concave watch-glass, on which, when well smoked, a drop of milk or water will lie with little or no adhesion.

On breaking the circuit of the two electromagnets the drop and timing-sphere are thus simultaneously released, and the former makes its splash at the moment that the latter, by passing between the fixed spherical terminals P and Q, insulated by supporting blocks of paraffin wax, discharges the Leyden-jars.

The timing of the spark is effected by adjusting the height of fall of the timing-sphere, which is done by sliding the releasing key up or down its vertical supporting rod, the height being read off on a millimetre scale which was pinned against a firmly fixed and well planed, oak batten.

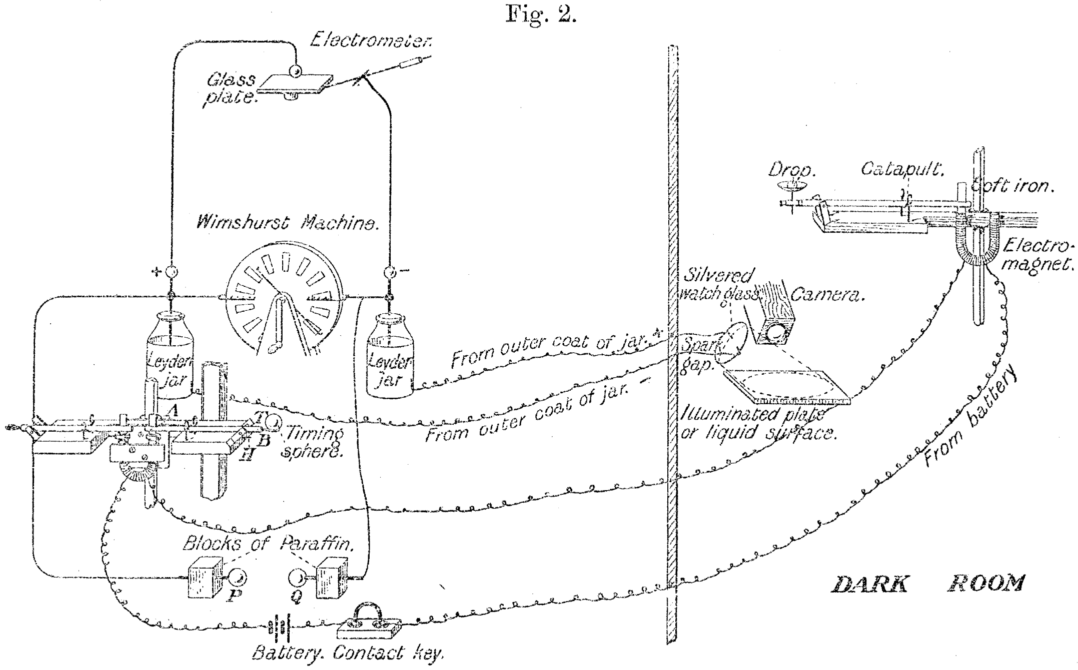
The general arrangement of the apparatus is shown in fig. 2.

It will be noticed that on the left-hand side of either figure there is an idle releasing lever. This projected over the edge of the table, and was used instead of the right-hand lever when the height of fall was more than about 2 metres, the paraffin blocks carrying P and Q being then put on the floor. Instead of the rough electrometer figured, a pith ball, hanging by a cotton-thread from the upright stem of one of the jars, was more frequently employed to show the extent to which charging had proceeded, of which also the sound of brush discharges was a useful indication, for, in order to secure a bright spark, we generally charged the jars up to the limit determined by leakage.

Photographic Apparatus and Details.—The chief necessity is to secure adequate illumination, and for this as little light as possible must be wasted. After many trials the difficulty was successfully met by using as a mirror a concave watch glass of a width about equal to that of the area to be illuminated, and very approximately parabolic in form and sufficiently deep for the focus to be very nearly in the plane of its circular edge. This glass was found to be sufficiently "silvered" by means of a

sheet of thin tinfoil rubbed smooth over the inside, and renewed occasionally after it had become too much dimmed by magnesium oxide. This mirror, with the sparking wires close in front of it, was brought within 8 or 9 centims. of the place of impact, and, in order to bring out the details of the configuration to the greatest advantage, the beam of light was directed down on the surface at an angle of between 30° and 45° with the horizontal, and the camera was so placed that the line of sight was at right angles to the plane of incidence of the axis of the illuminating beam, and also inclined at about 30° to the horizontal (fig. 2).

Fig. 2.



Arrangement of apparatus for photographing splashes.

The camera employed was an ordinary quarter-plate camera. For our earlier observations the ordinary camera lens was exchanged for a single quartz spectacle lens with the object of avoiding the absorption of useful actinic rays by glass. This, however, gave imperfect definition in parts of the field away from the centre, and the position of the best actinic focus was also troublesome to find. And we soon found that the illumination was amply sufficient for the ordinary lens. This had a focal length of 15 centims. and was used with full aperture of 2·22 centims., and placed at such a distance from the splash as to give an image three-fourths (linear) of the real size.

The plates used were Thomas's cyclist, and were developed in complete darkness by treatment with a saturated solution of eikonogen for about 40 minutes, according to the advice kindly given us by Professor Boys.

In order to identify the photographs it was necessary to number the negatives, and, to escape the difficulty of doing this in pitch darkness by scratching the film or

otherwise, we adopted the plan of "numbering the phenomenon" by means of a ticket which was photographed simultaneously.

The Duration of the Spark.—Although it was not necessary for the success of our experiments that the spark should be excessively short, yet we cannot doubt that its effective duration was less than three-millionths of a second. This was ascertained by photographing by its means a cardboard disc, 22 centims. in diameter, roughly graduated round its edge with pen and ink, and kept rotating by means of a small electromotor at a rate of between 52 and 54 revolutions per second. This rate of rotation was ascertained by smoking the back of the disc and touching it with a style attached to an oscillating tuning-fork, or with the fork itself, and the result was confirmed with a second fork. The edge of the disc was thus found to be moving at about 36·5 metres per second (or about 78 miles per hour) during exposure, yet no trace of motion is apparent in the photographs. A motion of one-tenth of a millimetre during illumination would correspond to less than three-millionths of a second, and would have produced in the photographs a blurring of three-fourths of one-tenth of a millimetre which, with a lens, would certainly be visible. This interval of less than three-millionths of a second bears to one second just about the same ratio as a day to a thousand years.

Although the outside limit thus obtained is 30 times greater than the effective duration of the spark employed by Professor BOYS with his flying bullets, yet we think it worth while to mention the result, for it shows how excessively short is the exposure necessary for taking even very detailed "objective views" as distinguished from shadow photographs requiring no camera.

It may be mentioned here that the illuminating spark-gap was sometimes as much as 3·3 centims. wide; that the two jars were of not quite equal capacity, the lesser consisting of a set of jars and presenting an area of about 4000 sq. centims. and a mean thickness of dielectric of about 0·3 centim., while the potential difference was such as would make a spark leap across from P to Q when the distance between them was about 3 centims., P and Q being spheres of 2 centims. in diameter.

The Accuracy of the Timing.—The interval between the release of the drop and the production of the illuminating spark is liable to slight variation, chiefly from two causes—(i.) irregularity in the potential difference between the two terminals P and Q, on account of which the spark would leap through varying distances to meet the timing sphere before it reached the line of centres, and (ii.) want of consonance in the rates of demagnetization of the two magnets. Thus, after long running, one magnet would get hotter than the other, and again an alteration in the strength of the magnetizing current was found to shift slightly the stage of the splash revealed by the spark. Nevertheless, after allowing the current to run for a few minutes, and after taking a few preliminary discharges, a condition of affairs was reached so steady that changes in the height of fall of the timing-sphere corresponding to intervals not greater than 2 or 3 thousandths of a second, produced

a very steady progress through the phenomenon, and in four test experiments that were made by photographing a solid sphere falling past a divided scale, three consecutive trials, made under ordinary good conditions, agreed within $\frac{1}{3000}$ second, while the fourth was not in error by as much as $\frac{1}{1000}$ second.

When, however, the splash, not of a solid sphere, but of a falling *drop* was being observed, a further cause of irregularity was introduced by the oscillations set up in the drop itself on its release, and by the slight adhesion between it and the supporting watch-glass. This adhesion is proved in the case of a water drop by its invariably carrying down with it a little lamp-black from the smoked surface. A drop of milk, on the other hand, carried down very little, and on this account, and probably also because of the greater viscosity of milk, the splash of a drop of milk is less troublesome to follow in its initial and most rapidly changing stages than is that of a drop of water. We had also reasons to suspect that after setting a drop in place on the watch-glass the film of intervening air gradually escaped and led to a suctional adhesion if the release were too long postponed. Dusting the watch-glass, after smoking, with lycopodium powder appeared to diminish the adhesion.

Nevertheless, when care was taken to preserve regularity in the procedure, the same one of us always manipulating the Wimshurst machine and the laboratory releasing key, and the other the dark-room releasing key and the setting of the drop in place, the apparatus worked and worked well, and if the steps taken between the photographs of a series are as much as $\frac{3}{1000}$ of a second, reversals of the proper order will be exceptional, and there is no difficulty in obtaining stages at closer intervals if desired.

We found, however, that between series of photographs taken on different days there were sometimes noticeable breaches of continuity in the timing, which may be attributed to changes in the potential difference between P and Q, and therefore in the distance from them of the timing sphere when the flash took place, and perhaps to other causes that escaped our notice; we have consequently distinguished photographs taken on different days by letters placed just above the right-hand corner.

For the rest it may be observed that it has not yet seemed worth while to press the accuracy of the timing much beyond what is required for a complete record of the consecutive phenomena.

No misapprehension can arise as to the times assigned, if it is remembered that they refer to the setting of the apparatus, and are liable to such uncertainties as have been mentioned.

The Photographs.—Series I. (Plate 1), consisting of 33 photographs, gives the splash of a water drop, weighing ·2 of a gram.,* falling 40 centims. into milk mixed with water,

* Drops of a constant size were obtained from a vertical glass tube, connected by indiarubber tubing, with a wide funnel, in which the level was slightly higher than the mouth of the delivery tube. The experimental drop was made up of a definite number (1, 2, 3, or 4) of such drops, caught in a smoked and lycopodium-dusted watch-glass and thus conveyed to the releasing cup.

scale $\frac{3}{4}$ of actual size (linear). The first 7 or 8 show the evolution and rise of the crater to its maximum height, which is attained in about two hundredths of a second; this crater then remains poised with but little change for another hundredth of a second (figs. 8 to 12), and then (figs. 13 to 20) in about two and a half hundredths more widens out and subsides till nothing but a lobed rim is left above the surface surrounding a central hollow (fig. 20). This is followed by the rise of a central column carrying the liquid of the original drop on its summit. The distinction between the more transparent water at the top and the comparatively opaque adherent milk below is quite observable in the original of Photograph (22) though hardly apparent in the reproduction, and, in all, the lamp-black carried down by the drop is seen to be collected chiefly at the summit. The rise of the column takes about $\frac{5}{100}$ second (figs. 21 to 26), and its subsequent subsidence (figs. 27 to 29) about $\frac{7}{100}$ second more. In Photograph 24 is seen the first appearance of an outward-spreading ripple. Photographs 26 to 30 show how the base of the column gradually flattens down into a "cake" of liquid, whose edge marks the position of the next well-marked ripple, while figs. 31, 32, and 33 show how by the oscillations of the centre, a third "cake" is superposed on this, contributing the third outward-spreading ripple and so on. We were not able conveniently to follow the phenomenon further, through the laboratory being too low for the height of fall necessary for the timing-sphere at these late stages.

It should be mentioned that it is known (WORTHINGTON, 'Proc. Roy. Soc.,' 1882, vol. 34, p. 217) that the subsidence of the central column gives rise to a vortex ring that descends through the liquid.*

The reason for mixing milk with the water into which the drop fell was to secure something which would photograph. It was found that the addition of milk in the proportion of about one part of milk to three of water, though it must have reduced the value of the surface tension, did not make any decided or very noticeable change in the phenomena. If pure milk was used the crater thrown up was indeed somewhat higher and had longer arms, indicating a smaller efficiency of the surface tension in opposing the rise of the liquid.

Series II. (Plate 2).—This gives, in 37 photographs, the splash of a milk drop of diameter ·75 centim. (*circa*) falling 100 centims. into water. Scale $\frac{2}{3}$ linear, as far as No. 18 (the single quartz lens being used). Thence onward $\frac{3}{4}$ linear (with the ordinary lens of the camera). In Nos. 15–18 a little milk was added to the water to make the photographs clearer, and from 19 onward a good deal of milk (about one part of milk to three of water). In this splash the crater rises to a greater height and closes completely over the central hollow, opening again, however, very shortly afterwards to make way for the column that rises from the base, and whose subsidence produces "cakes" as before. In Photograph 18 the bubble has apparently not yet burst before its top is struck by the column rising inside. Sub-group A consists of special

* See also THOMSON and NEWALL, 'Proc. Roy. Soc.,' 1885, vol. 39, p. 417.

studies showing the bubble opening quite centrally round the emergent column, and the fact that the base of this does not photograph shows how completely the original milk drop is collected at the top of the column. Sub-group B illustrates what happens when, as in Photograph 18, the top of the bubble is struck by the column and burst at one side. Under the influence of the surface tension, rotundity of form is soon regained, and by the time the stage of Photograph 21 is reached all traces of previous irregularities have disappeared.

Examination with a lens of Photographs 3, 4, and 5 shows how the drop, on first entering, punches a very sheer-walled hole.* From the fact that these early stages photograph so well as compared (see next series) with corresponding stages when the drop is of water and the liquid is milk, we infer that the first liquid thrown up is milk drawn from the fringe of the drop itself. It must be remembered that owing to the closeness of the camera, front and back parts of the crater cannot be quite in focus together. The first flow of the liquid appears to be very much *along* the surface, afterwards it is much more perpendicular to the surface, and this alone appears sufficient to account for the sharp curling-over of the edge of the crater (Photographs 4 to 6); for superposition of the photographs seems to show that in the early stages each particle continues to move for some distance in the straight line along which it was first projected from the surface. As to the reason of the closing in of the crater we shall make some remarks in connection with the next series.

Series III. (Plate 3).—This gives, in 24 photographs, the splash of a water-drop weighing ·4 gram. falling from a still greater height, 137 centims., into milk mixed with water. Taken with the quartz spectacle lens. Scale $\frac{1}{2}$ linear. The crater closes up at a much earlier stage and forms a bubble which becomes smoother in outline as the liquid drains down its sides or distributes itself more evenly over its walls. This bubble may remain closed (Photograph 16) or may open at a comparatively early stage, following the course shown by Photographs 13, 14, and 18. Or it may be from the first much depressed by the heavy mass of liquid at its top (Photographs 11, 15, and 17). Sub-group A shows the configurations of early stages when the water-drop is exchanged for an equal drop of milk and falls into water. The increase in visibility is very marked. The original of No. 1A bears examination with a lens. In Sub-group B the crater obtained was smaller than usual, perhaps through the drop striking the water in a very prolate form, as in Series I., Photograph 1.

With respect to the closing-in of the crater, it will be noticed that in Photographs 6, 7, and 8, the upper edge is surmounted by a rim of greater thickness than the walls below; there can be no doubt that the accumulation of liquid here is due to the upward flow being checked by the surface tension. When such an annular rim is formed, an elementary calculation shows that the centripetal acceleration with which

* So much of the detail of the original photographs has been lost in the reproductions that it is only in fig. 5 that the edge of the vertical cliff of liquid is visible at the far side of the crater. This edge marks the free horizontal surface of the, as yet, undisturbed liquid.

it will contract under the influence of the surface tension exceeds the inward acceleration of the cylindrical walls of the crater arising from the same cause, so long as the diameter of the rim is less than 1·61 of the thickness of the wall. Although this must be a *vera causa* in determining the more rapid contraction of the upper portion of the crater, yet it may not be the sole cause. Photograph 8, and particularly Photograph 2_b, of the sub-group suggest that there may be a diminution of air-pressure within the crater, owing to the descent of its base whereby the crater is in part forced in by excess of external air-pressure. (See also, with a lens, Photograph 5 of Series IX.)

It appears to be characteristic of all closing bubbles that the arms are inclined outwards (see also Series II. and IX.), as if they were being dragged in by the contracting rim from which they spring. In an opening bubble they are much more erect (Series III., 13 and 14), or even inclined inwards (No. 18). A late stage in a bubble is also differentiated from an early one by the greater smoothness of its surface, and by the absence of very small drops in air above it, such smaller drops having apparently had time to agglomerate into larger.

Splashes of Solid Spheres.—The remaining Series exhibit the splash of solid spheres. It was already known (WORTHINGTON, 'Proc. Roy. Soc.,' 1882, *loc. cit.*) that the disturbance set up by a very smooth and well-polished sphere is quite different from that due to the impact of the same sphere when rough or wet, and it is a matter of great interest to find that the difference is quite pronounced from the first instant of contact.

Series IV. (Plate 4) gives, in 17 photographs, the splash of a well-polished sphere of ivory, 1·9 centim. in diameter, falling 60 centims. into water mixed with milk, contained in a glass bowl about 1 foot deep and 9 inches in diameter (scale $\frac{3}{4}$ linear). In order to secure that the splash shall follow the lines here recorded, the polishing with a dry cloth or wash-leather must be repeated just before each observation, and after this the sphere must be handled as little as possible; with these precautions a stone sphere behaves in just the same way. Photographs No. 2 and No. 3* show that the liquid rises over and surrounds the sphere with a thin close-fitting sheath. Figs. 5 and 6 show a subordinate side-sheath, which, without doubt, was due to the fact that the sphere had a crack in it, which occasionally carried down air with it, and disturbed the symmetry of the splash. In Photograph No. 7, however, the symmetry is complete, and it is nearly so in Photograph No. 8. When any failure of the polishing occurs, the liquid is kept away from the sphere, and the splash, instead of being almost noiseless, is accompanied by a sound of bubbles rising to the surface and bursting. Photograph No. 4 shows this driving away of the liquid, and our note-book records that this splash was attended by "noise, bubbles," &c. In Photograph No. 8 there is a similar sign of roughness on the right-hand side. Very important is the information given by the shadow thrown across the surface in such figures as 8 and 9.

* The light marking on the right side of Photograph No. 3 is due to a flaw in the negative.

The sphere has passed below the surface, yet this is almost undisturbed, and there is no trace of the equivalent quantity of displaced liquid. Indeed, in Photograph No. 9 (as in Photograph No. 3 of Series V.) there is an indication of a slight depression surrounding the small column. The conclusion we arrive at is that the general level of the whole liquid surface rises simultaneously with the entry of the sphere, or, at any rate, after an interval corresponding to the velocity of sound through the liquid. Direct evidence of this will be given later. But the surface, though undisturbed, is no longer the surface of dead liquid. Already in Photograph No. 9, and in the corresponding Photograph No. 3, of the next series, there are traces of convergent radial stream lines, indeed, the slight depression is itself evidence of velocity; in Photograph No. 10, after a relatively long interval, the base of the column has gathered liquid, and Nos. 11, 12, and 13, which are coincident in point of time, show the very considerable column that subsequently rises (No. 13 probably owes its double column to some such antecedent condition as is shown in Photographs 5 and 6). Photographs 15 and 16 show the curious and characteristic manner in which this column topples over, while No. 17 shows how it occasionally succeeds in attaining a more considerable height.

Series V. (Plate 5) shows the similar splash of a rather smaller stone sphere, 1·5 centim. in diameter, falling through the same height of 60 centims. Examination of No. 2, with a lens, shows how, on the front side, the sheath (owing, no doubt, to imperfect polishing) has been driven away from the surface of the sphere, while at the back it has run up almost to the vertex. Of this splash we recorded that "bubbles were heard." Photographs 4 to 9* are all characteristic of the manner in which the column breaks up or topples, and appear to deserve record, if only to help future observers in what is sometimes a rather puzzling identification.

Series VI. (Plate 6) was taken with a large stone sphere 3·2 centims. in diameter, falling only 14 centims. (scale $\frac{3}{4}$ linear), with a view to obtaining further information about the displaced liquid. In Photograph No. 1, the plate was accidentally exposed to a spark beforehand. No. 2 shows very well the rise of the sheath. No. 4 is interesting as illustrating in a very complete manner the influence of some slight roughness on one side only. The puckering of the surface, which is strongly marked in No. 5, seems to us to show that lines of flow near the surface when once determined are very persistent, for we should otherwise expect to find a gradual thickening of the sheath as the vertex is approached, but not these separate radial streams. In No. 6 the general surface is very level, while the amount of liquid in the column can hardly be $\frac{1}{10}$ of the volume of the whole sphere. It still remained, however, just doubtful whether a very gradual sloping-off of the surface might not provide, in a manner not easily noticed, accommodation for a large amount of liquid just round the place of impact. We, therefore, choosing the narrower vessel of No. 8 to make the phenomenon more apparent, filled it brim-full and placed the lower edge of a card

* The dark streak on the left side of No. 9 is an accidental flaw on the plate.

millimetre scale, just in contact with the liquid surface at one side. Photograph No. 9 shows the general rise of level due to the entry of the sphere. The rise at the edge of the scale is about 3 millims., but the rise at the spout of the vessel is much more marked, though this is at a greater distance from the place of impact, and the liquid enveloping the sphere seems to rise very abruptly out of the flat surface on this side. We think that all the facts point to rise of level at great distances from the impact even when the vessel is much wider.

When the ivory sphere, which when dry and well polished gave the splash of Series IV., was allowed to fall *wet* into the liquid, all other circumstances remaining the same, the splash of *Series VII.* (Plate 7) was obtained, which from the very first is entirely different. The wetting was effected by dipping the sphere into the bowl of milky water in which it was to fall and then shaking off as much as possible of the adherent liquid, but in all cases the splash quickly becomes unsymmetrical, probably through the liquid during the fall drifting to one side of the sphere, indeed, in all the figures from 4 onward, but especially in 4 and 5, there is seen a tendency to behave as a smooth dry sphere on the left-hand side where convergent foldings may (in the original photographs) be seen on the surface. The confusion arising from this want of symmetry made it seem unprofitable to examine this splash any further.

This disturbing want of symmetry entirely disappears, however, when we employ a rough sphere, as in *Series VIII. and IX.* (Plate 8). In Series VIII. the impinging sphere was of marble 1·5 centims. in diameter, and the height of fall was 15 centims. The sphere was on each occasion dried and then well rubbed with emery paper. When dipped into the liquid it was at once "wetted" in the usual sense of the term. Yet the liquid on impact seems to do anything but wet it. The first flow is evidently very much along the surface away from the place of impact, and the subsequent behaviour of the crater, as far as Photograph No. 14, is very similar to that of Series I., which was due to the impact of a liquid sphere. Indeed, figs. 8 to 10 of this series hardly differ from Nos. 17–20 of Series I. In the column that afterwards emerges there is, however, a very wide difference. In each case it rises from the bottom of a hollow, but in the present series it is a far finer jet and moving with much greater velocity. This jet was, in fact, observed with the naked eye, in continuous daylight, to rise even to a greater height than that from which the sphere had fallen.

Comparing the crater of this series with that of Series I., we observe that while the outside dimensions are not very different, the crater of the present series is distinctly thinner in the wall, also that the number of lobes or arms is larger. The number seems always to be decided at a very early stage, and to be due, as was suggested (WORTHINGTON, 'Proc. Roy. Soc.,' 1882, *loc. cit.*), to the instability of the annular rim. Thus, in Series I., fourteen appears to be a frequently recurring number in the earlier stages, and in Series VIII., twenty-six or twenty-eight, and in both

series the number afterwards diminishes, often by coalescence, as the annulus subsides and thickens. This view of their origin appears to gain confirmation from the fact that there is a larger number in the crater with the thinner walls. It is not, however, easy, even from the photographs, to estimate the number very accurately. The reader will best ascertain the nature of the difficulty by trying. Sometimes, on account of the foreshortening of the front rays, these are more easily counted in the image of the crater, that is, reflected by the smooth liquid surface in front of it.

In *Series IX.*, we have the splash of a rough stone sphere, 1·25 centims. in diameter, falling 60 centims., into milky water. Photograph No. 1 shows even better than No. 1 of the previous series the way in which the liquid, from the very first, is driven away from the sphere. The subsequent crater is very like that of Series II. or III. obtained from a liquid sphere, and the manner in which the bubble is formed does not seem to differ materially from the course followed in Series III. It is perhaps doubtful whether the creasing on the left of the neck of the bubble in Photograph No. 5 is due to an excess of external air pressure, as suggested on p. 145, or whether it is a puckering due to radial inflow, as when the sheath closes over a smooth sphere.

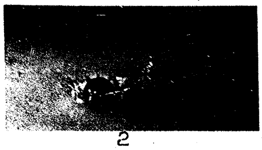
This series terminates the record of phenomena that we have at present to lay before the Society. We hope next year to be able to complete the survey, and to obtain information as to what is proceeding below the surface, and to secure also a succession of photographs of different stages of the same identical splash.

It will have been noticed that useful information is yielded by the comparison of one kind of splash with another, and for this reason it appears desirable that the study of each shall be fairly complete and minute. Observations that we have already made on the impact of a drop with a solid surface, seem to throw light on some of the phenomena that are here described.

In presenting the results so far obtained without waiting for a further accumulation, we are influenced by the reflection that there can be, happily, no doubt about the accuracy of the photographic record, and by the hope of eliciting from competent judges some expression of opinion as to the value of the investigation, with suggestions as to the points which it would be most profitable to elucidate. So little seems to be known about the actual behaviour of real, as opposed to imaginary fluids that we cannot but think that trustworthy information about the motions that follow very simple initial conditions may prove of real value, and not of merely curious interest.

1

t=0 (b)



2

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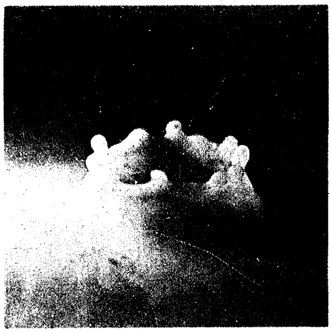
3

t=·0257 (b)

10

t=·0290 (a)



11

t=·0307

12

t=·0401

17

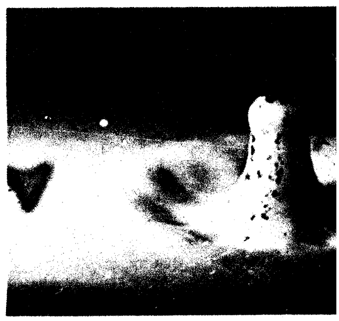
t=·0433

18

t=·0816

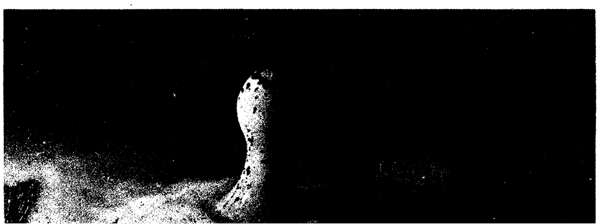
23

t=·0925

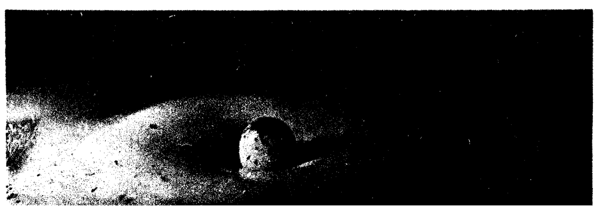


24

t=·1526



t=·1970



(b)

t=·0055 sec. (b)

4

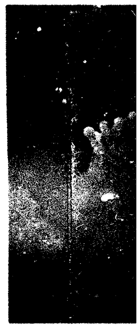
t=·0072 (b)

5

t=·0124 (a)

6

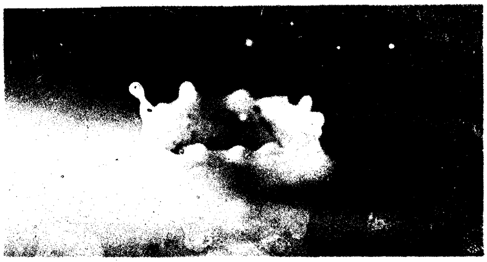
t=



·0307 (a)

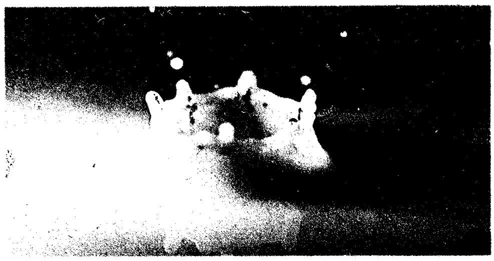
2

t=·0322 (a)

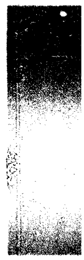


13

t=·0322 (b)



14



t=·0495

19

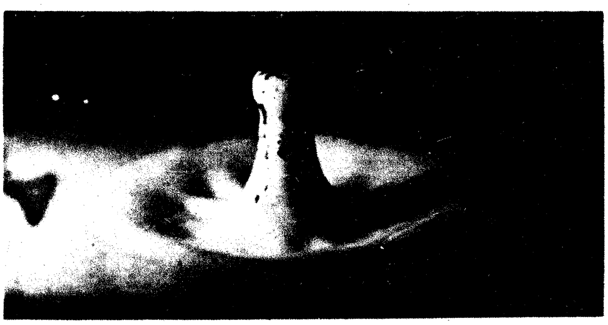
t=·0556

20

t=·0925

24

t=·1032



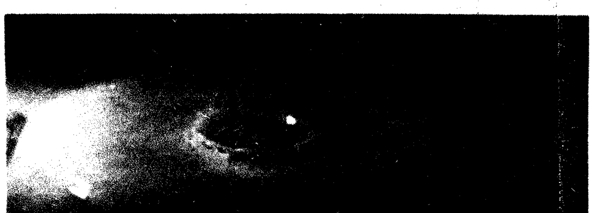
25

t=·11

26

t=·2175

t=·2372



t·0175 (*a*)

7

t·0201 (*b*)

8

t·0242 (*b*)

9

t·0338 (*a*)

15

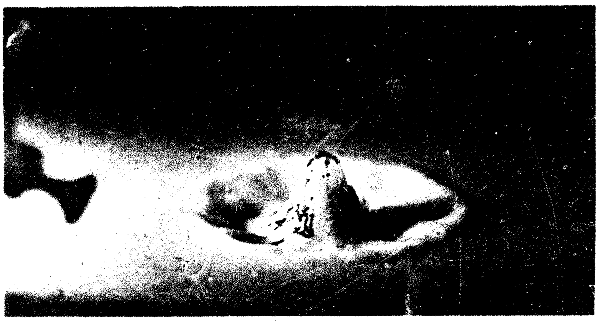
t·0369 (*b*)

16

t·0644

21

t·0732



22

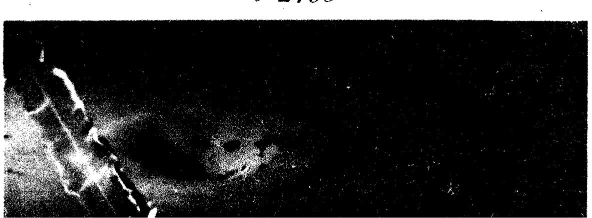
t·1160

26

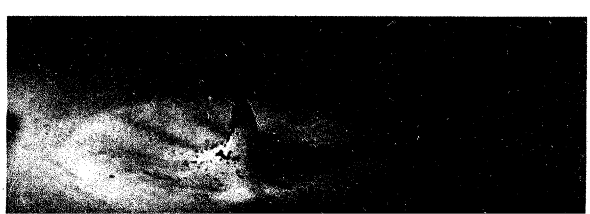
t·1287

27

t·2755



t·3107



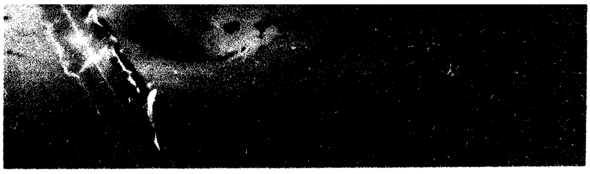
28

29

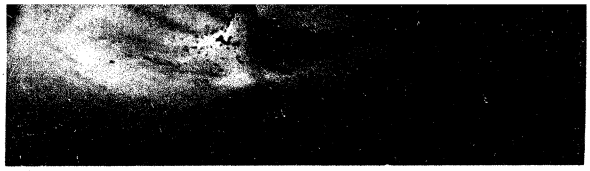
30

31

Series I.

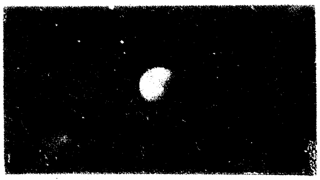


32



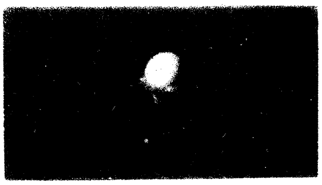
33

t=·0033



1

t=·0045



2

t=0

3

t=·002

4

t=·0245

11

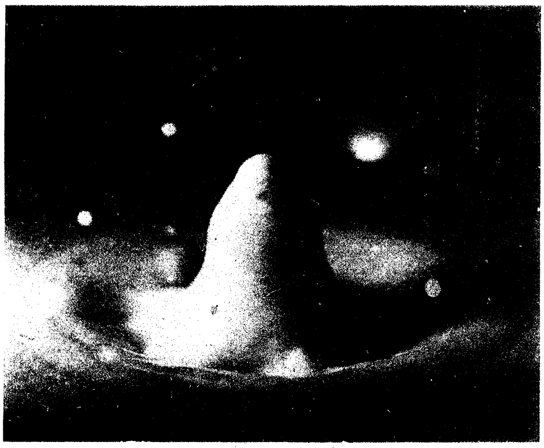
t=·0331

12

t=·0394

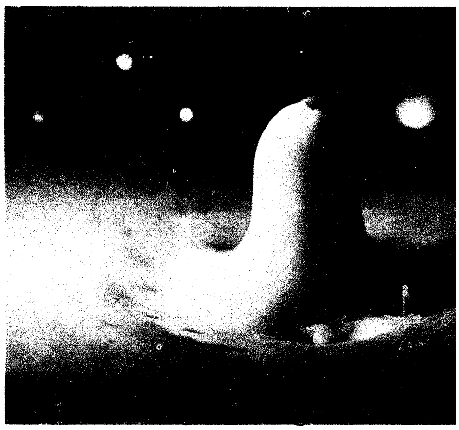
13

t=·1319



19

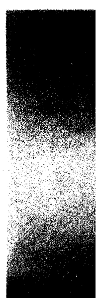
t=·1492



20

t=·1938

t=·2093



t=·002 (a)

4

t=·002 (a)

5

t·002

6

t=·009

7

t=·0394

13

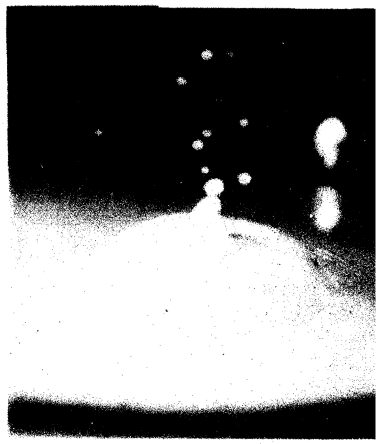
t=·0538

14

t=·0677

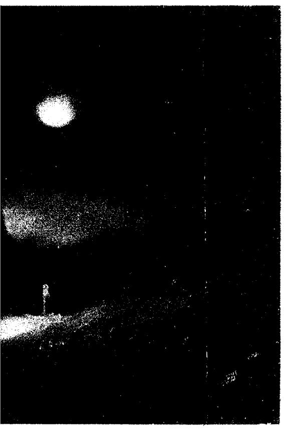
15

t=·0854

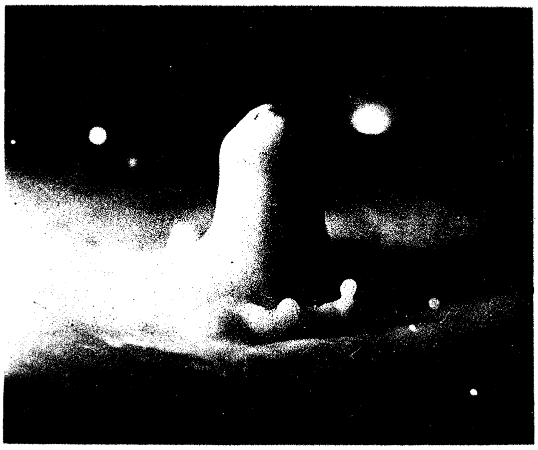


16

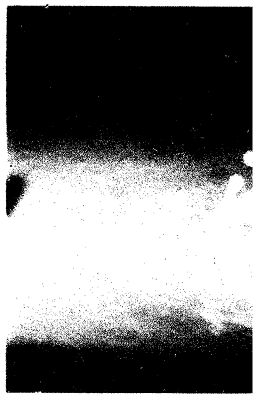
92



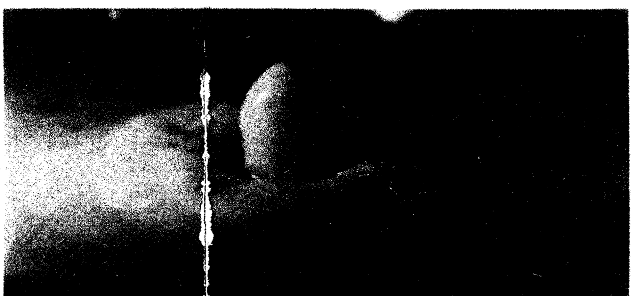
t=·1610



21

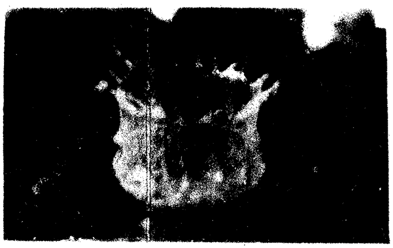


t=·2173



t=·2400

t·0133



8

t·0179

9

t·0179

10

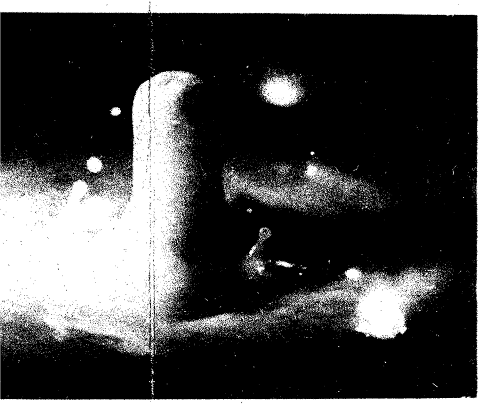
t·1045

17

t·1045

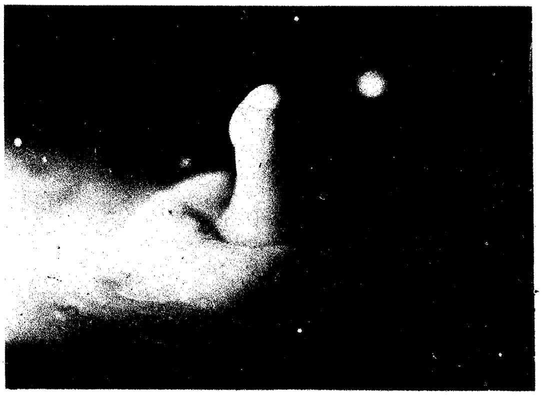
18

t·1694



22

t·1938



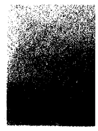
23

t·2718

t·3106

24

25



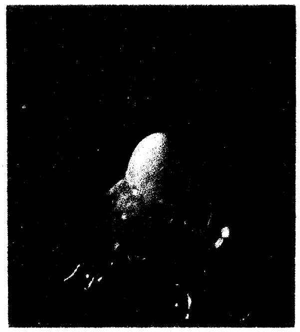
t=1025

1a

t=1106

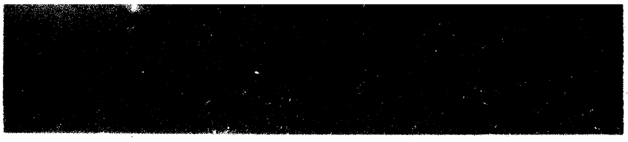
2a

t=1182



3a

26



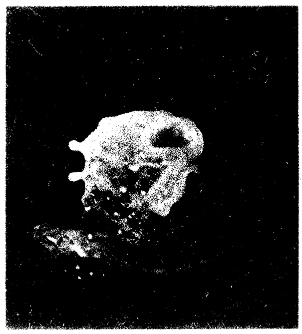
27

t-1319

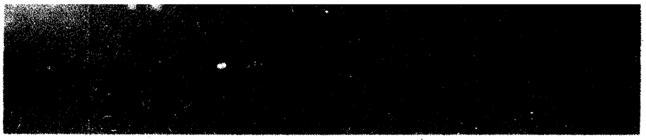
4a

Series II.

t-0950



1b



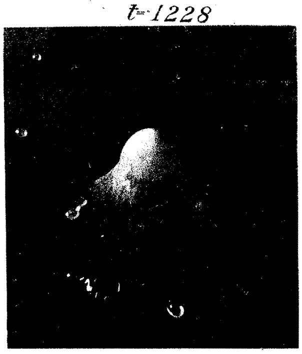
28

29

t-1134

2 b

t-1228

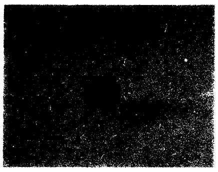


3 b

t-1319

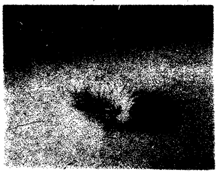
4 b

t=0 *(a)*



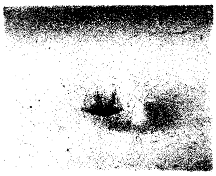
1

t=·0041 sec. *(b)*



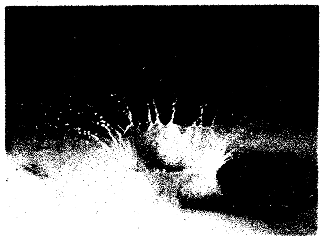
2

t=·0032 sec. *(a)*



3

t=·0050 sec. *(b)*



4

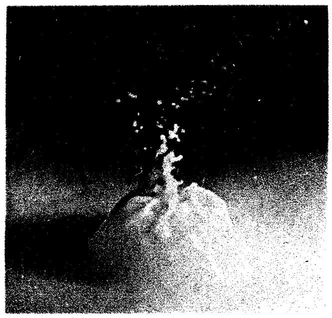
t=·0195 sec. *(a)*

8

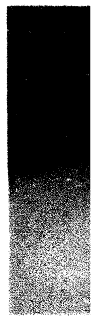
t=·0165 sec. *(c)*

9

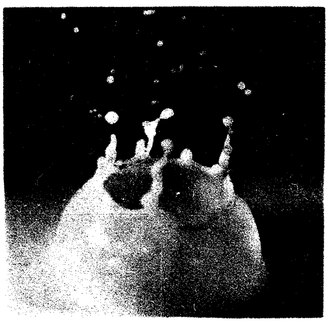
t=·0195 sec. *(c)*



10



t=·0460 sec. *(d)*



14

t=·0498 sec. *(d)*

15

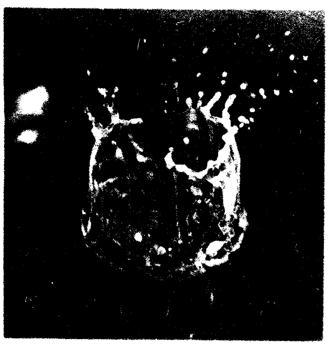
t=·0531 sec. *(d*

16

Sub-group A.

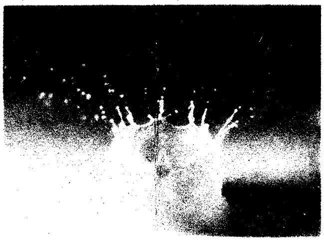
1 *(a)*

3 *(a)*



4 *(a)*

t=·0126 sec. (b)



5

t=·0165 sec. (a)

6

t=·0185 sec. (c)

7

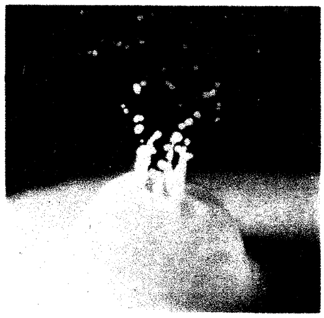
t=·0312 sec. (d)

11

t=·0351 sec. (d)

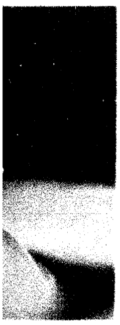
12

t=·0398 sec. (d)



13

ec. (d)



t=·0585 sec. (d)

17

t=·0704 sec. (d)

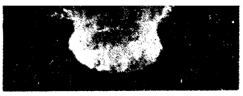
18

Sub group B.

1 (b)

2 (b)

3 (b)



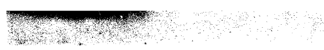
2 (a)

3 (a)

4 (a)

Series III.

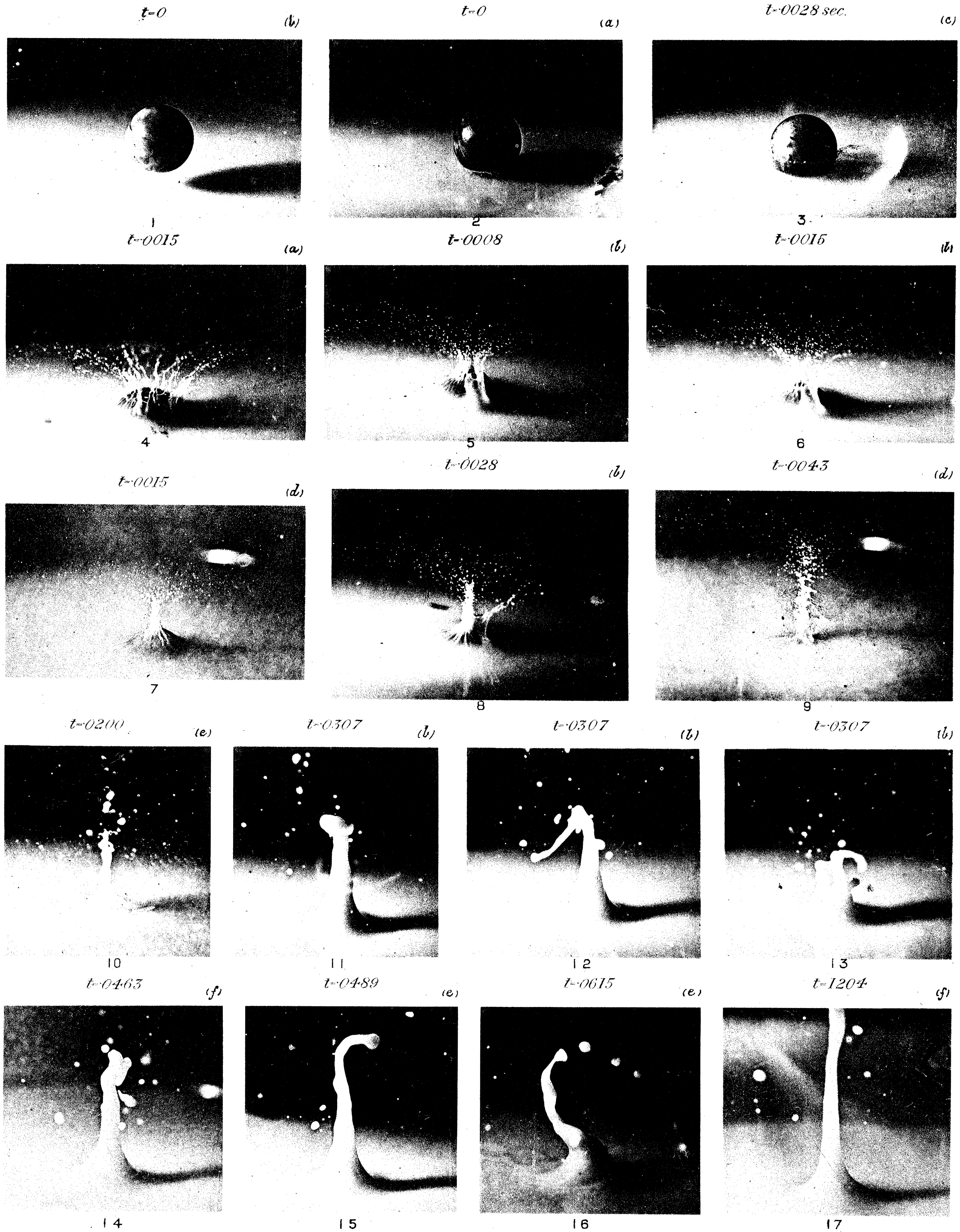
1(b)



2(b)

3(b)

III.

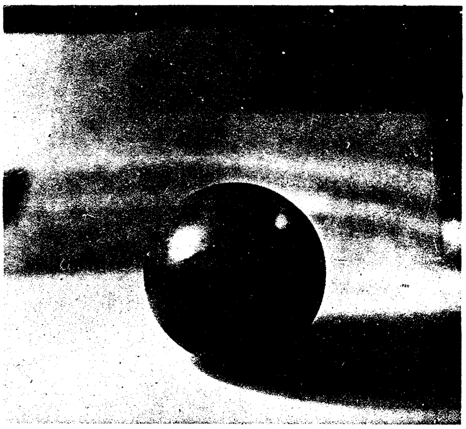

t=0 (b)
t=0 (a)
t=·0028 sec. (c)
1
2
3
t=·0015 (a)
t=·0008 (b)
t=·0016 (b)
4
5
6
t=·0015 (d)
t=·0028 (b)
t=·0043 (d)
7
8
9
t=·0200 (e)
t=·0307 (b)
t=·0307 (b)
t=·0307 (b)
10
11
12
13
t=·0463 (f)
t=·0489 (e)
t=·0615 (e)
t=·1204 (f)
14
15
16
17

Series IV.


t=0 (b) 1
t=·0044 sec. (a) 2
t=·0074 sec. (a) 3
t=·0374 sec. (c) 4
t=·0479 sec. (d) 5
t=·0504 sec. (c) 6
t=·0571 sec. (d) 7
t=·0571 sec. (d) 8
t=·1021 sec. (c) 9

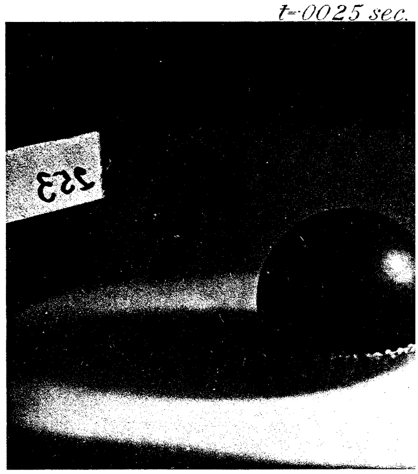
Series V

t=0



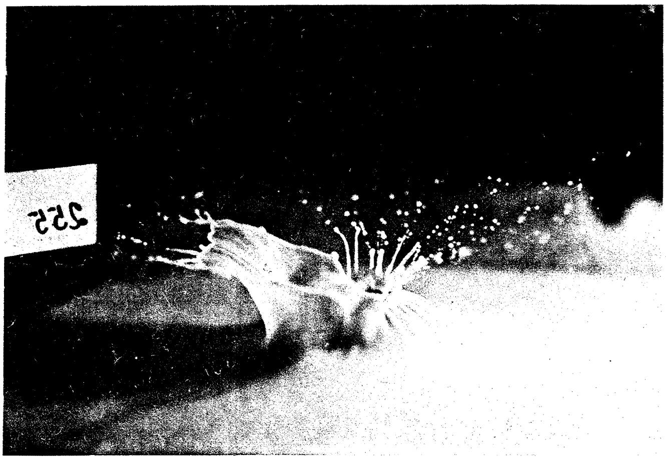
1

t=·0025 sec.



2

t=·0110 sec.



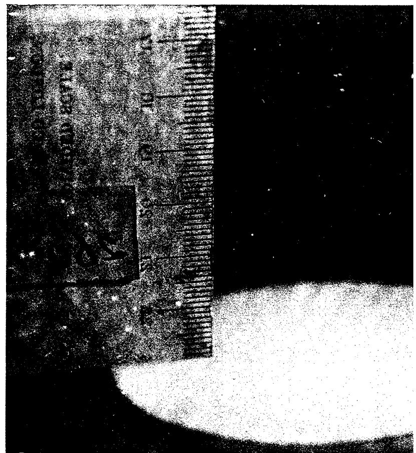
4

t=·0134 sec.

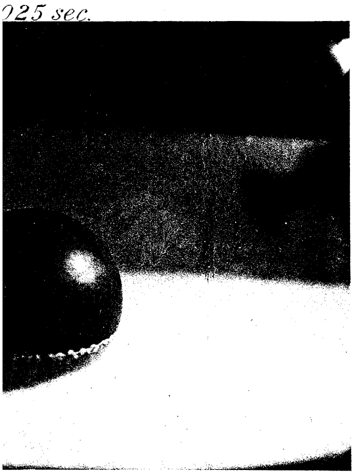
5

t=·0391 sec.

7

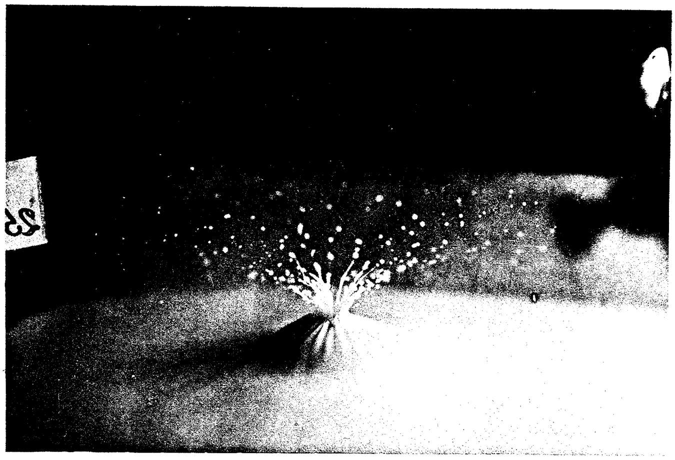


025 sec.



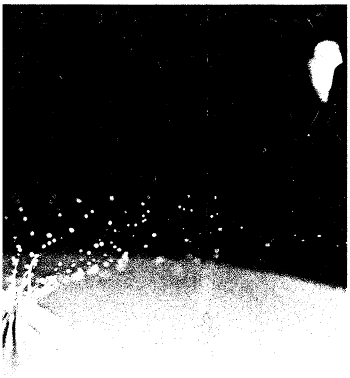
2

t=·0080 sec



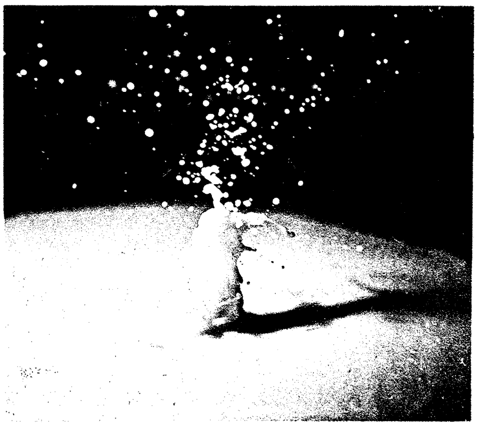
3

34 sec.

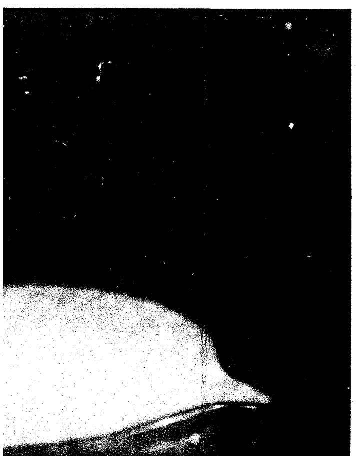


5

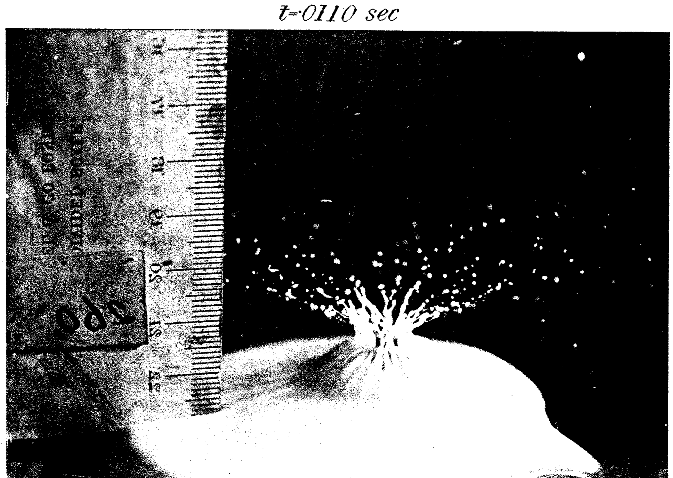
t=·0242 sec.



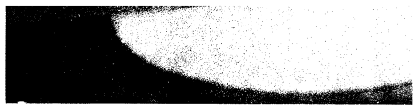
6



t=·0110 sec



7



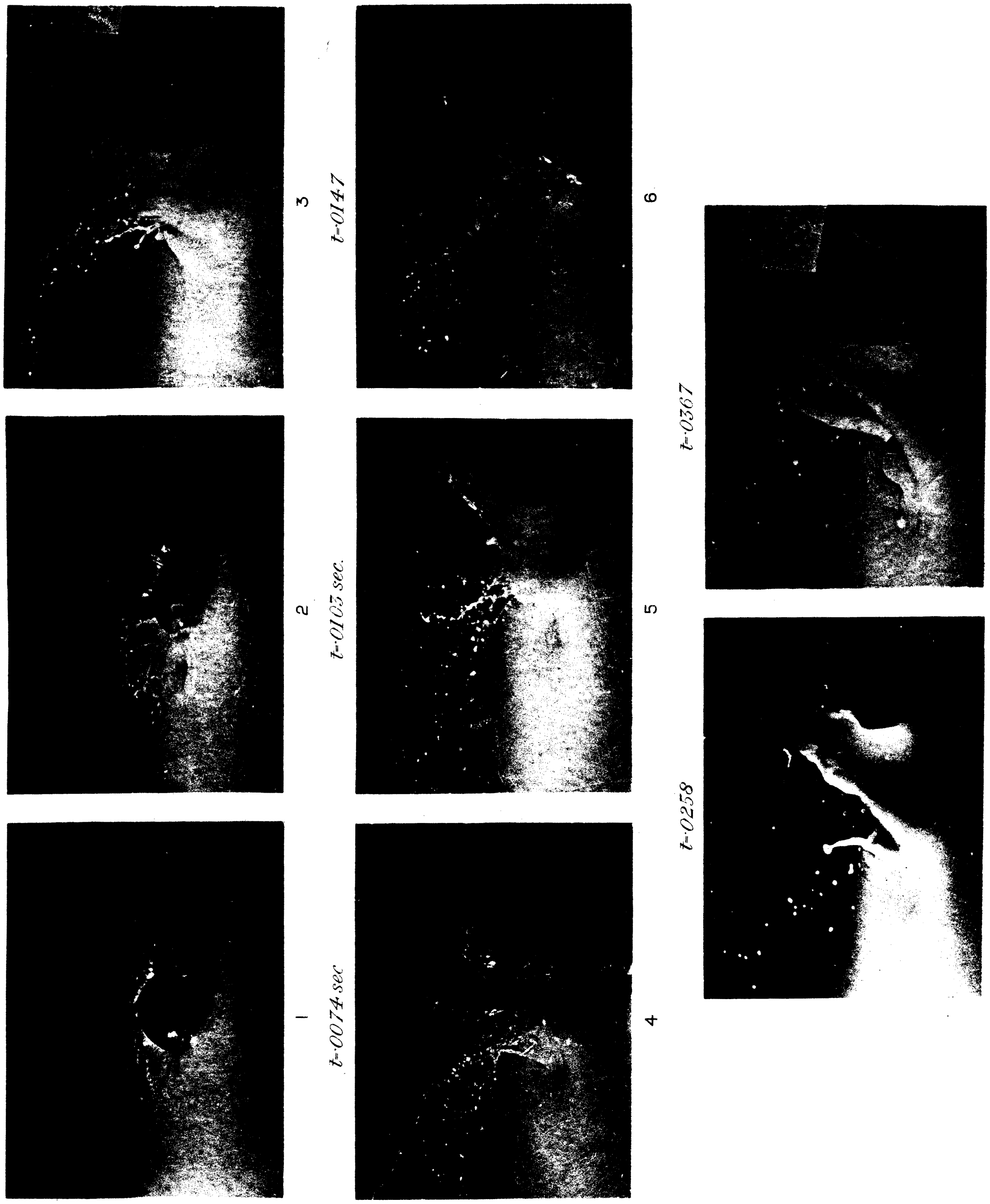
8

Series VI

8

9

es VI.



1 *t*=0
2 *t*·0029 *sec.*
3 *t*·0068 *sec.*
4 *t*·0074 *sec.*
5 *t*·0105 *sec.*
6 *t*·0147
7 *t*·0258
8 *t*·0367

Series VII.

t=0

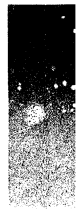
1

t=·0080 sec.

2

t=·0020 sec.

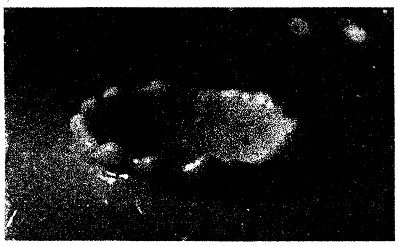
3



t=·0360 sec.

8

t=·0545 sec.



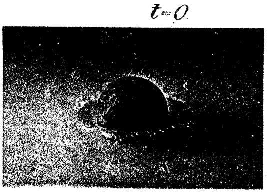
10

t=·(

t=·0456 sec.

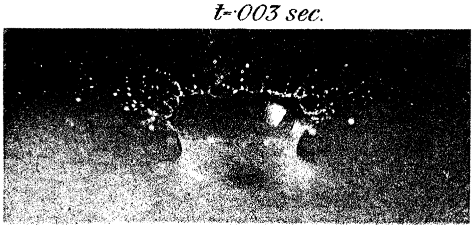
9

t=0



1

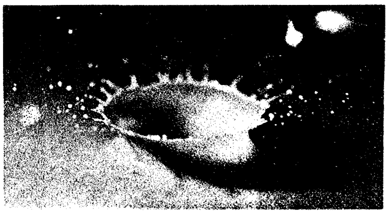
t=·003 sec.



2

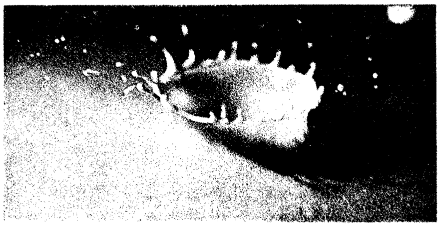
t=·006 sec.

t=·0080 sec.



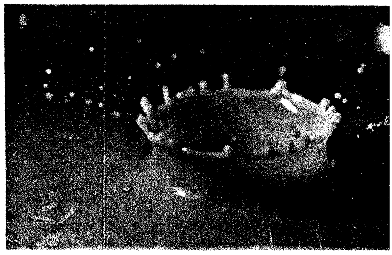
4

t=·0105 sec.



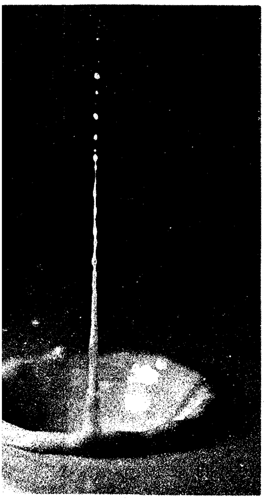
5

t=·0212 sec.



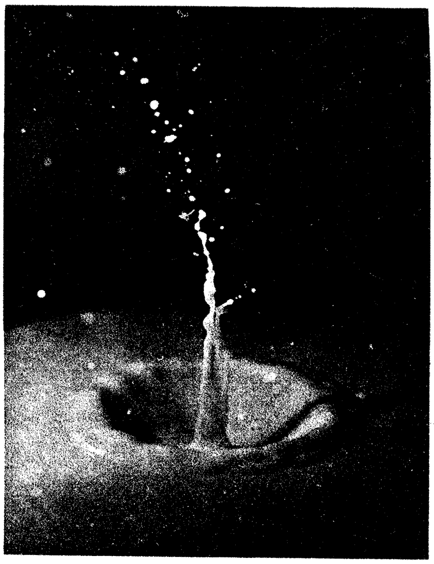
6

t=·0633 sec.



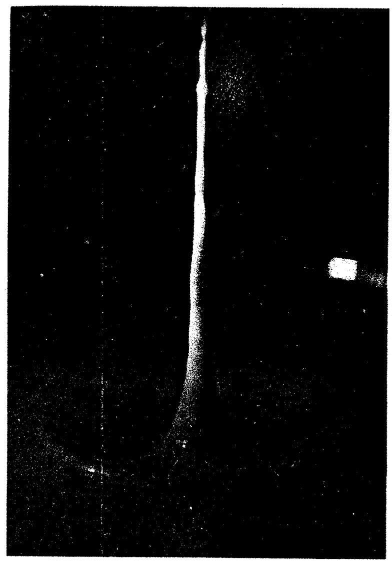
11

t=·0715 sec.



12

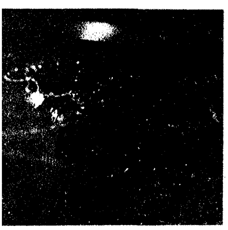
t=·0844 sec.



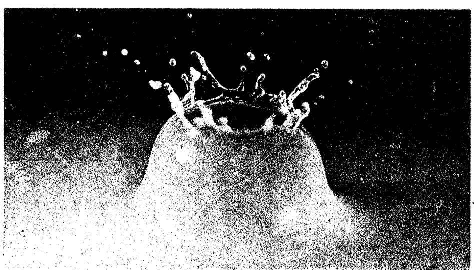
13

Series VIII.

06 sec.



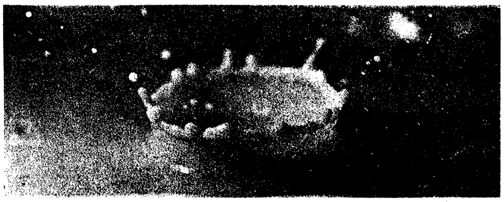
t=·017 sec.



t=·017 sec.

sec.

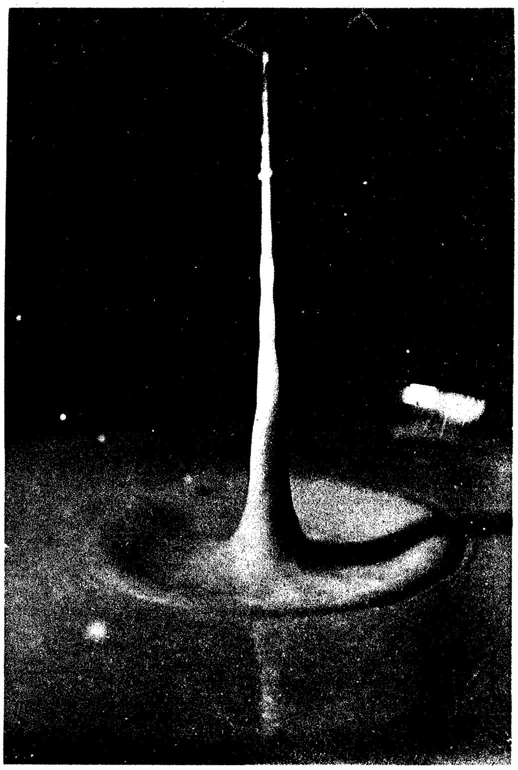
t=·0261 *sec.*



7

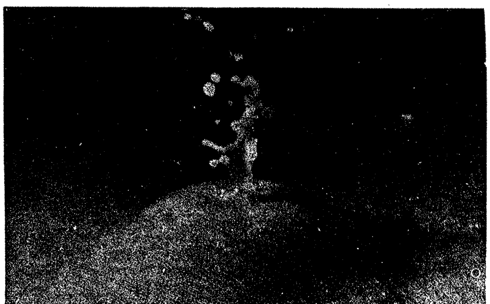
t=·0962 *sec.*

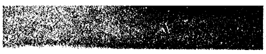
c.



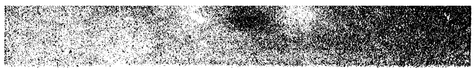
14

t=·0335 *sec.*

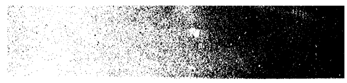




1

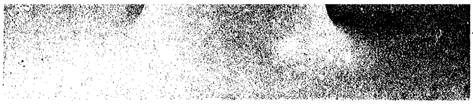


2



3

3



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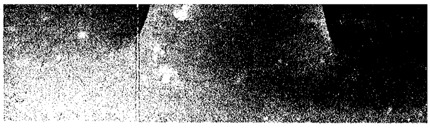
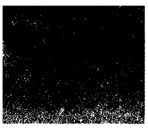
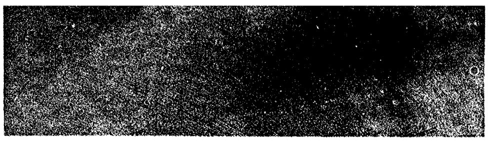


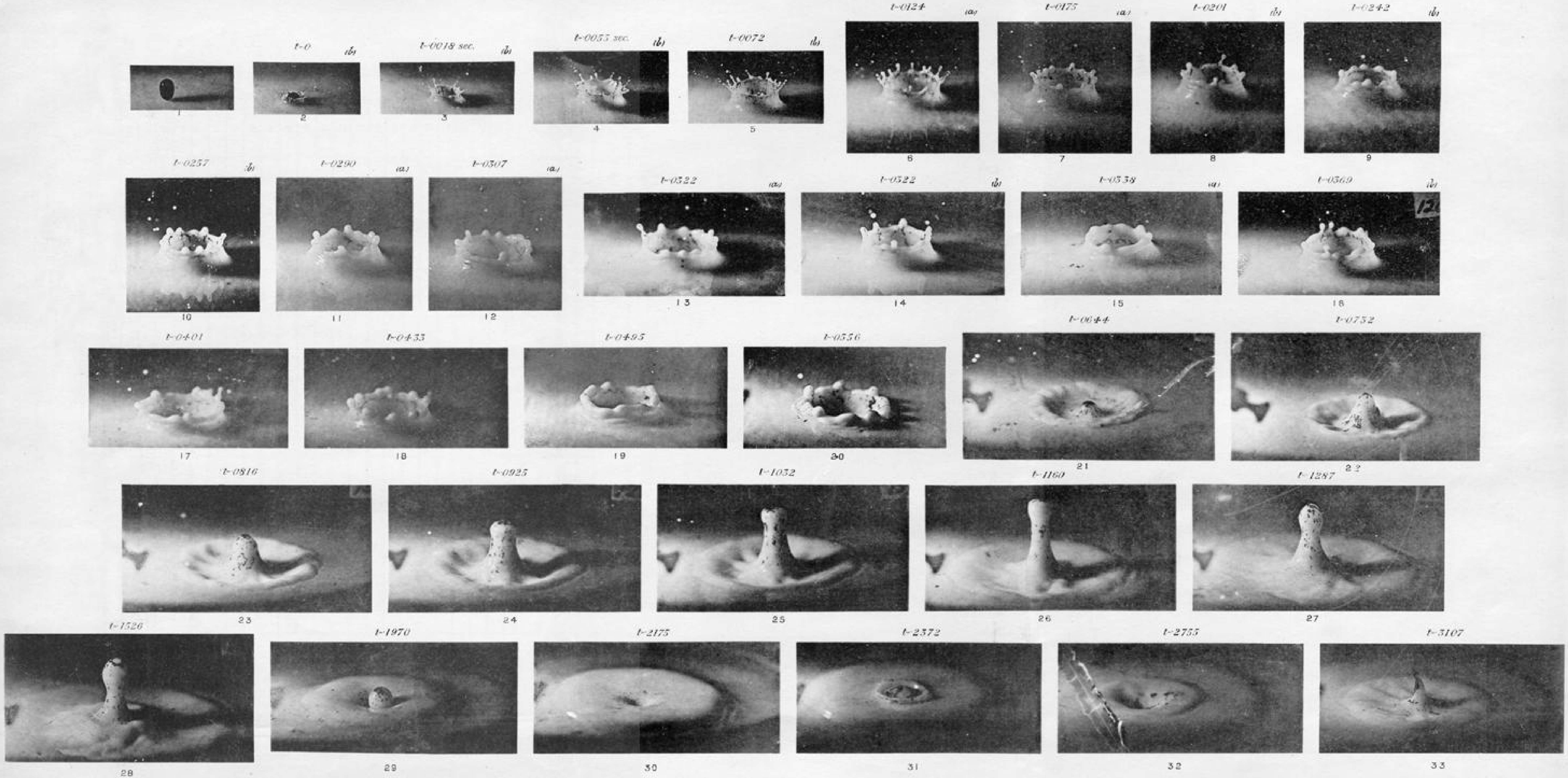
5

Series IX

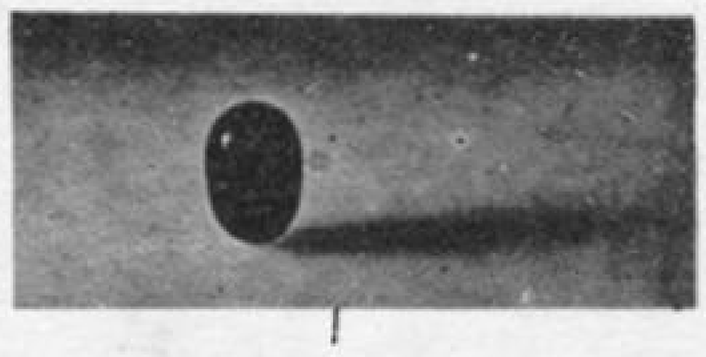




6


1
t-0 (b) 2
t-0018 sec. (b) 3
t-0055 sec. (b) 4
t-0072 (b) 5
t-0124 (a) 6
t-0175 (a) 7
t-0201 (b) 8
t-0242 (b) 9
t-0257 (b) 10
t-0290 (a) 11
t-0307 (a) 12
t-0322 (a) 13
t-0322 (b) 14
t-0338 (a) 15
t-0369 (b) 16
t-0401 17
t-0433 18
t-0495 19
t-0556 20
t-0644 21
t-0732 22
t-0816 23
t-0925 24
t-1032 25
t-1160 26
t-1287 27
t-1526 28
t-1970 29
t-2175 30
t-2372 31
t-2755 32
t-3107 33

Series I.



1

t=0 (b)

2

t·0018 sec. (b)

3

t·0257 (b)

10

t·0290 (a)

11

t·0307

12

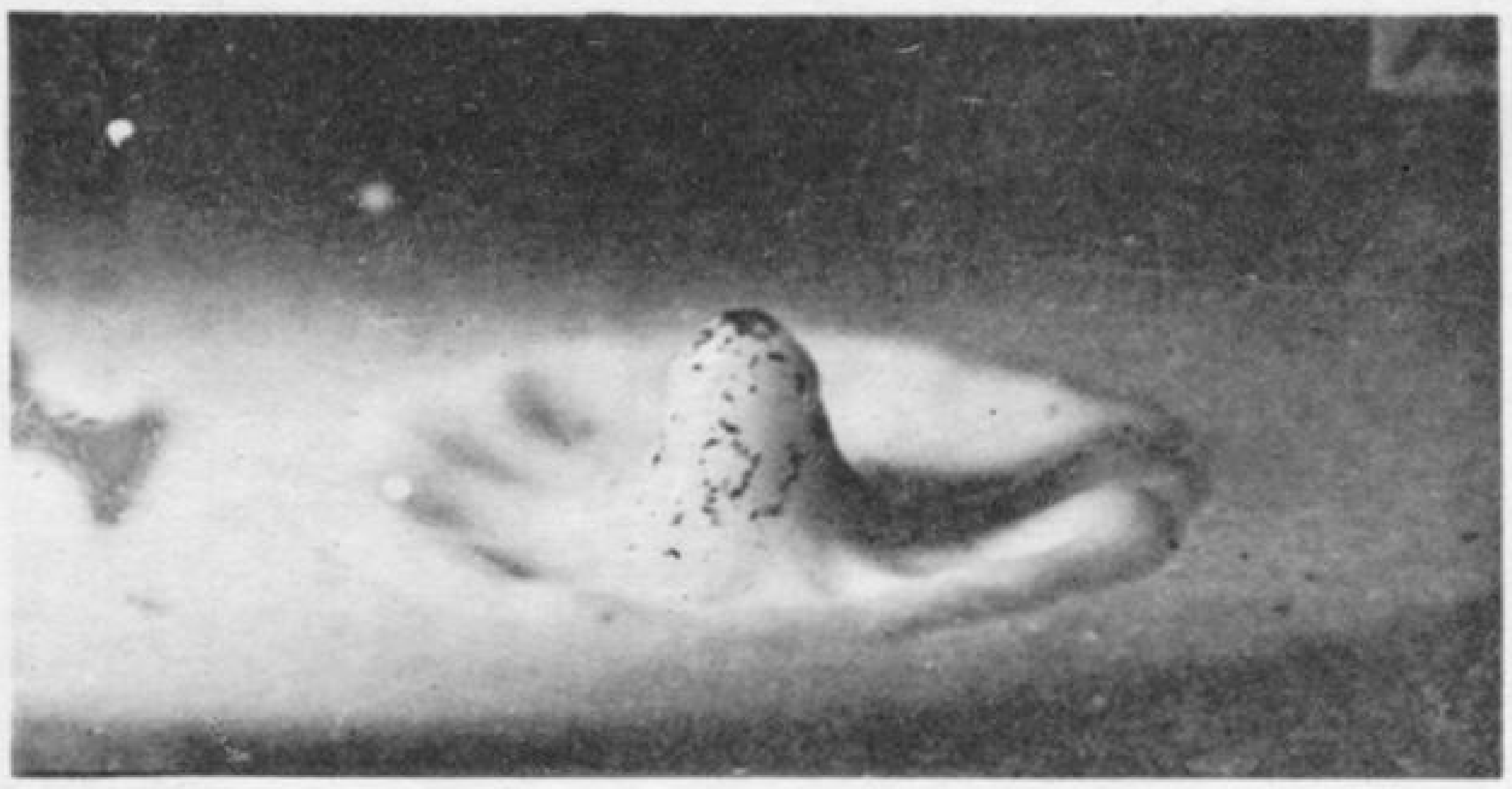
t·0401

17

t·0433

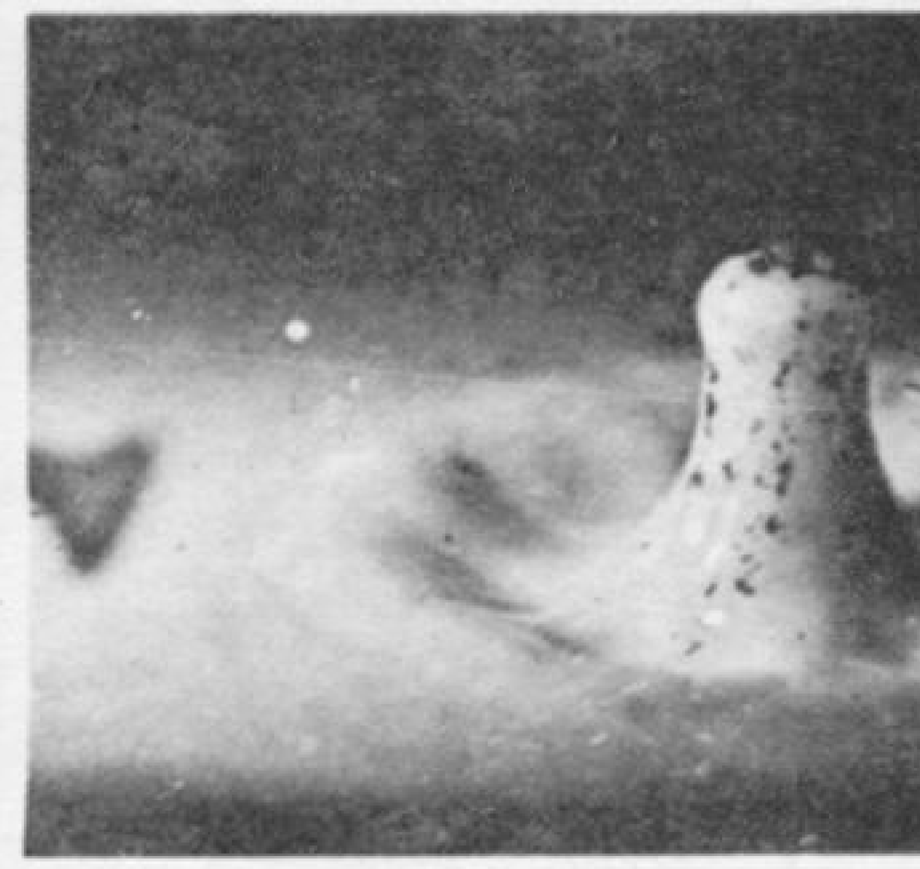
18

t·0816



23

t·0925



24

t·1526

t·1970

(b)

t-0055 sec. (b)

4

t-0072 (b)

5

t-0124 (a)

6

t-

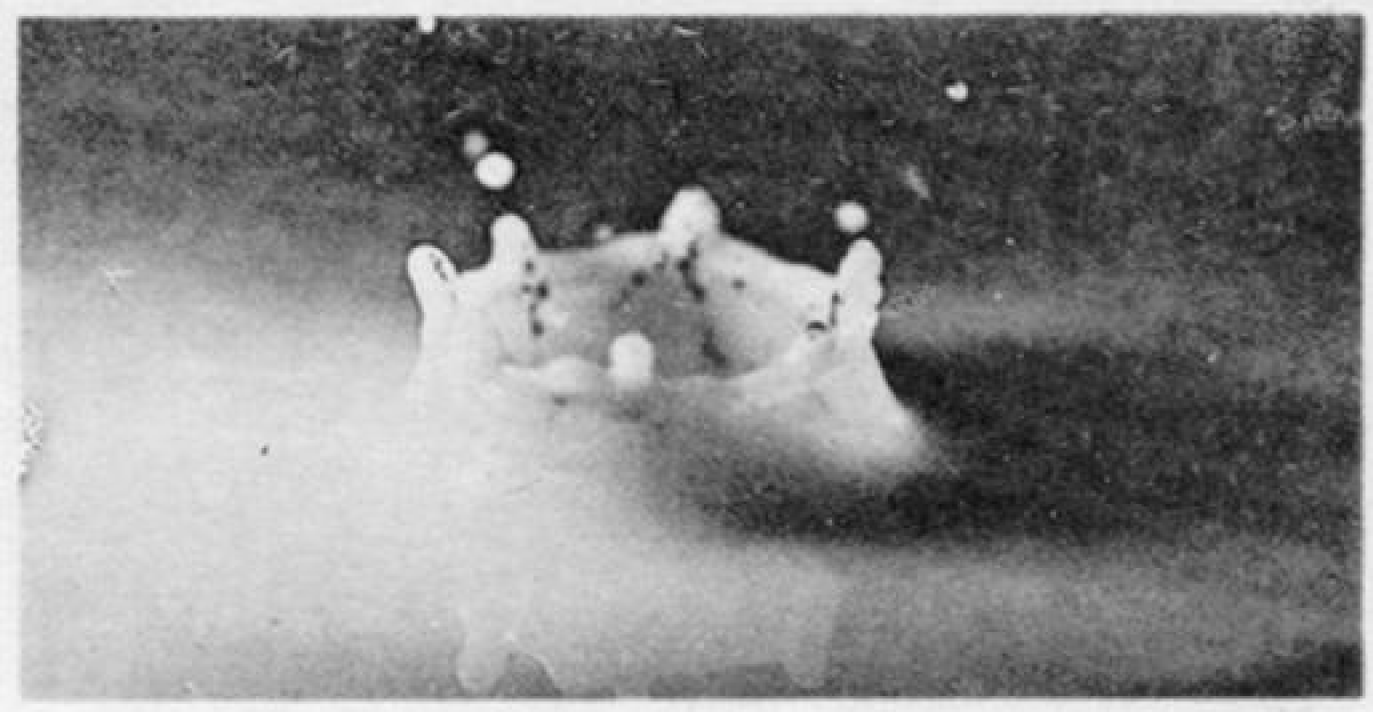
0307 (a)

12

t-0322 (a)

13

t-0322 (b)

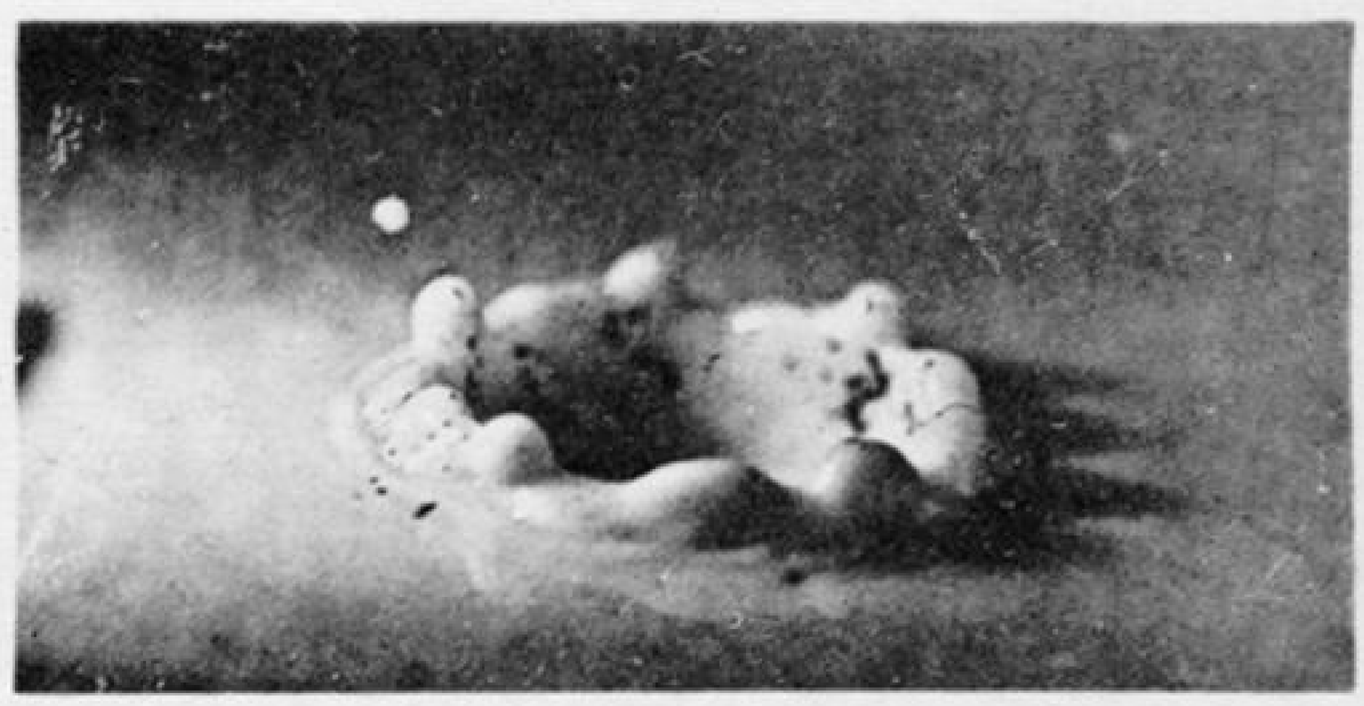


14

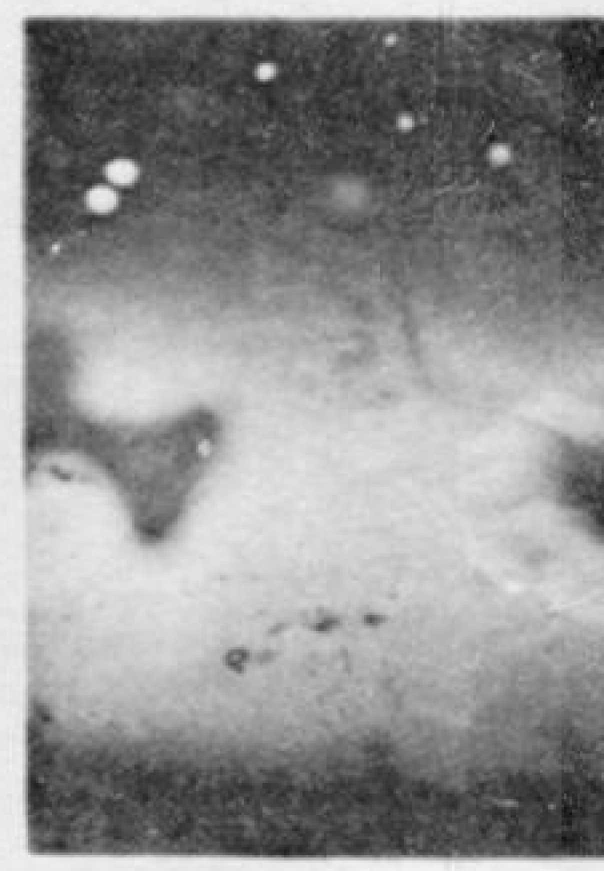
t-0495

19

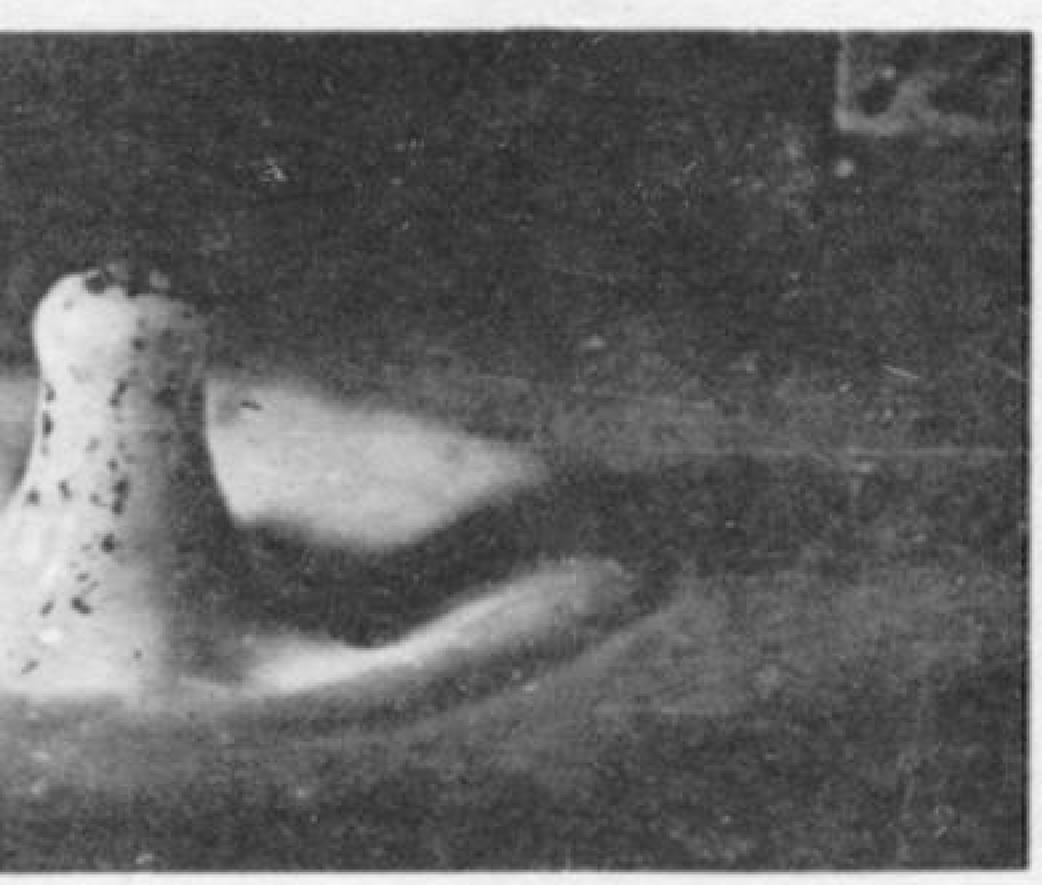
t-0556



20

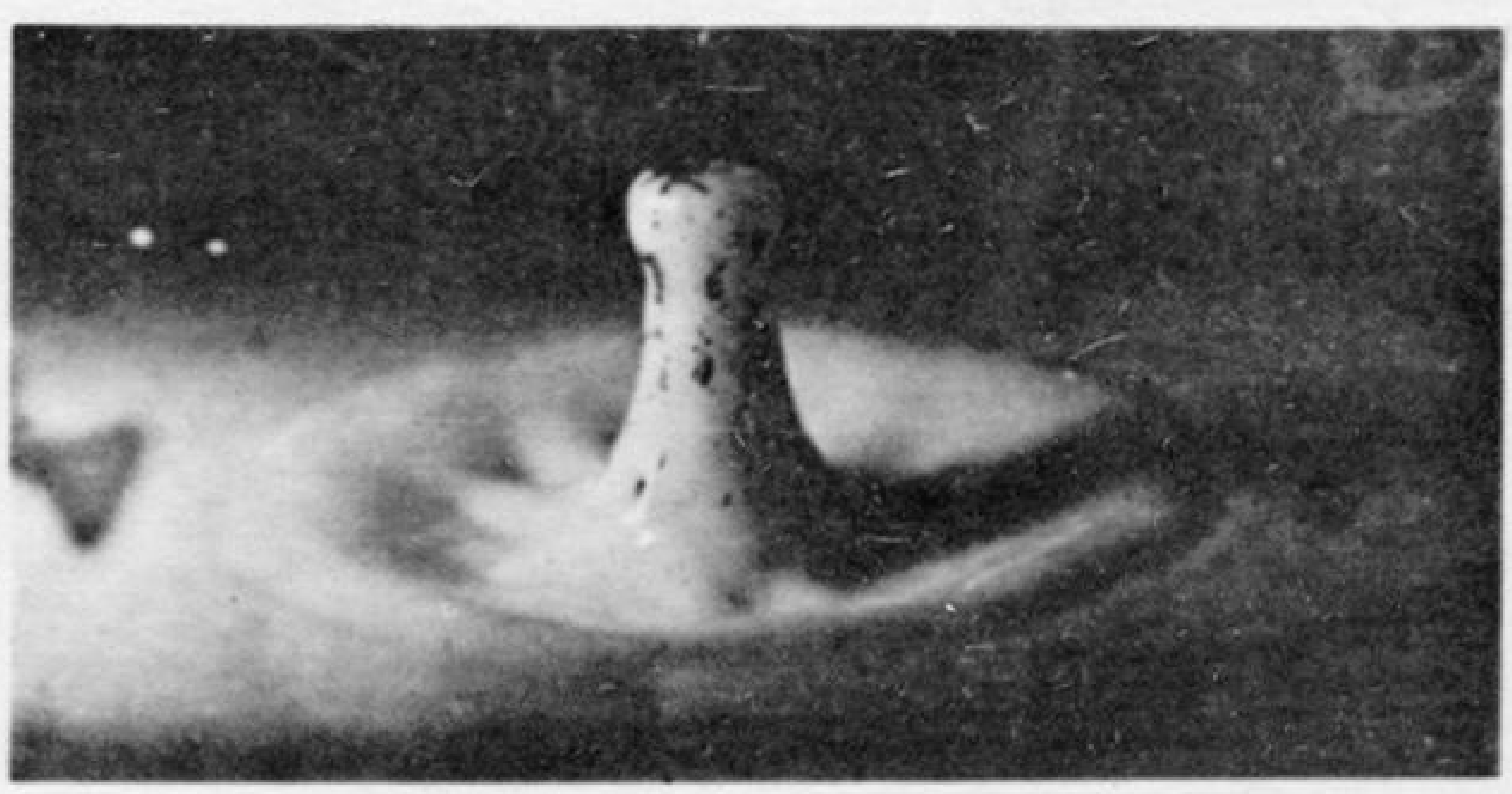


t-0925



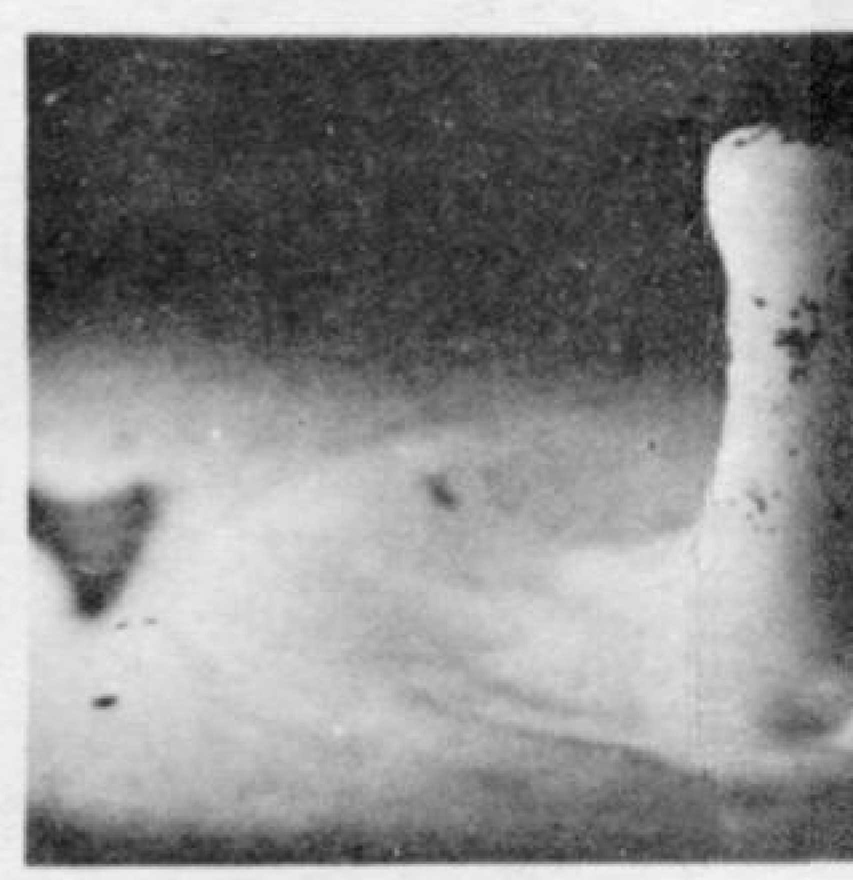
24

t-1032



25

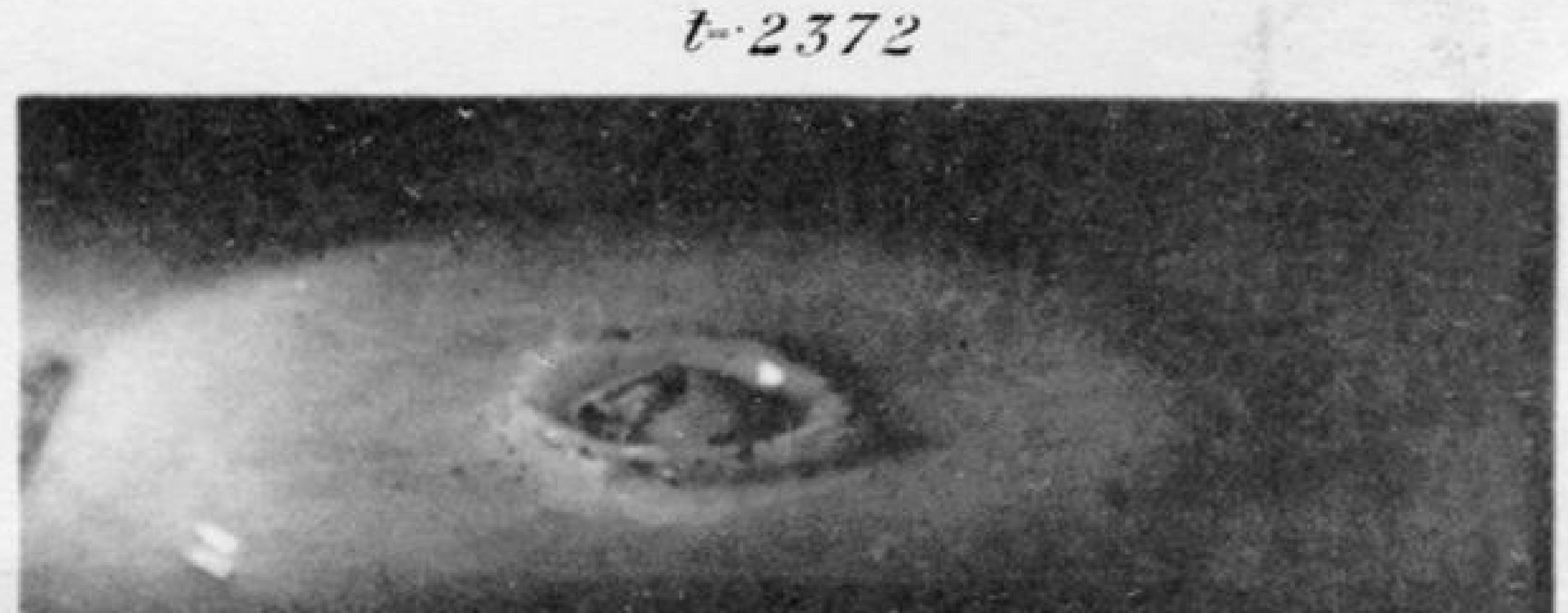
t-11



26

t-2175

t-2372



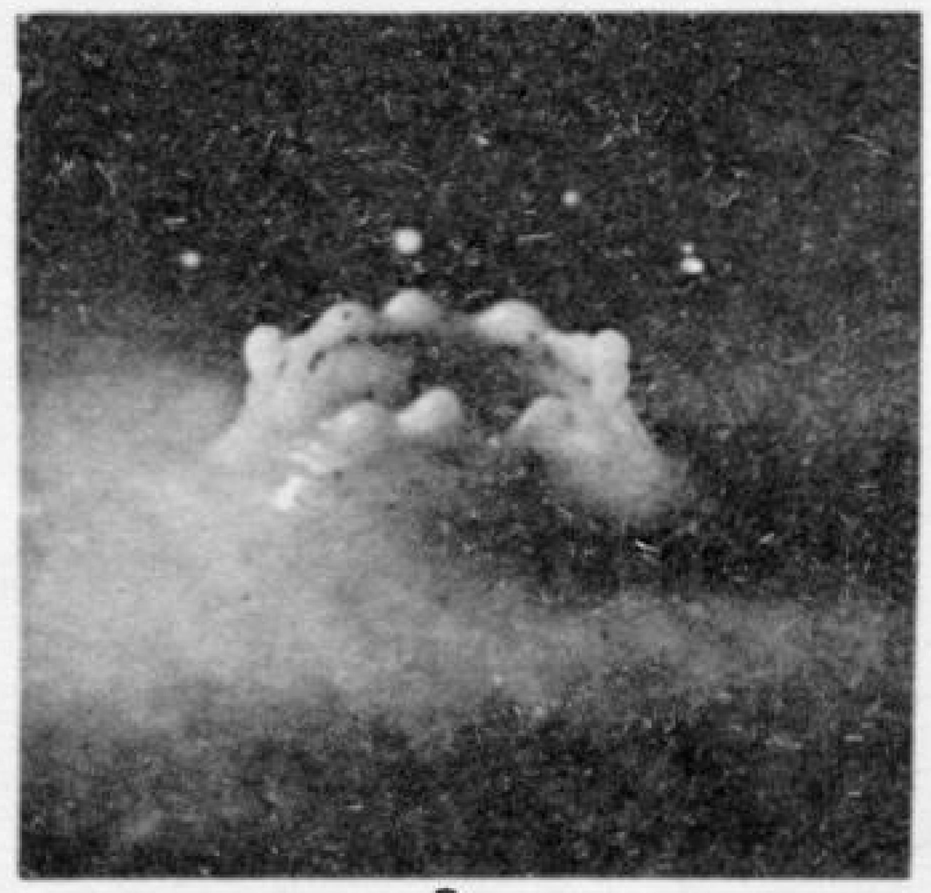
t=·0175 (a)

7

t=·0201 (b)

8

t=·0242 (b)



9

t=·0338 (a)

15

t=·0369 (b)

16

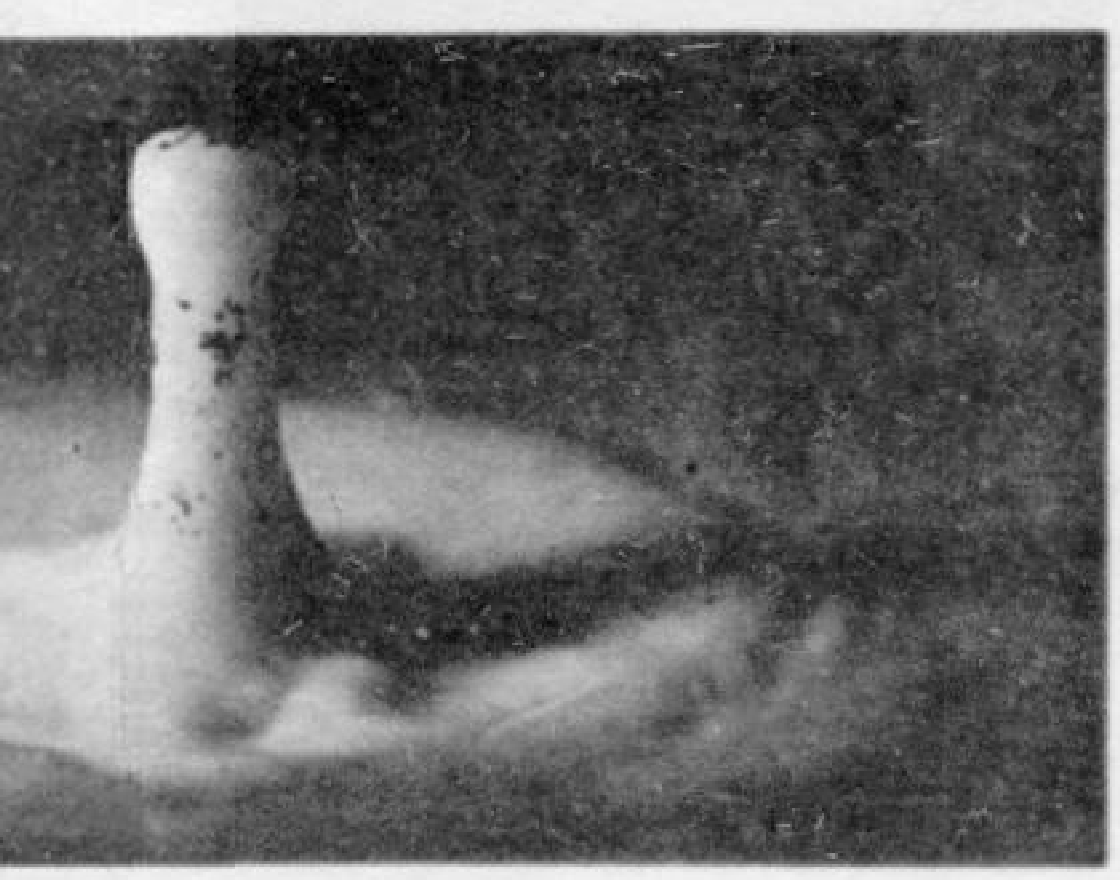
t=·0644

21

t=·0732

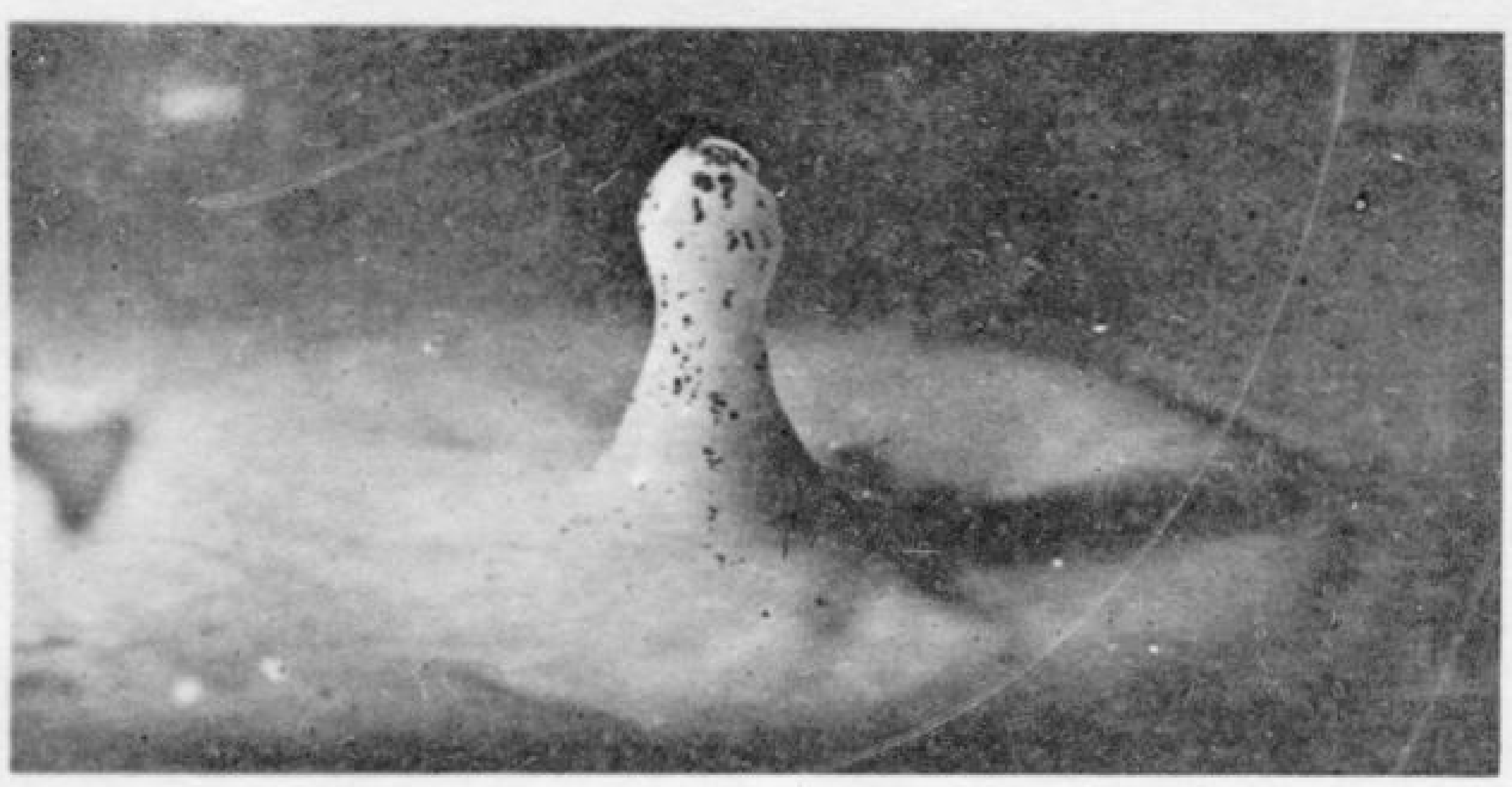
22

t=·1160



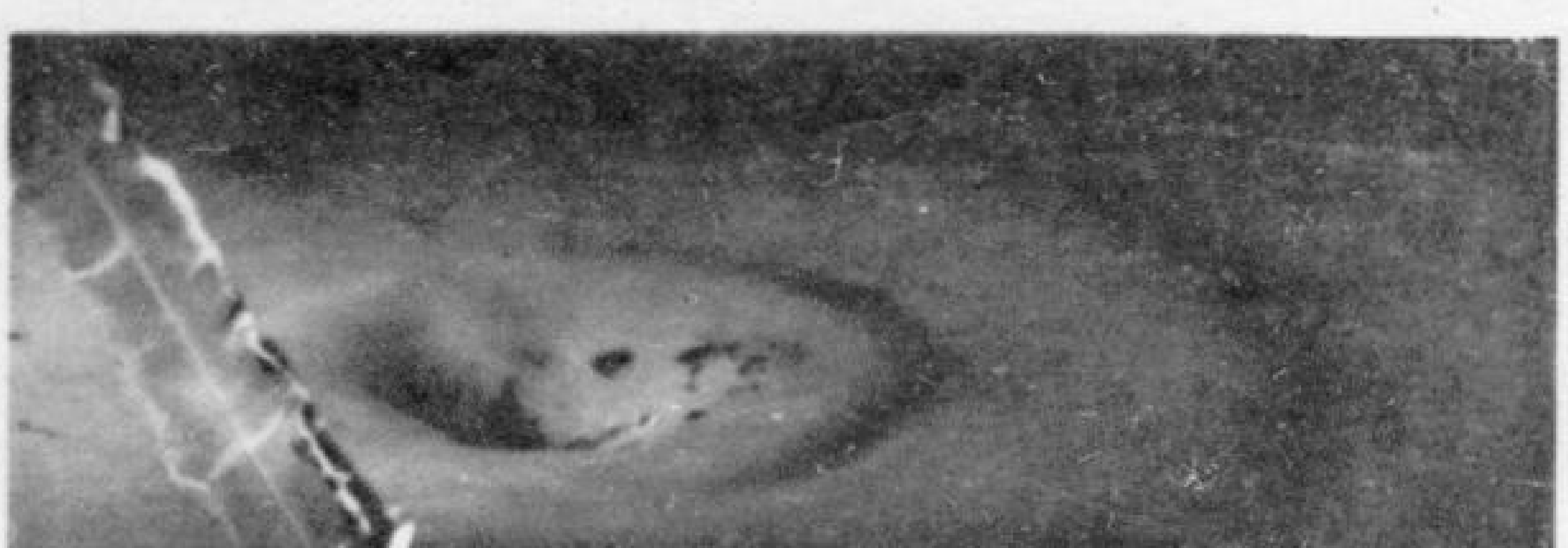
26

t=·1287



27

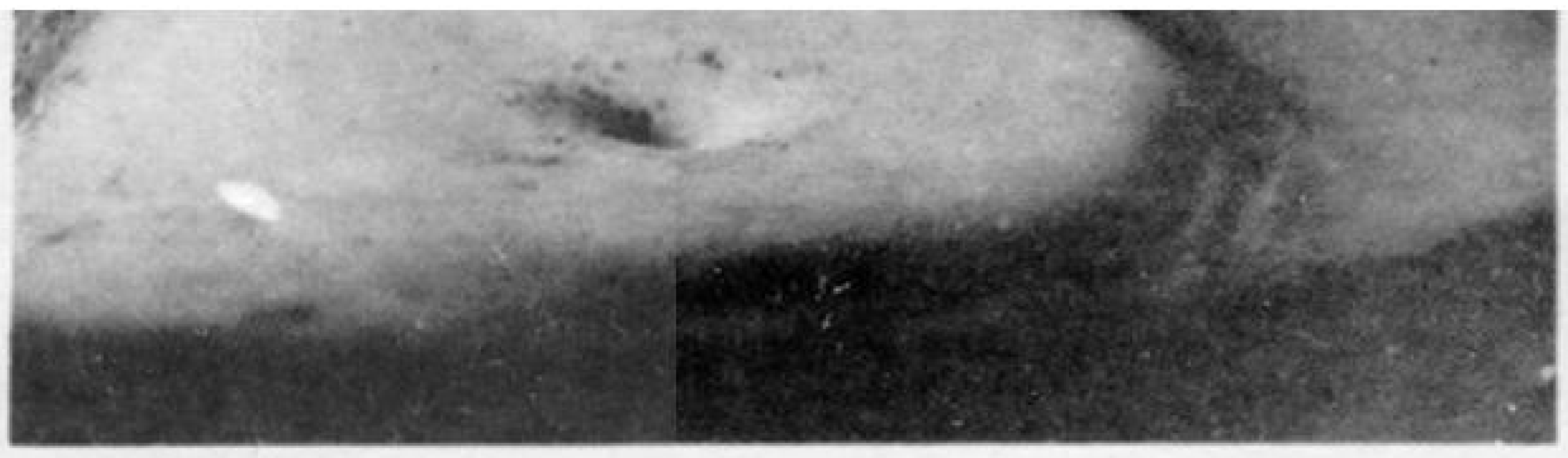
t=·2755



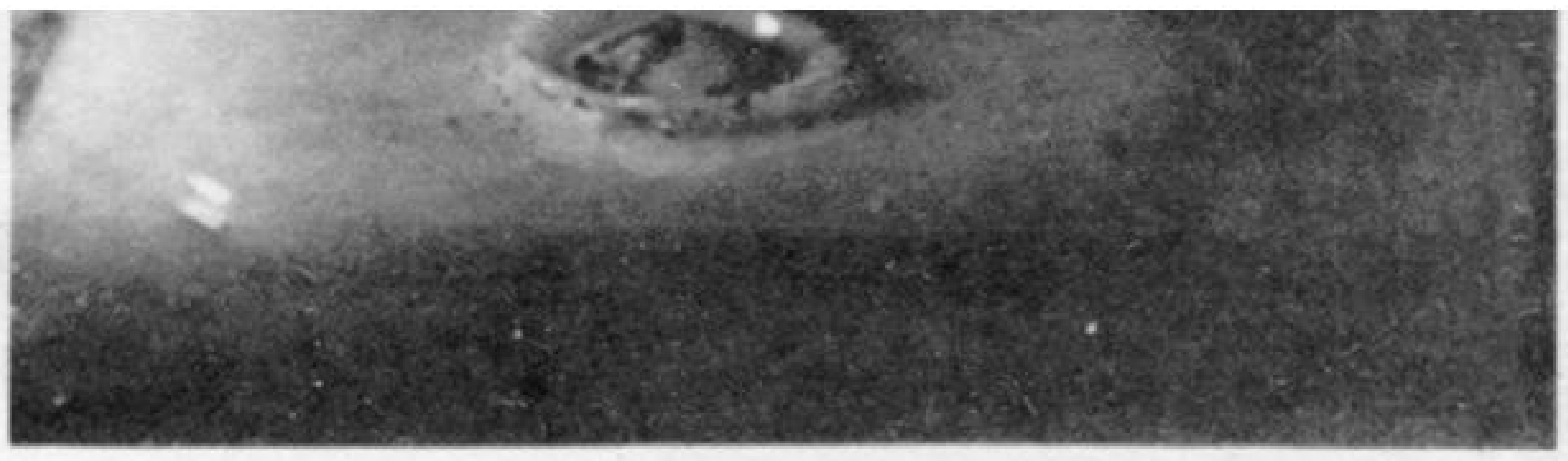
t=·3107

28

29

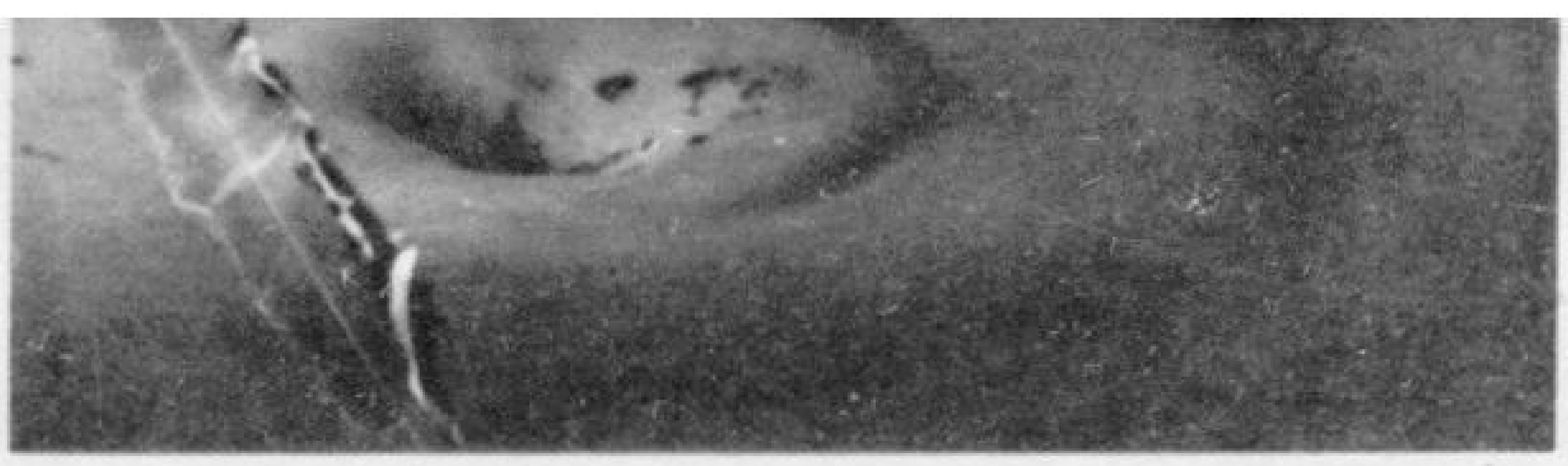


30

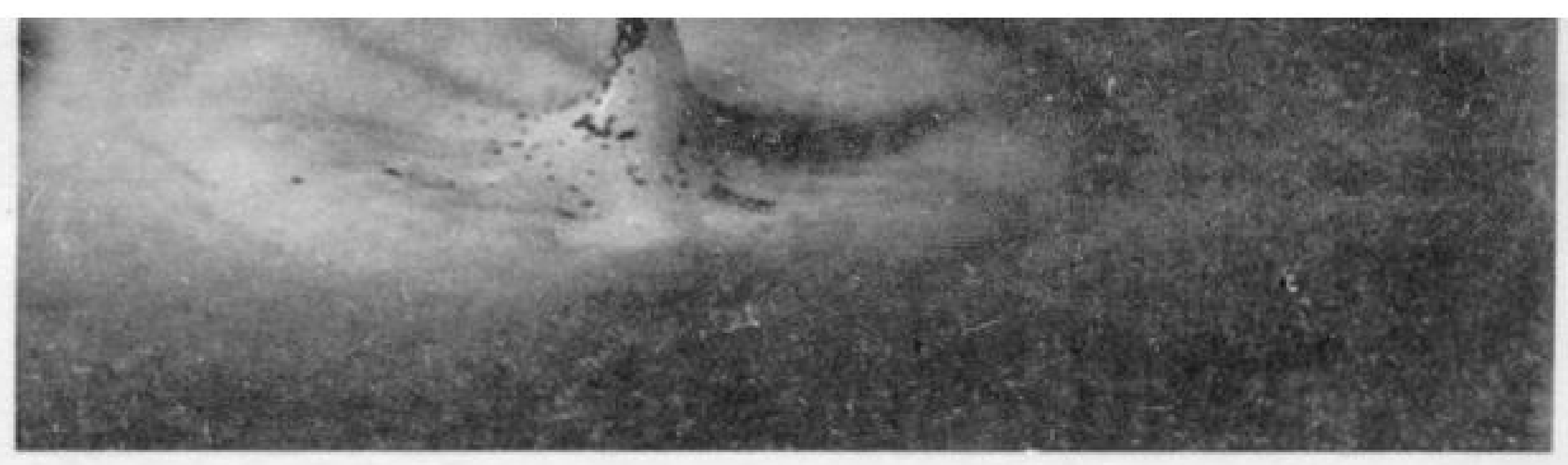


31

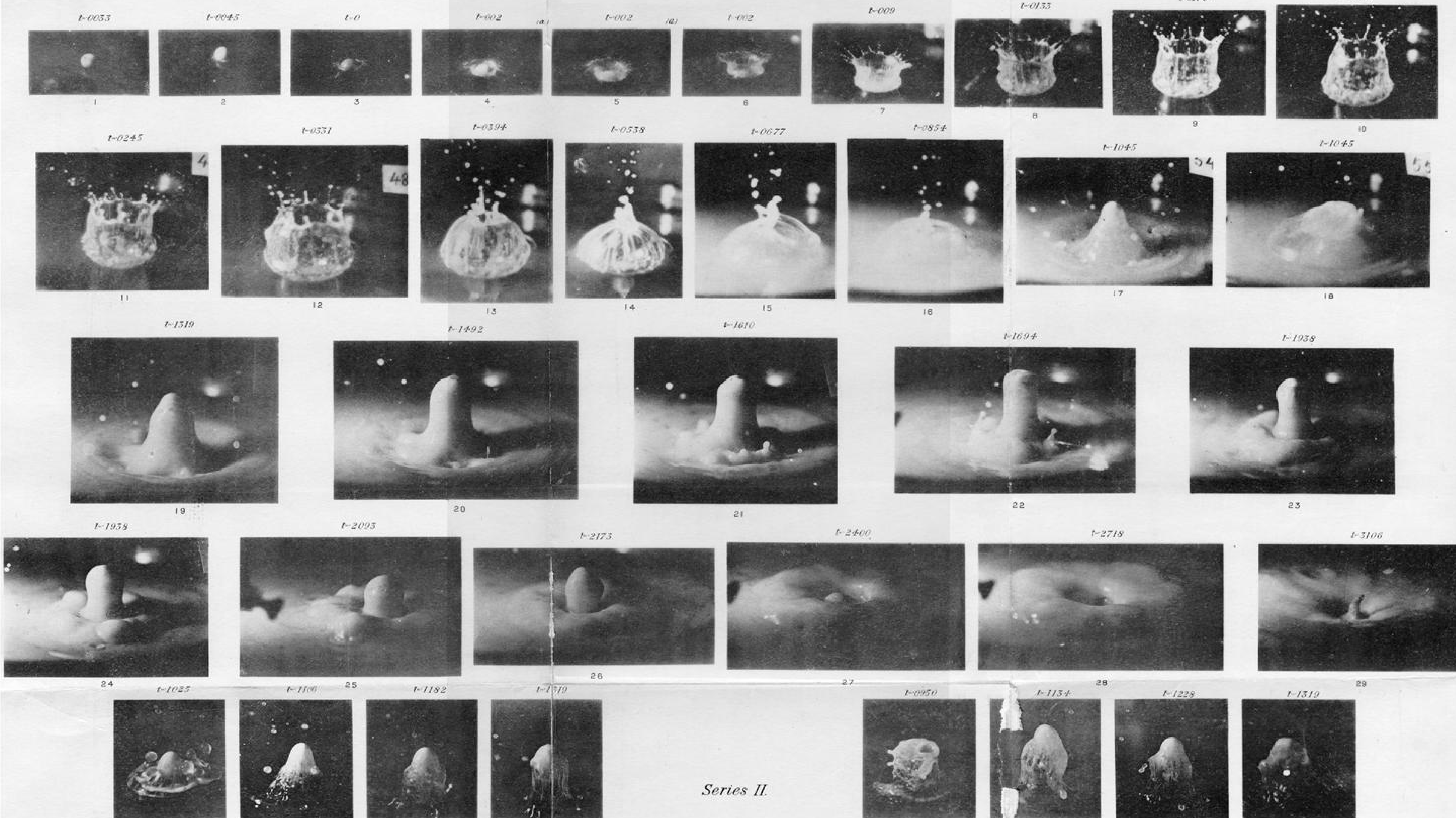
Series I.



32



33



1 (t-0033), 2 (t-0045), 3 (t-0), 4 (t-002 (a)), 5 (t-002 (a)), 6 (t-002), 7 (t-009), 8 (t-0133), 9 (t-0179), 10 (t-0179)

11 (t-0245), 12 (t-0331), 13 (t-0394), 14 (t-0538), 15 (t-0677), 16 (t-0854), 17 (t-1045), 18 (t-1045)

19 (t-1319), 20 (t-1492), 21 (t-1610), 22 (t-1694), 23 (t-1938)

24 (t-1938), 25 (t-2093), 26 (t-2173), 27 (t-2400), 28 (t-2718), 29 (t-3106)

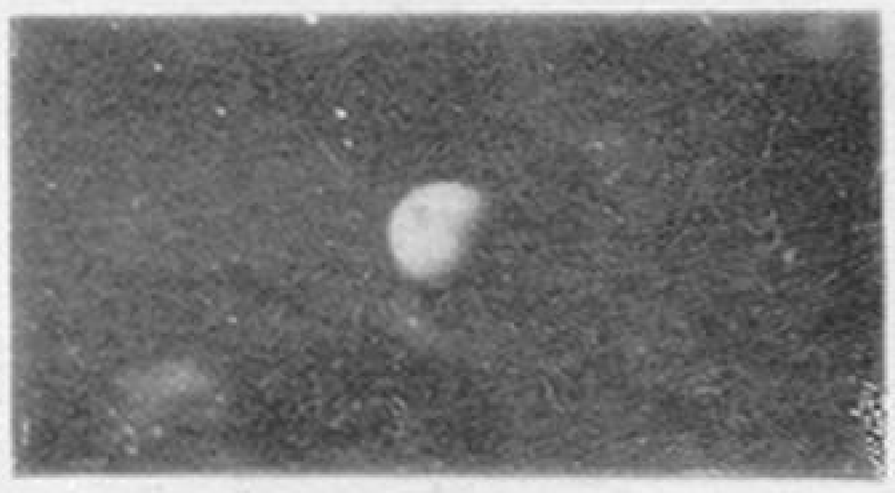
1a (t-1025), 2a (t-1106), 3a (t-1182), 4a (t-1[illegible]19)

Series II.

1b (t-0950), 2b (t-1134), 3b (t-1228), 4b (t-1319)

Worthington & Cole,

t-·0033

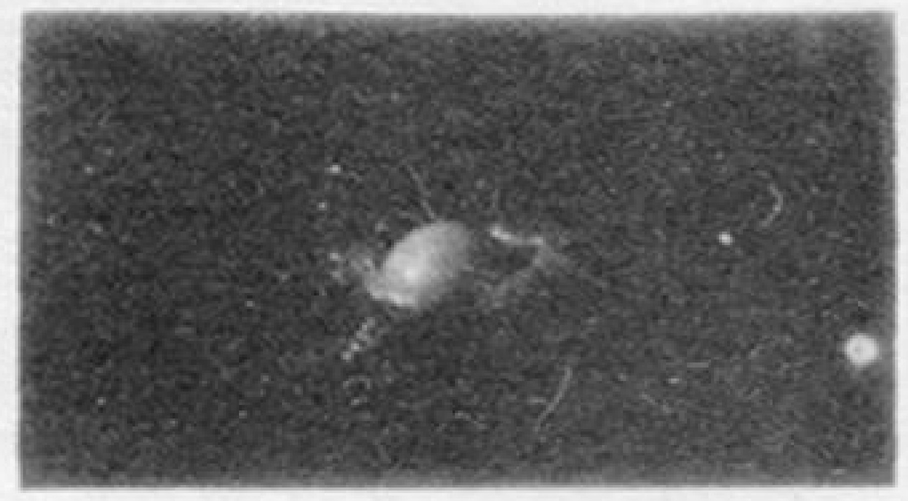


1

t-·0045

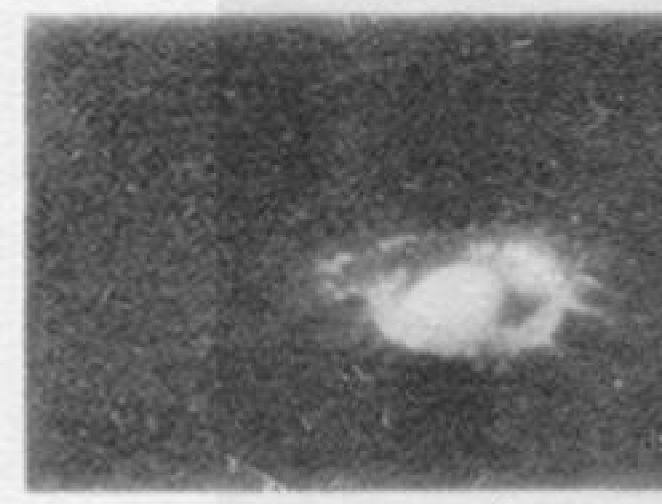
2

t-0



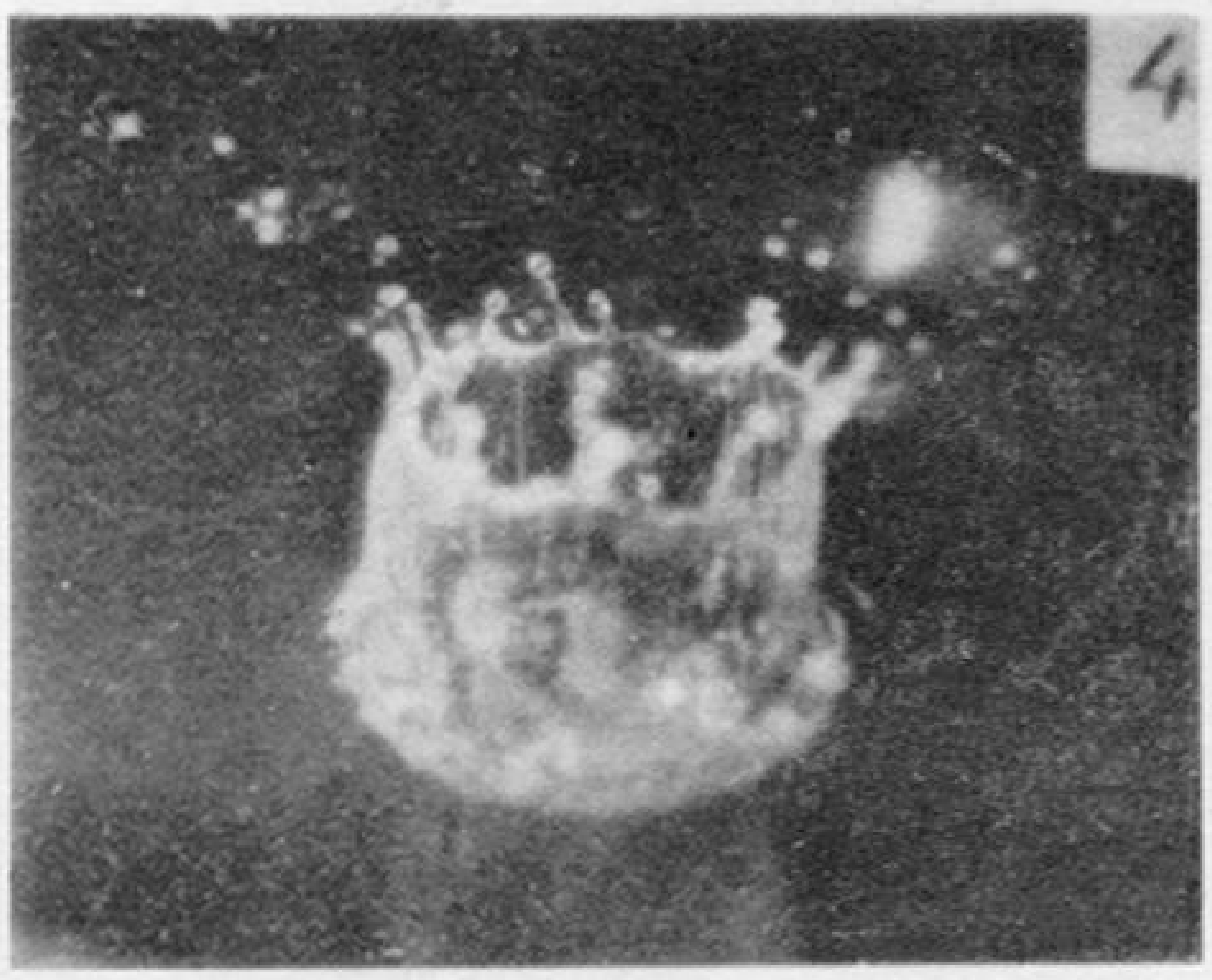
3

t-·002



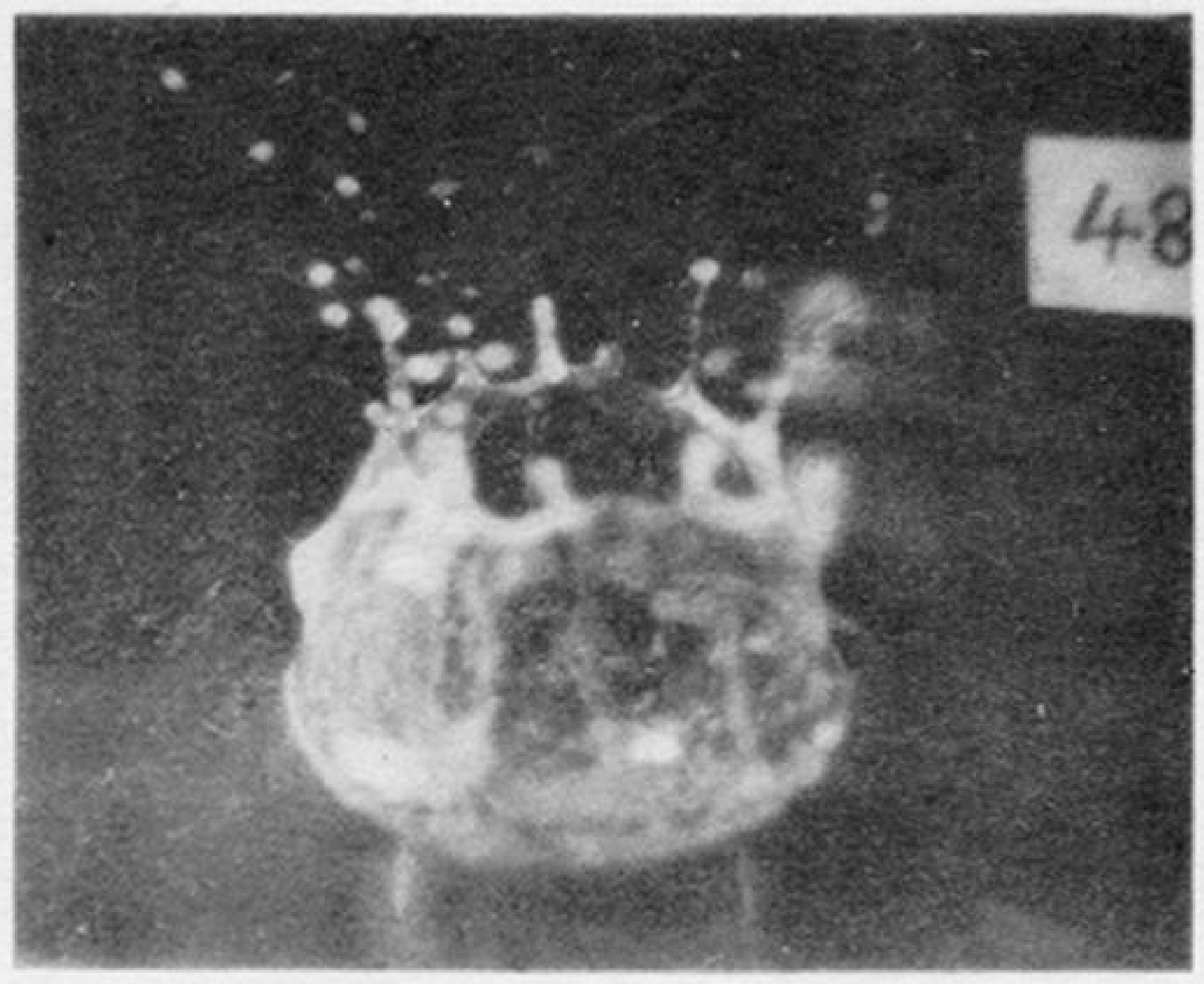
4

t-·0245



11

t-·0331



12

t-·0394

13

t-·1319

19

t-·1492

20

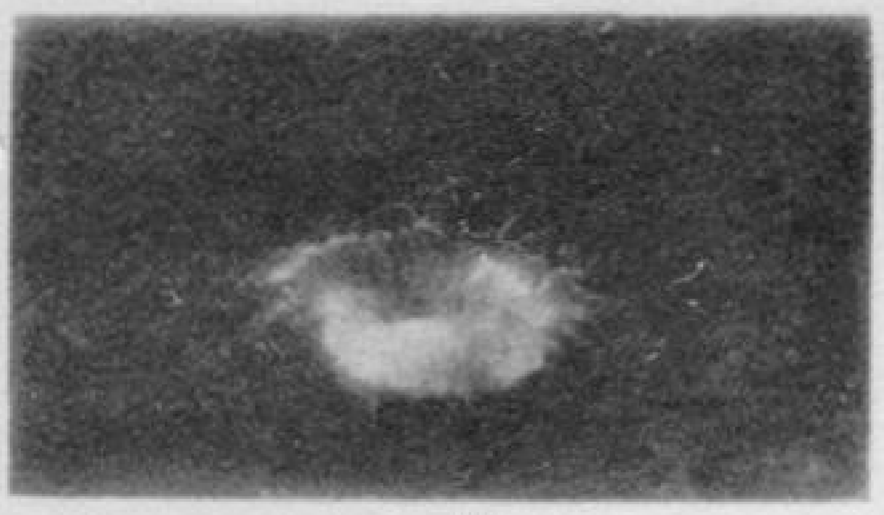
t-·1938

t-·2093

t-002 (a)

4

t-002 (a)

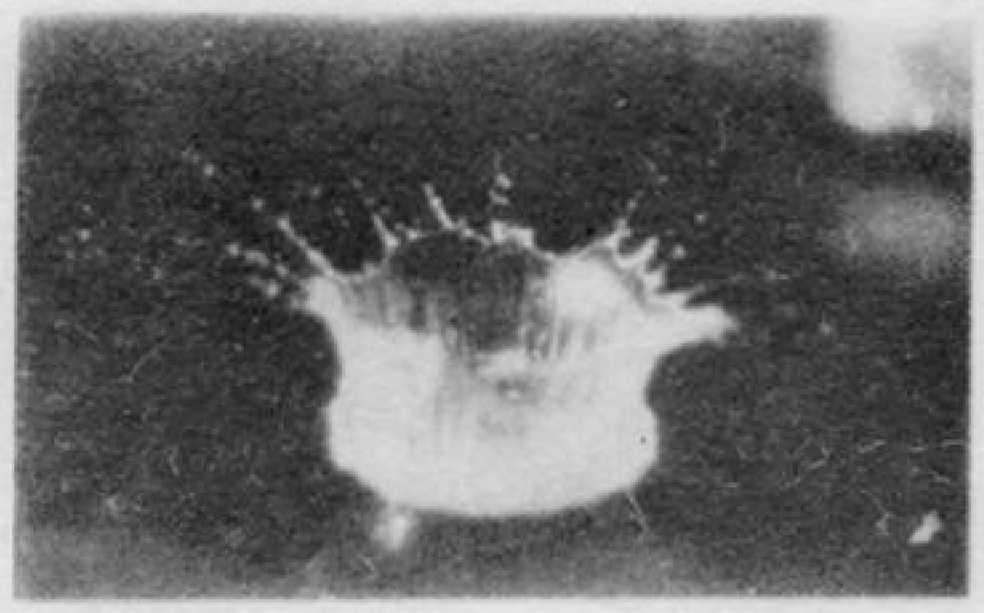


5

t-002

6

t-009



7

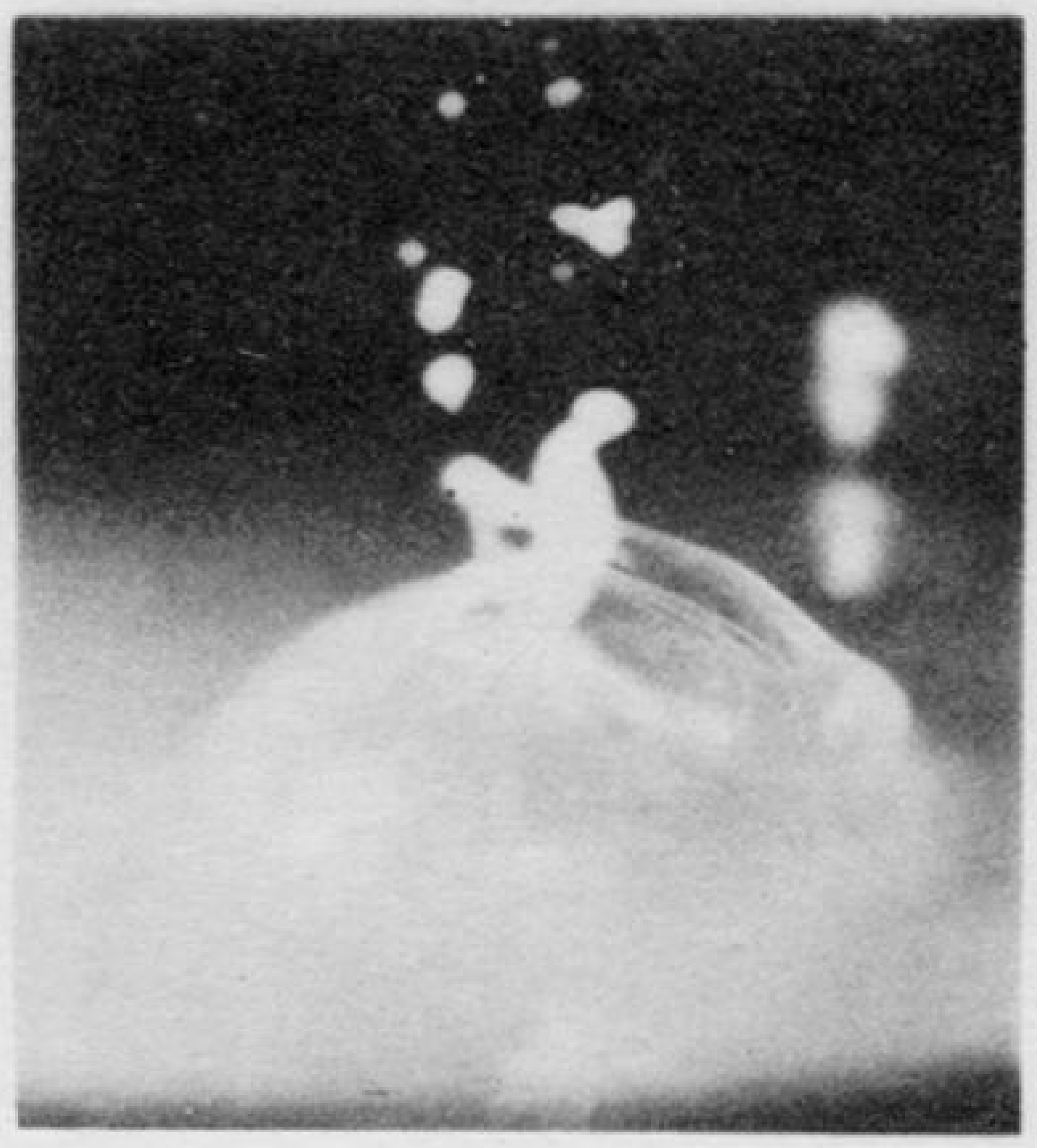
t-0394

13

t-0538

14

t-0677



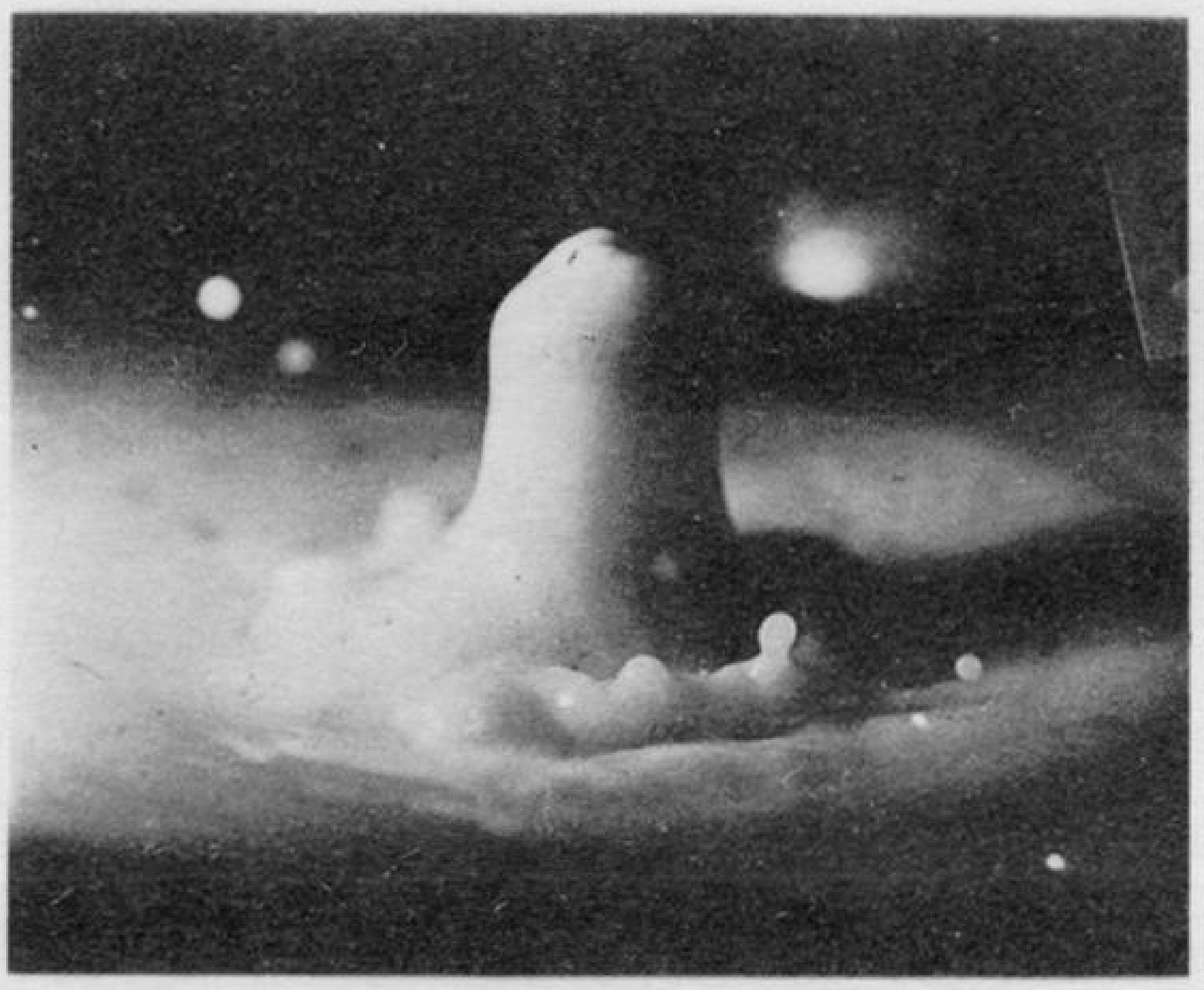
15

t-0854

16

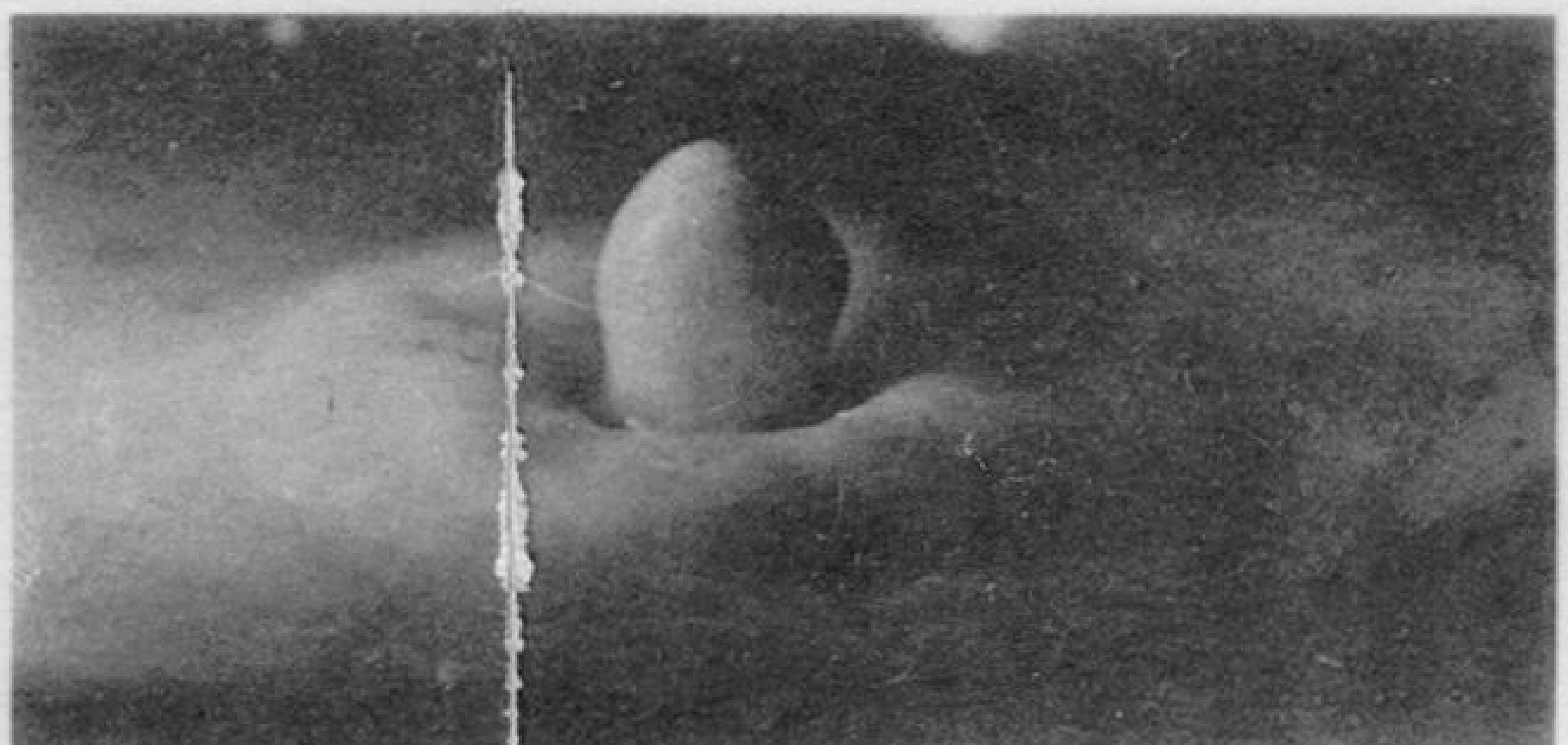
92

t-1610



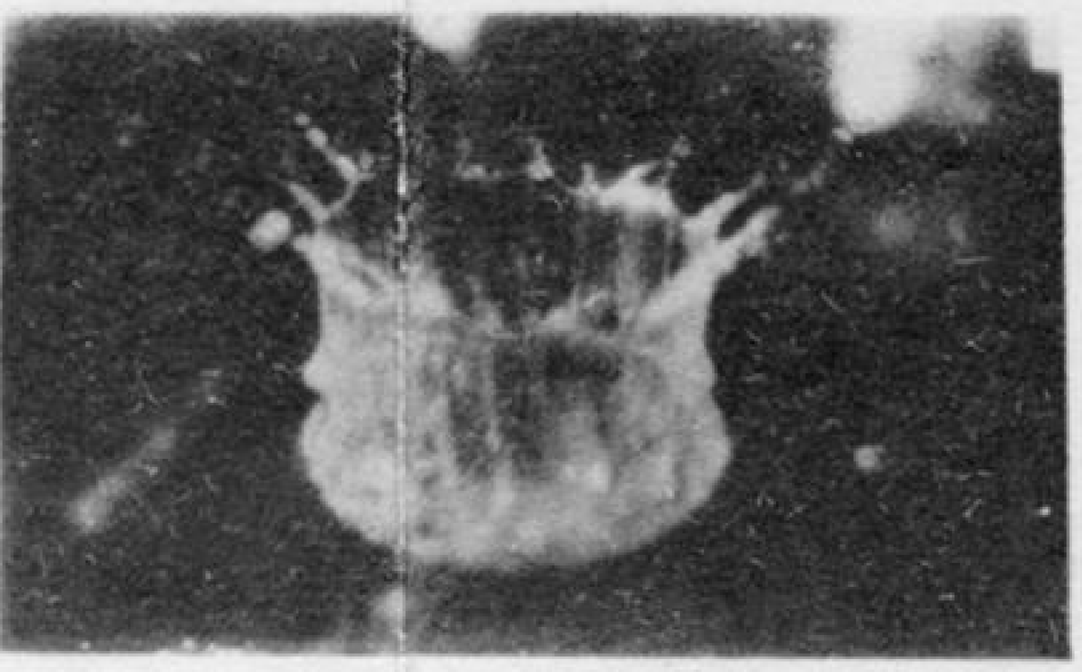
21

t-2173



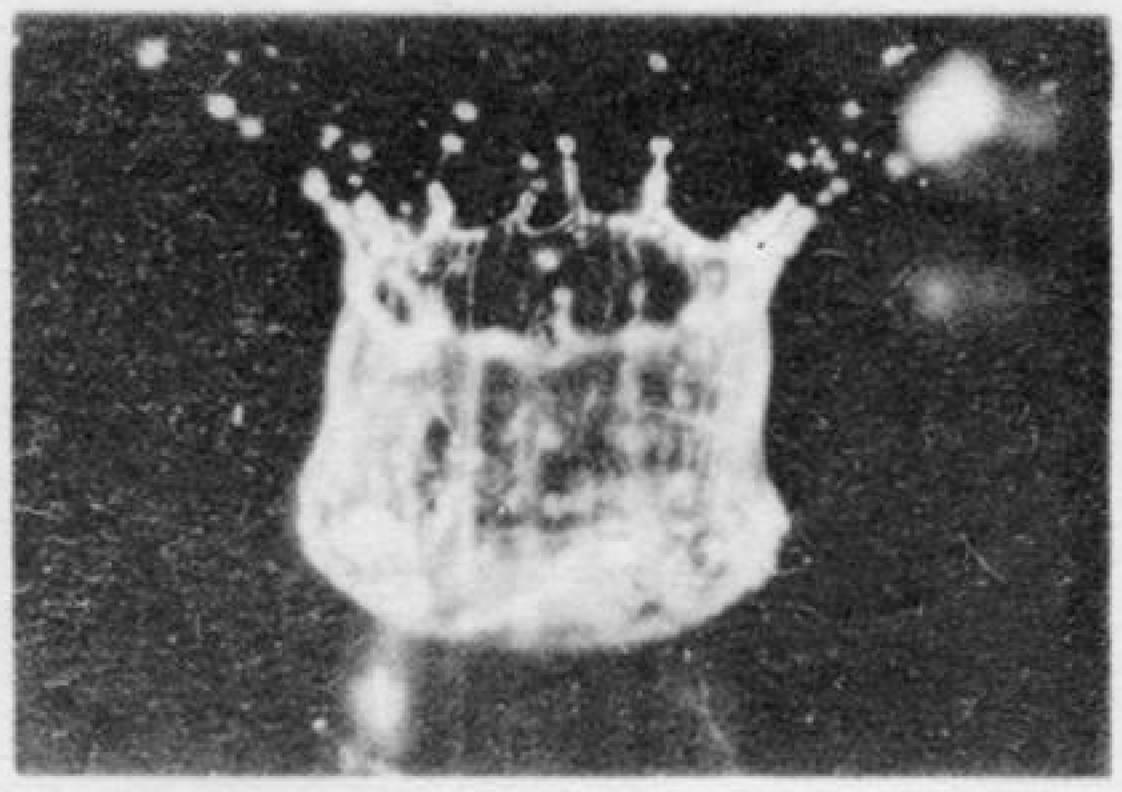
t-24·00

t=·0133



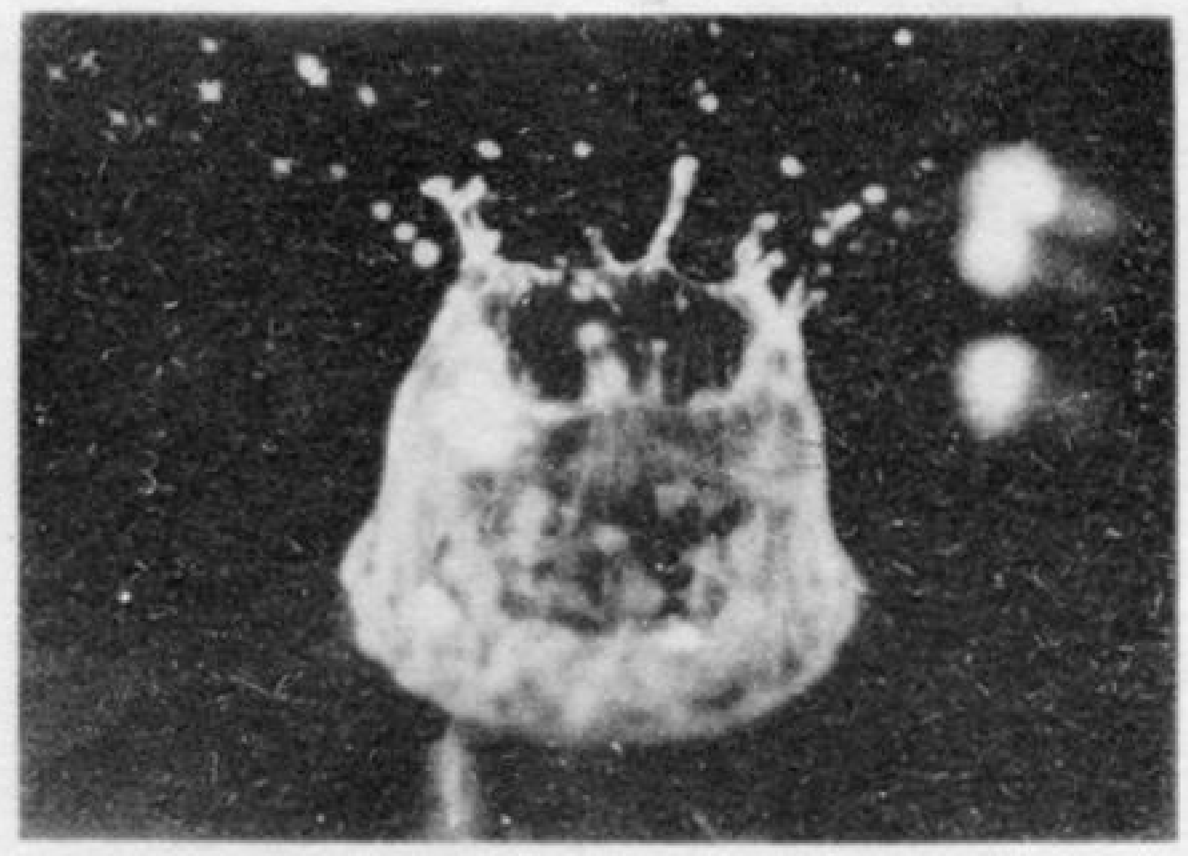
8

t=·0179



9

t=·0179

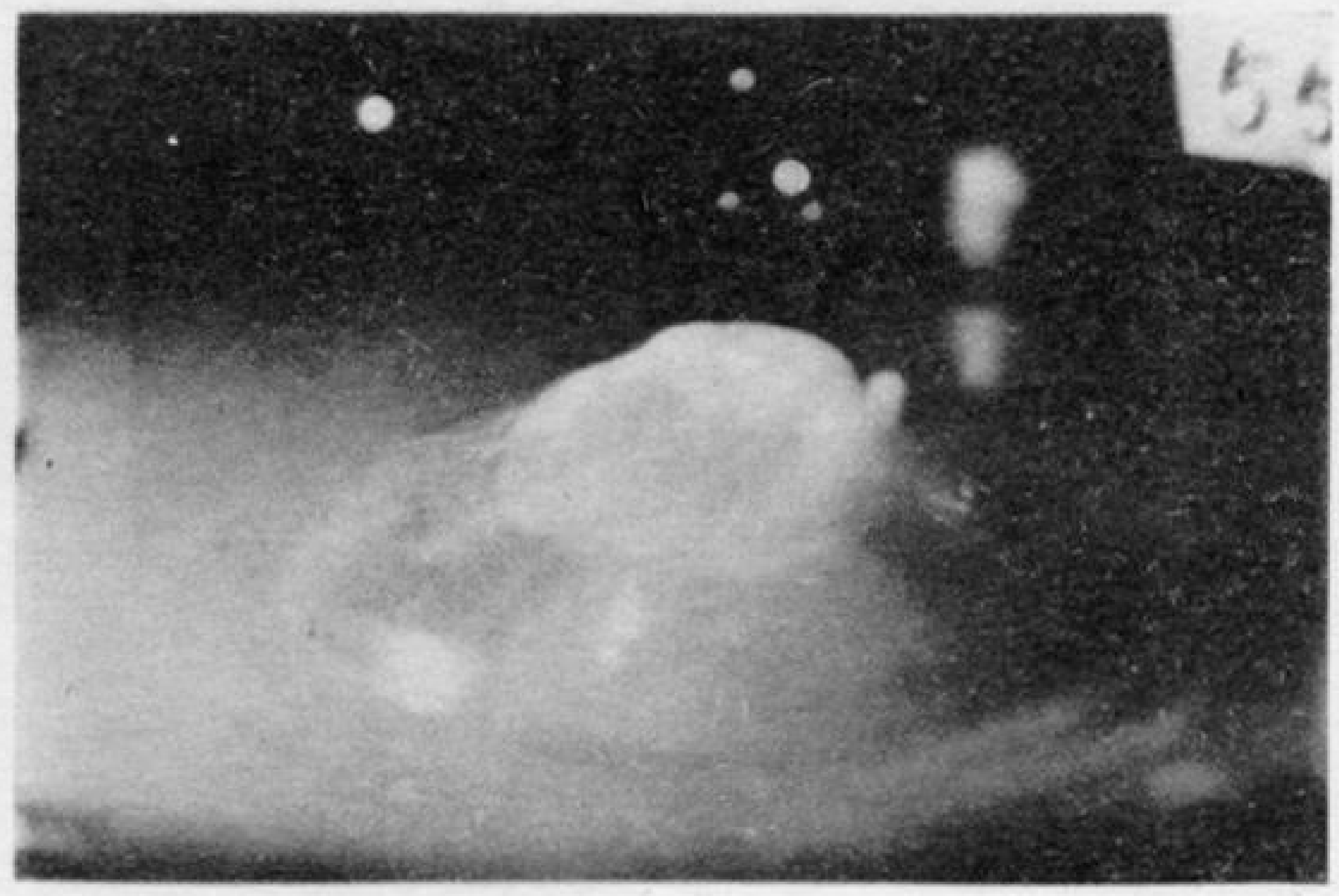


10

t=·1045

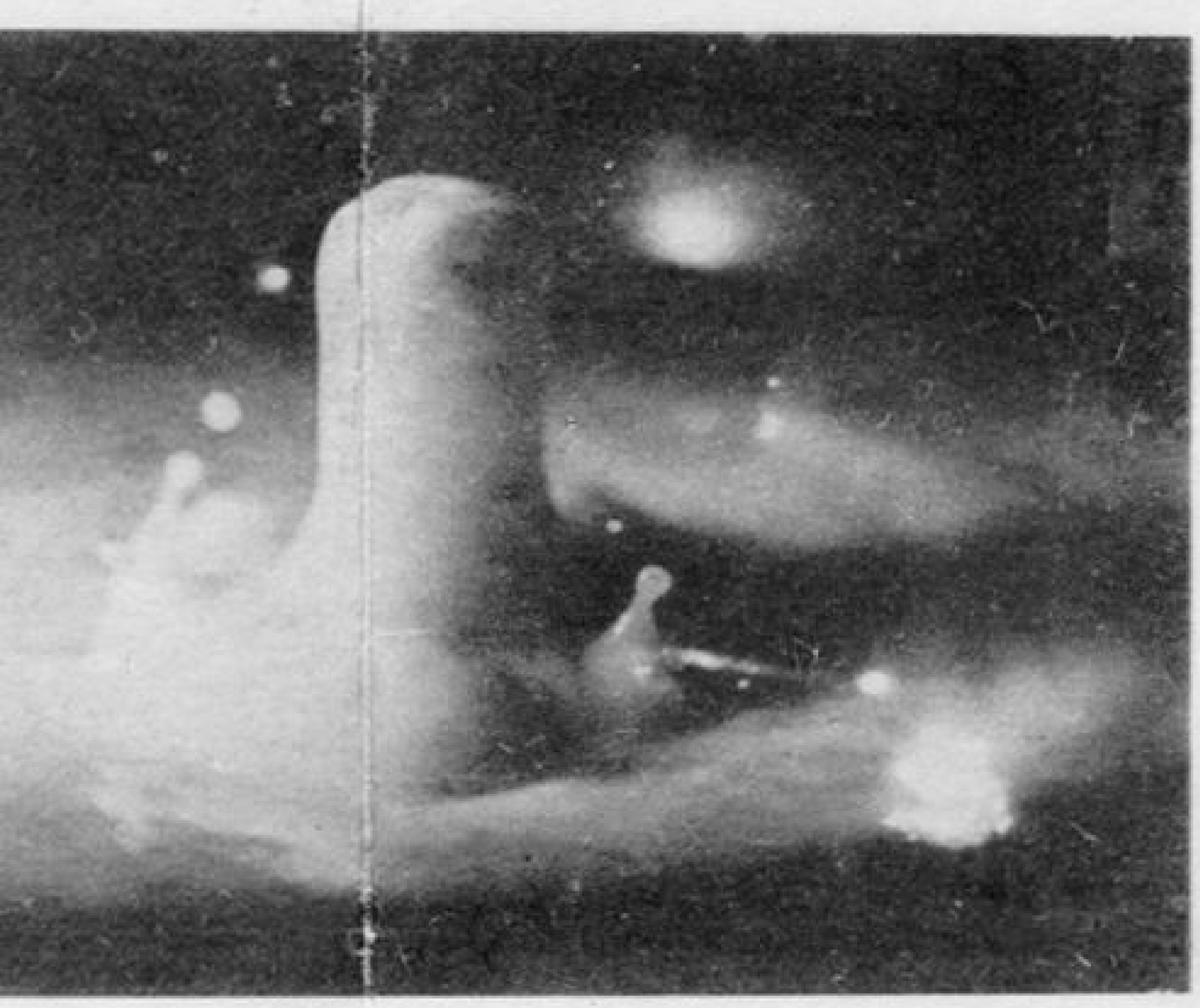
17

t=·1045



18

t=·1694



22

t=·1938

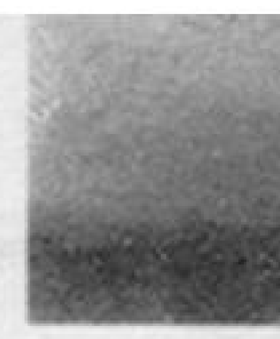
23

t=·2718

t=·3106

24

25



t-1025

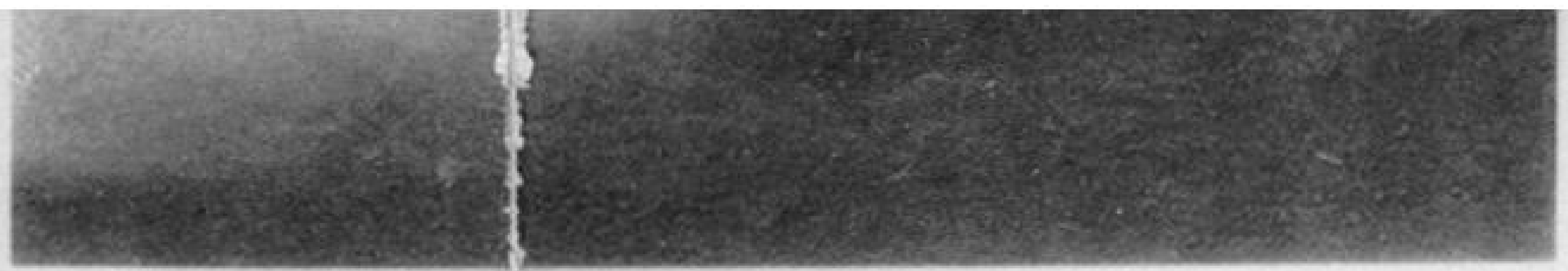
1a

t-1106

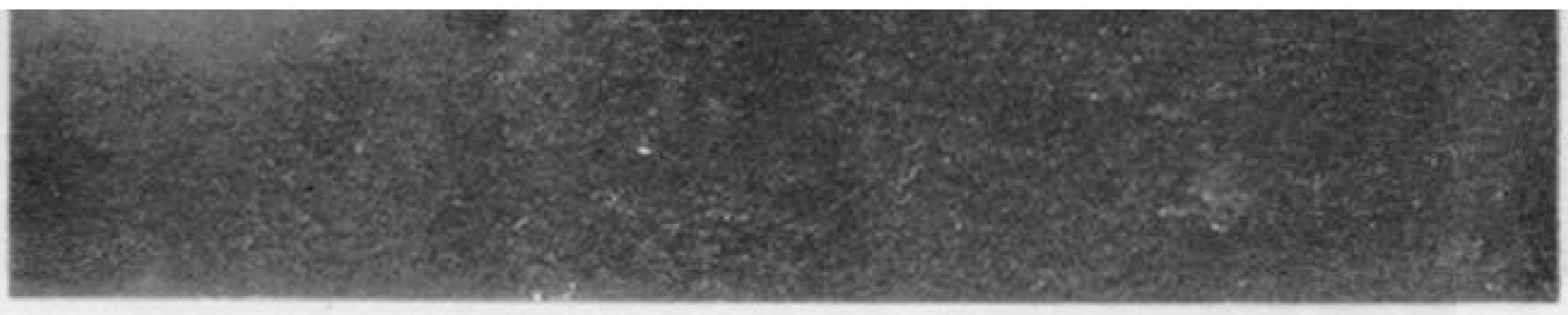
2a

t-1182

3a

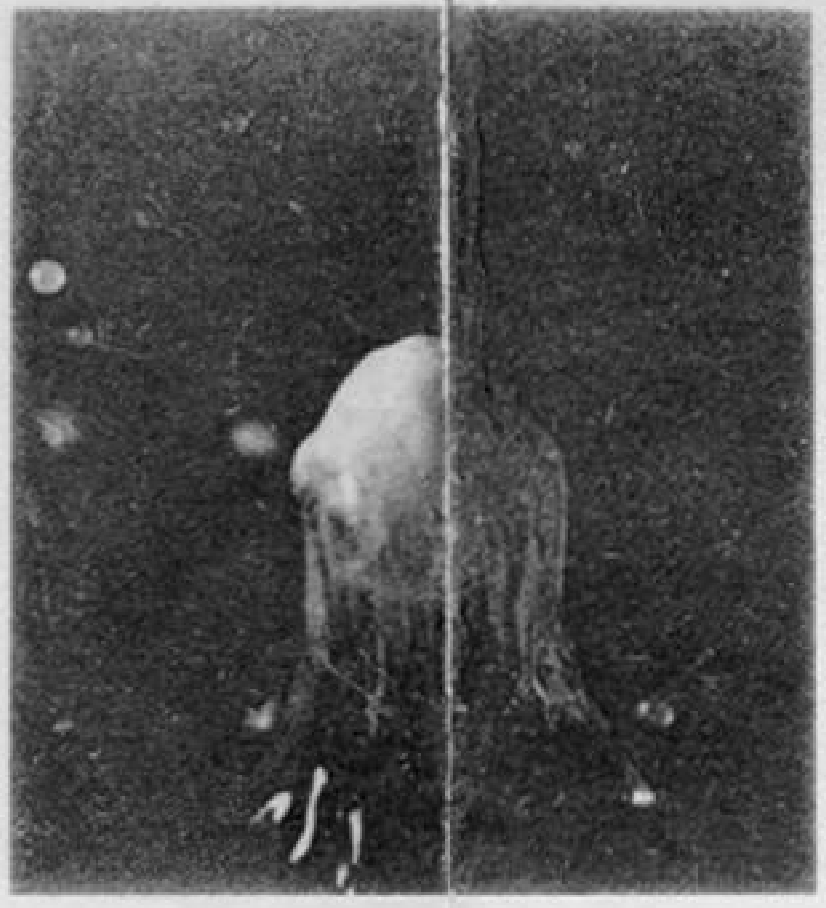


26



27

t-1319

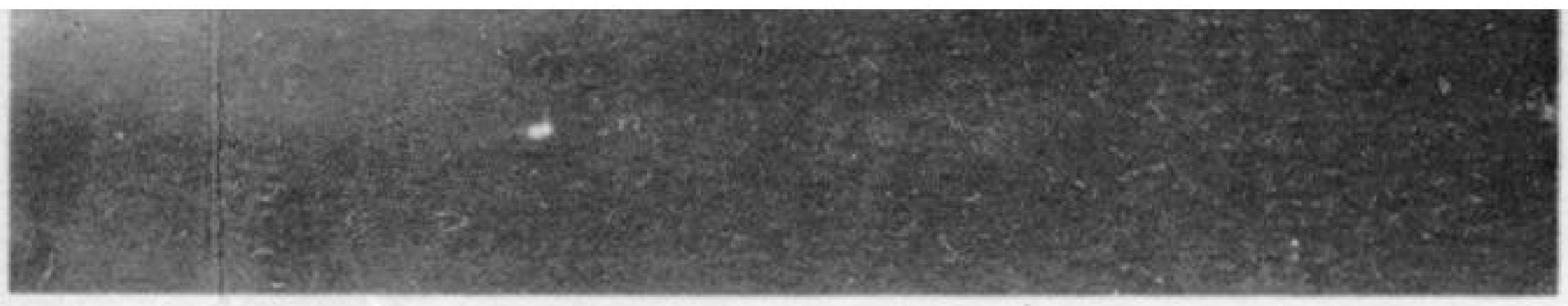


4a

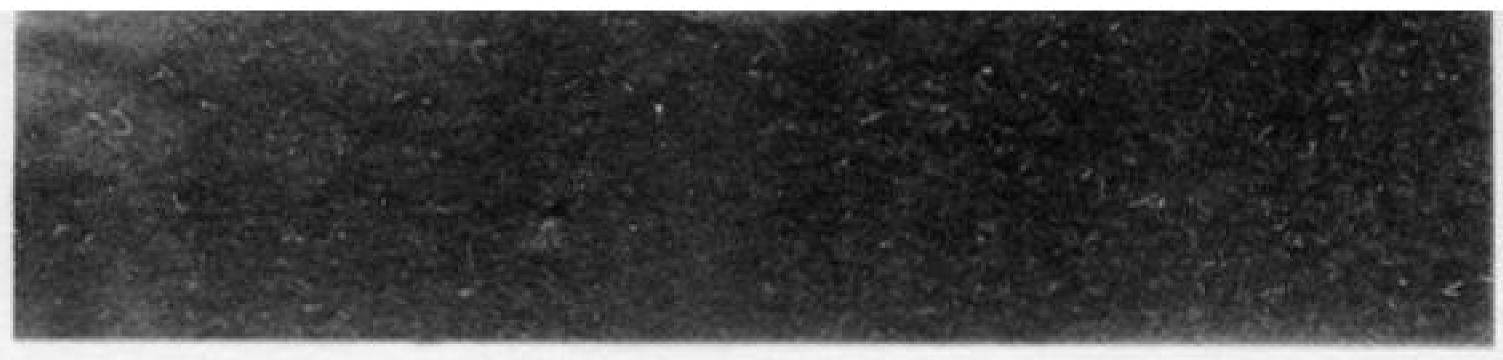
Series II.

t-0950

1b



28



29

t=1134

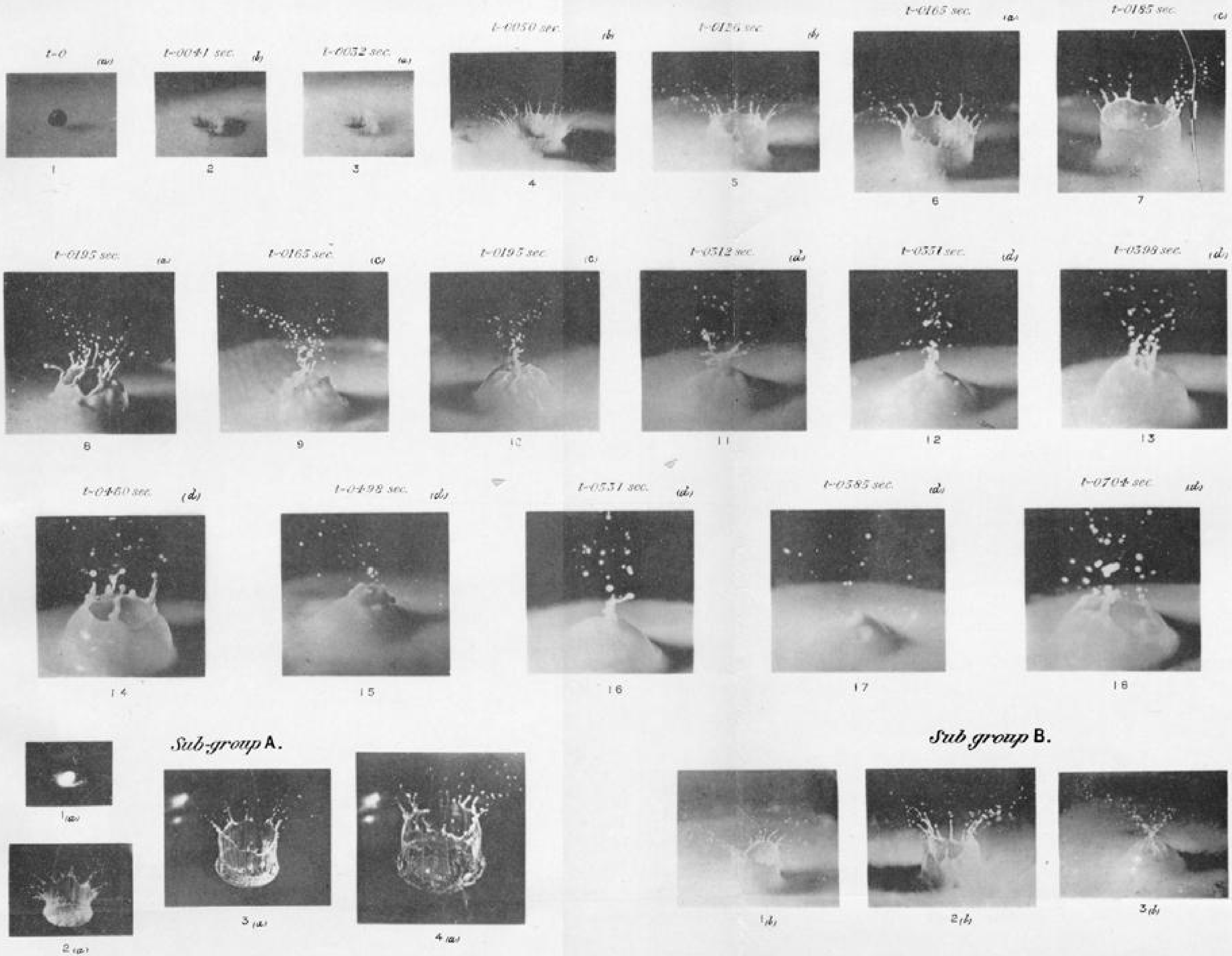
2b

t=1228

3b

t=1319

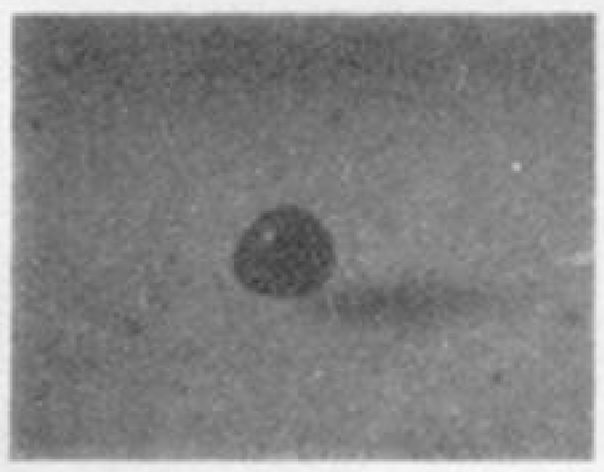
4b


t-0 (a)
1
t-·0041 sec. (b)
2
t-·0032 sec. (a)
3
t-·0050 sec. (b)
4
t-·0126 sec. (b)
5
t-·0165 sec. (a)
6
t-·0185 sec. (c)
7
t-·0195 sec. (a)
8
t-·0165 sec. (c)
9
t-·0195 sec. (c)
10
t-·0312 sec. (d1)
11
t-·0351 sec. (d1)
12
t-·0398 sec. (d1)
13
t-·0450 sec. (d1)
14
t-·0498 sec. (d1)
15
t-·0531 sec. (d1)
16
t-·0585 sec. (d1)
17
t-·0704 sec. (d1)
18
Sub-group A.
1 (a)
2 (a)
3 (a)
4 (a)
Sub group B.
1 (b)
2 (b)
3 (b)

Series III.

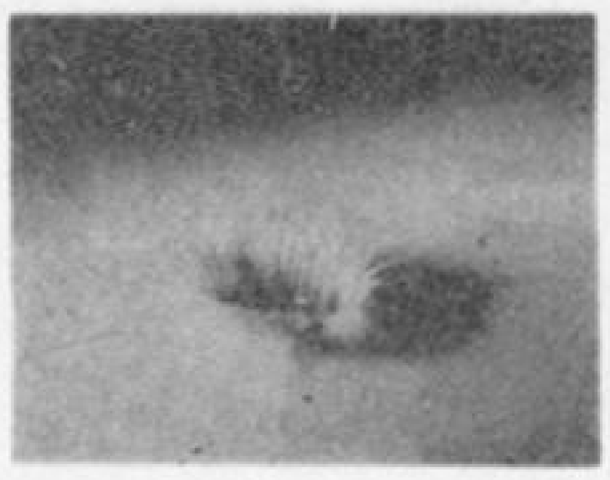
Worthington & Cole,

t=0 (a)



1

t=·0041 sec. (b)



2

t=·0032 sec. (a)

3

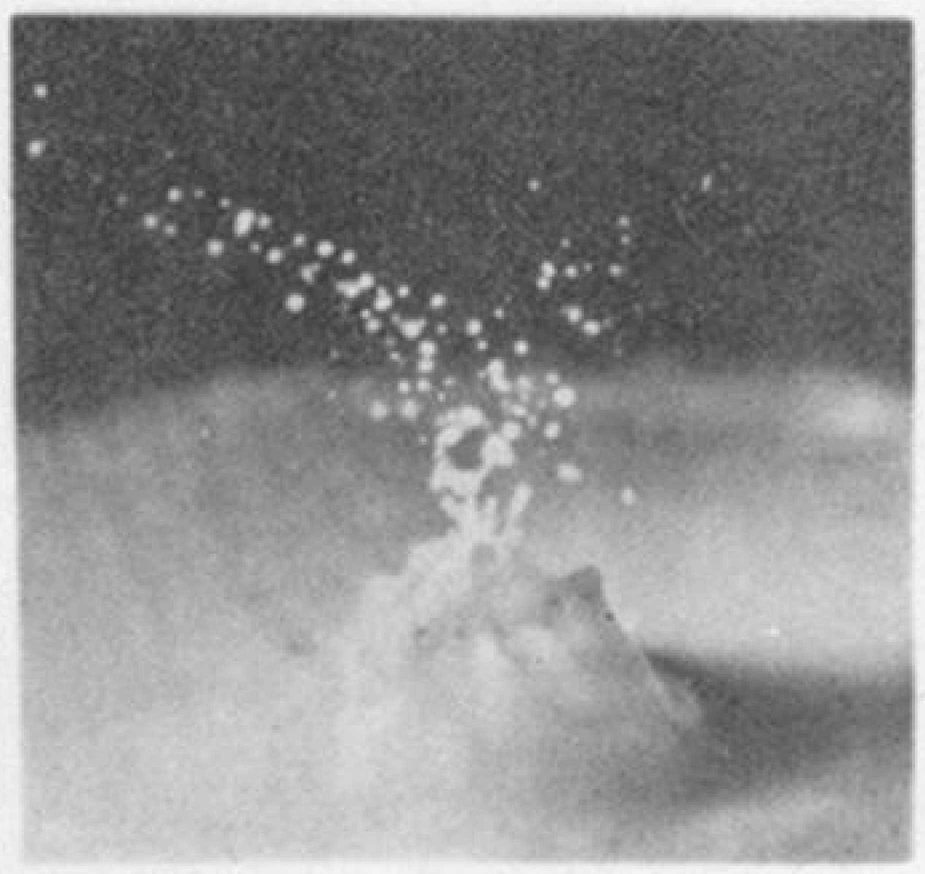
t=·0050 sec. (b)

4

t=·0195 sec. (a)

8

t=·0165 sec. (c)

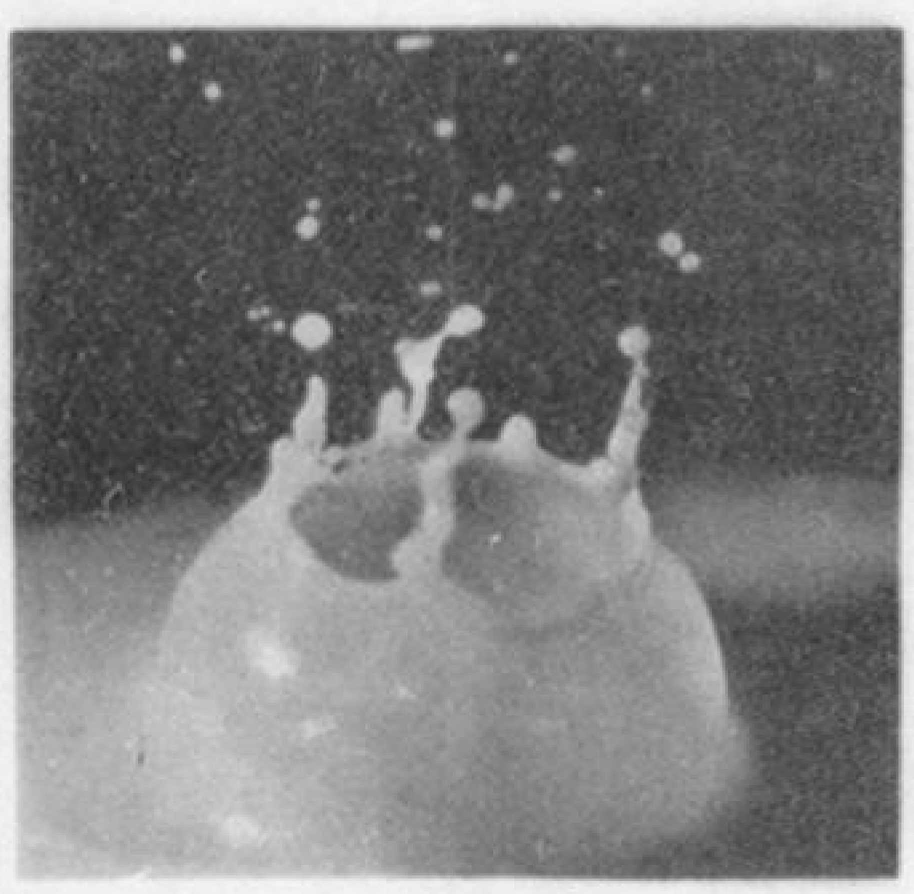


9

t=·0195 sec. (c)

10

t=·0460 sec. (d)

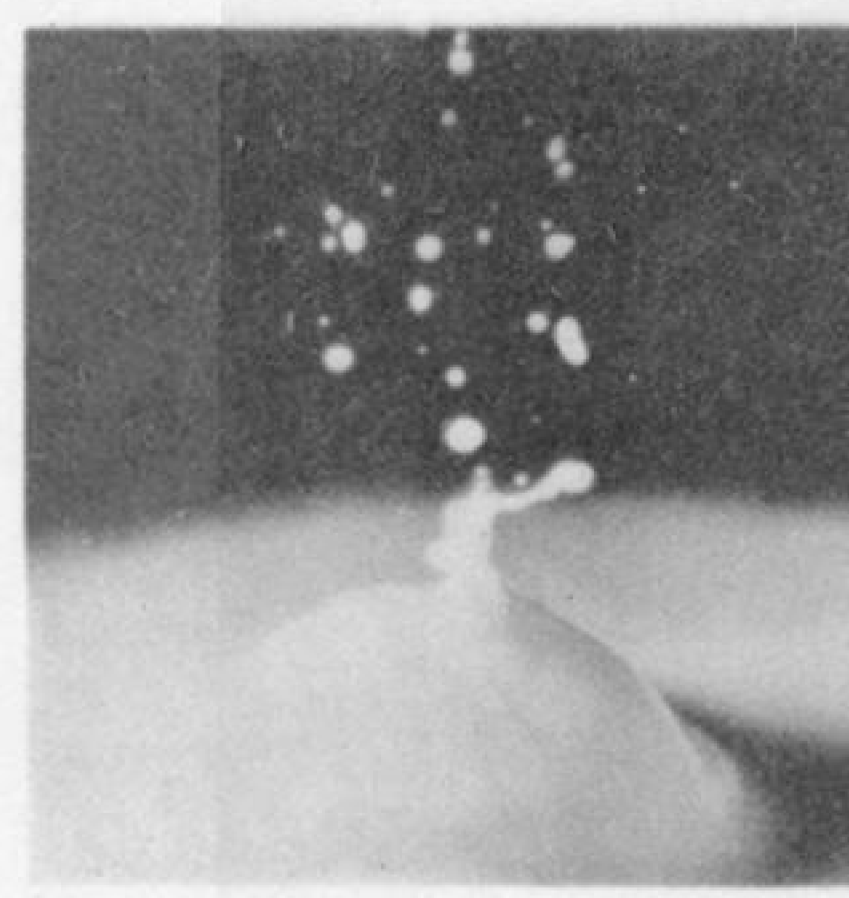


14

t=·0498 sec. (d)

15

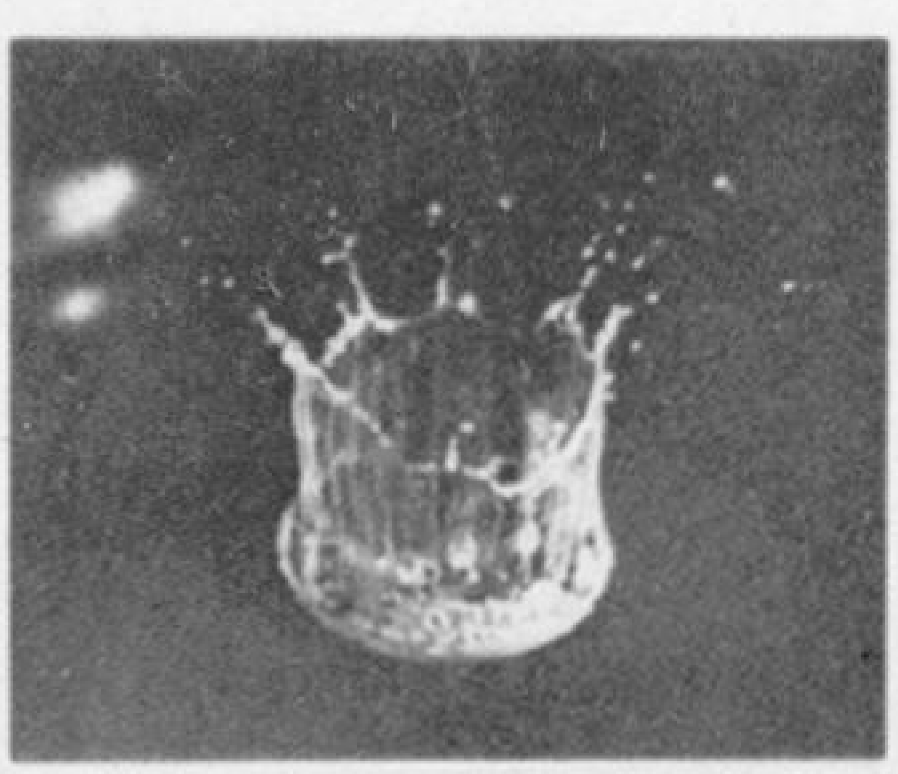
t=·0531 sec. (d



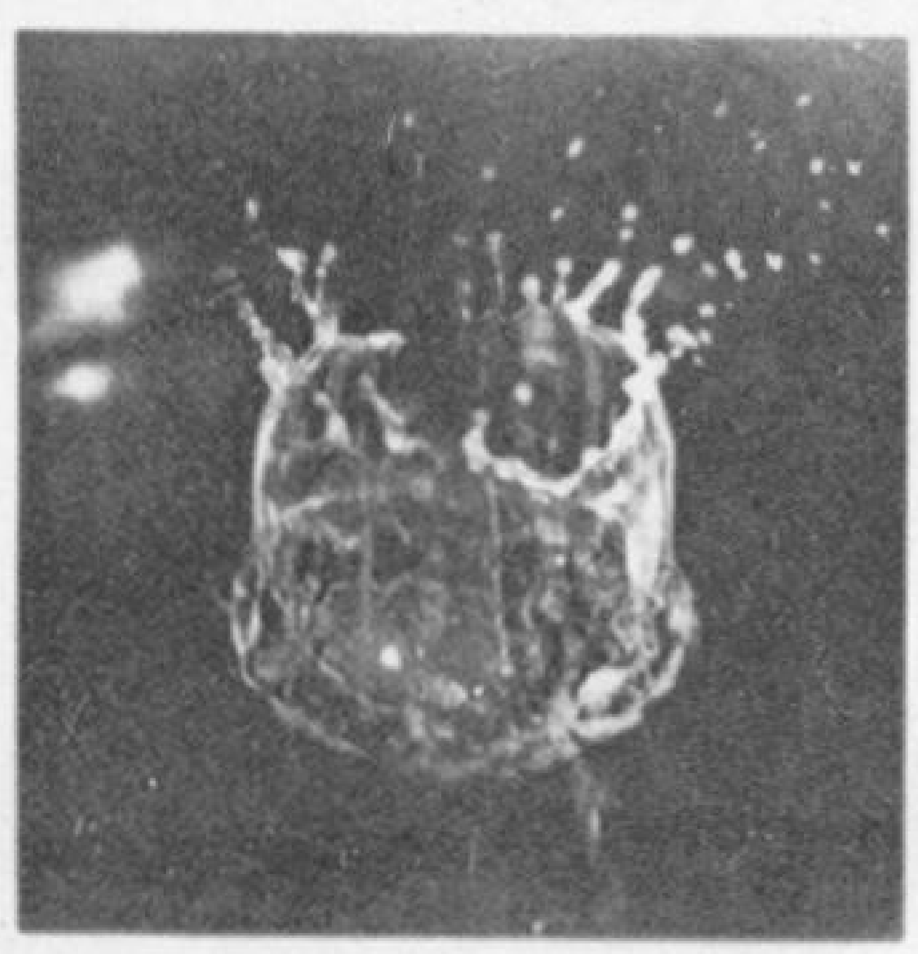
16

Sub-group A.

1 (a)



3 (a)

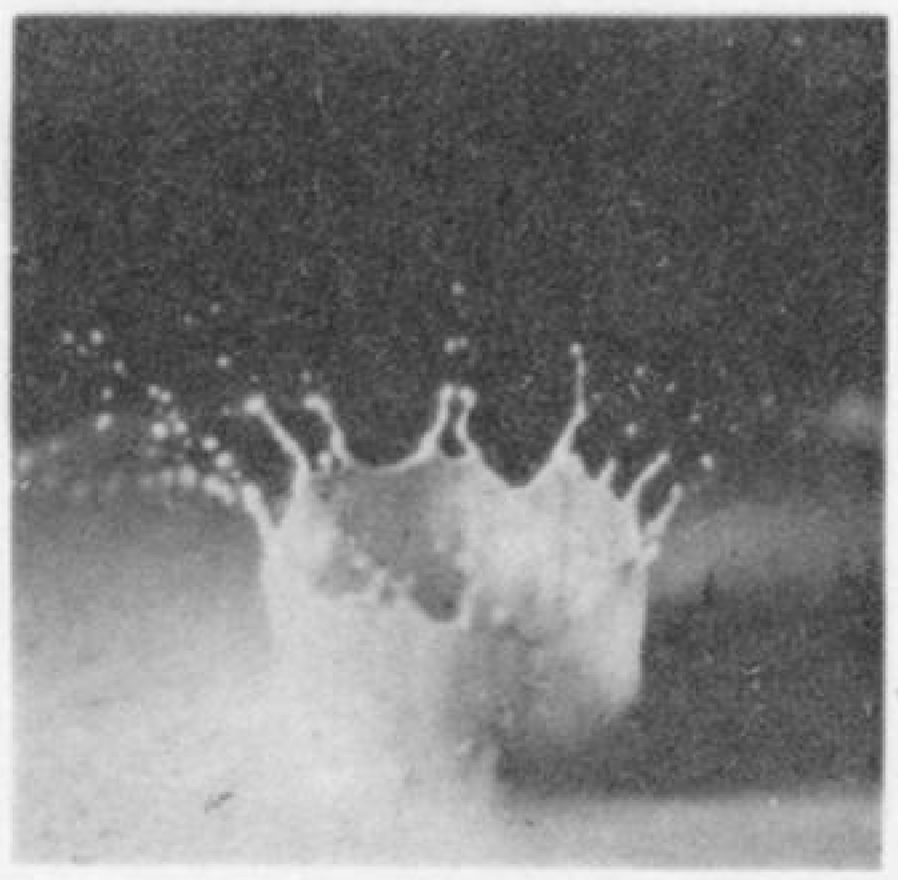


4 (a)

t = ·0126 *sec.* (*b*)

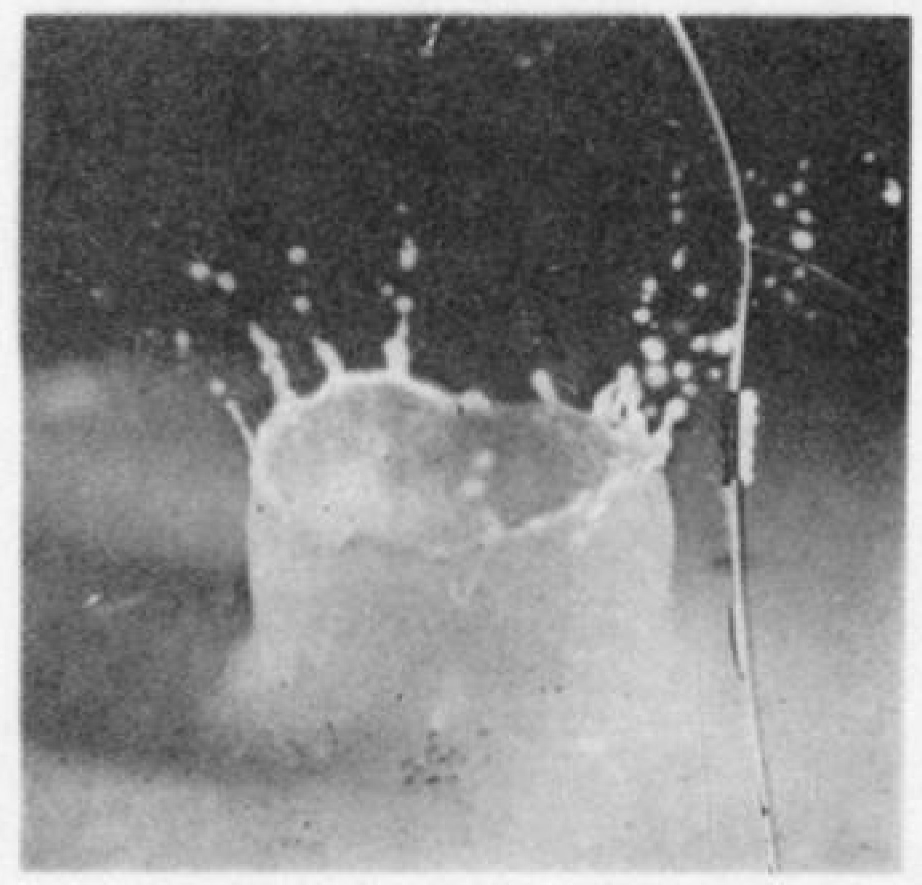
5

t = ·0165 *sec.* (*a*)



6

t = ·0185 *sec.* (*c*)



7

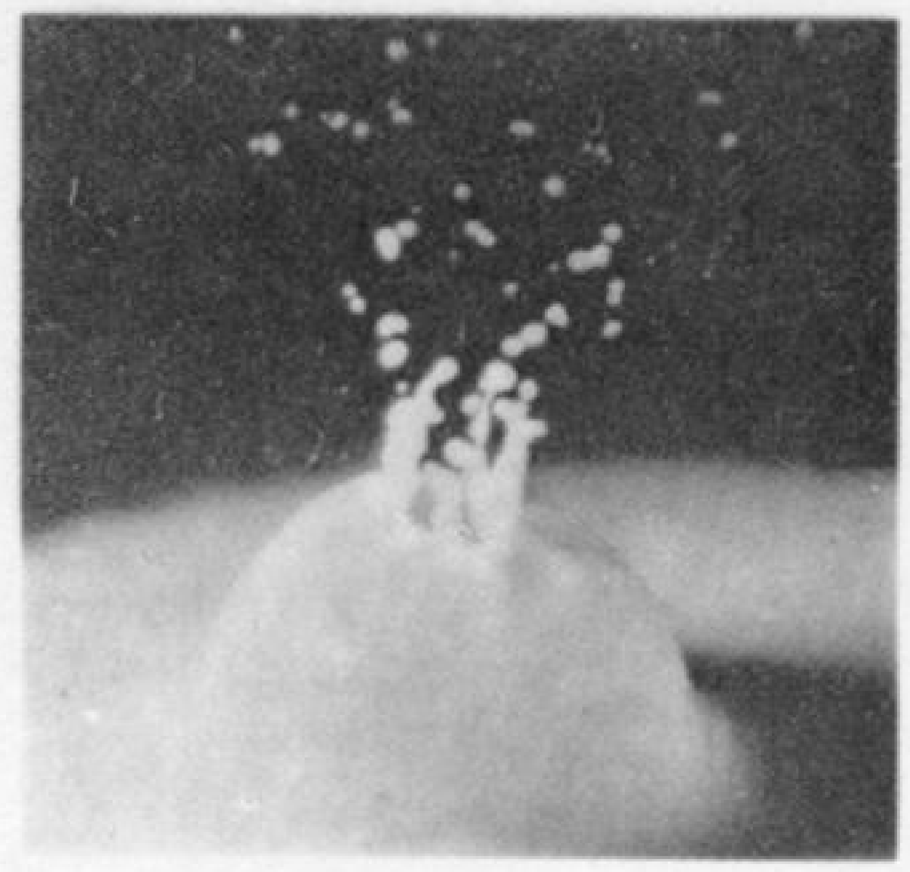
t = ·0312 *sec.* (*d*)

11

t = ·0351 *sec.* (*d*)

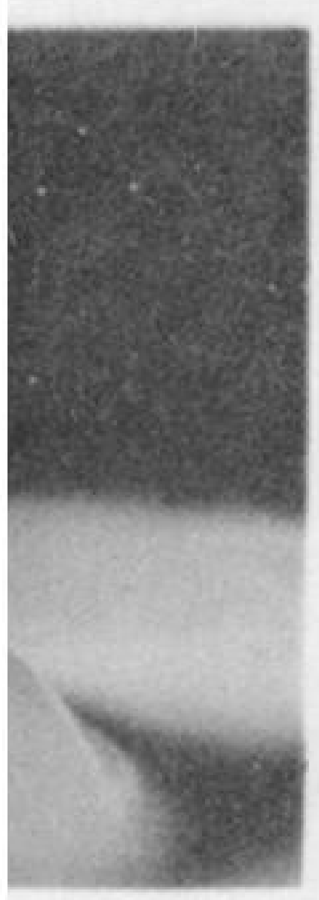
12

t = ·0398 *sec.* (*d*)



13

…c. (*d*)



t = ·0585 *sec.* (*d*)

17

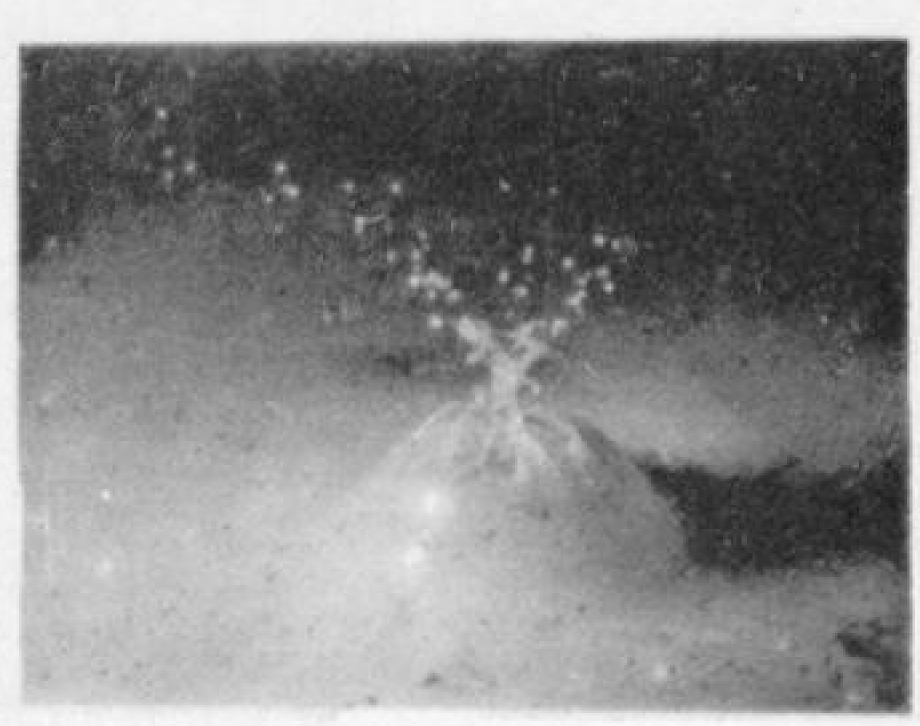
t = ·0704 *sec.* (*d*)

18

Sub group B.

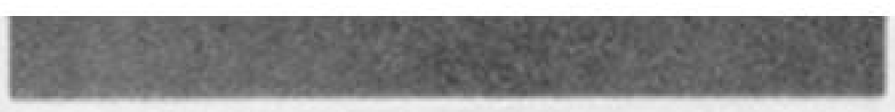
1 (*b*)

2 (*b*)

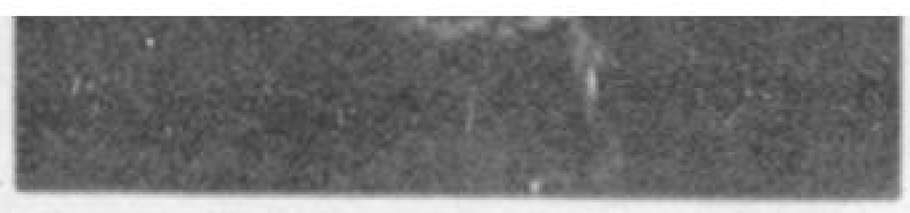


3 (*b*)

2 (a)



3 (a)



4 (a)

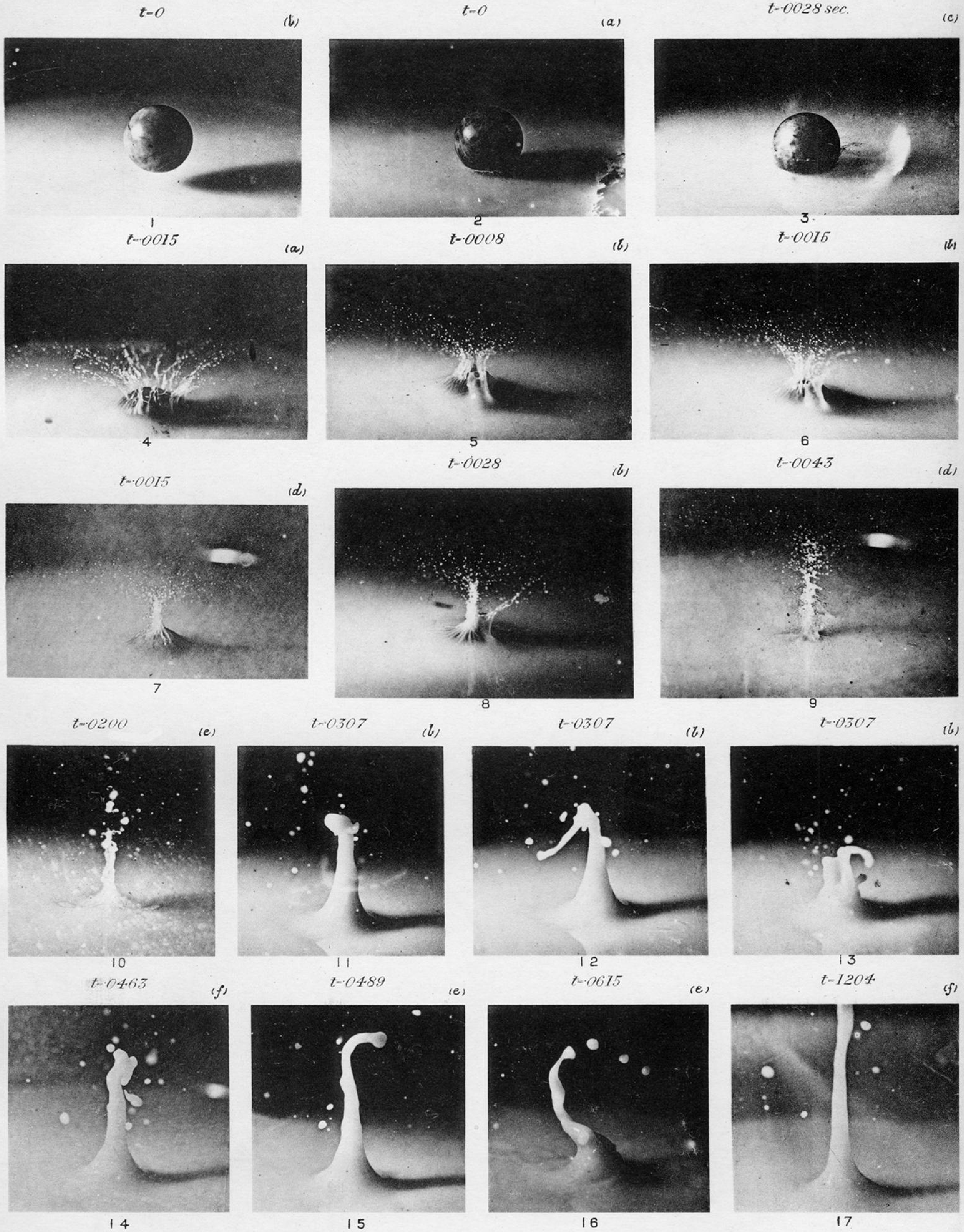
Series III.

1(b)

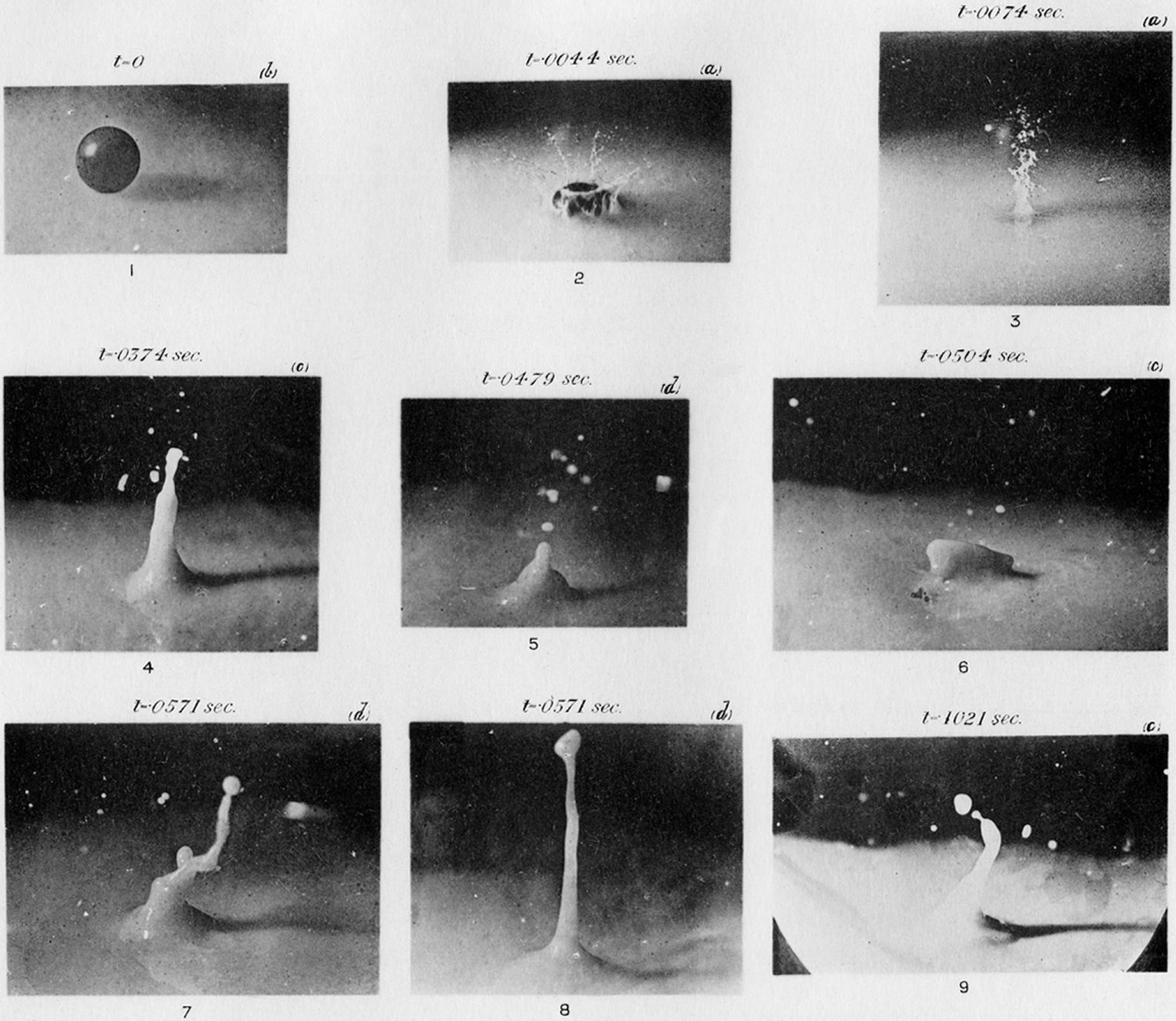
2(b)

3(b)

III.

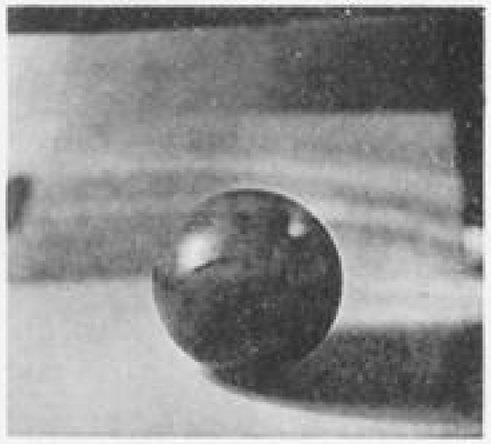

t-0 (b)
t-0 (a)
t-·0028 sec. (c)
1
2
3
t-·0015 (a)
t-·0008 (b)
t-·0015 (b)
4
5
6
t-·0015 (d)
t-·0028 (b)
t-·0043 (d)
7
8
9
t-·0200 (e)
t-·0307 (b)
t-·0307 (b)
t-·0307 (b)
10
11
12
13
t-·0463 (f)
t-·0489 (e)
t-·0615 (e)
t-·1204 (f)
14
15
16
17

Series IV.


t = 0
(b)
1
t = ·0044 sec.
(a)
2
t = ·0074 sec.
(a)
3
t = ·0374 sec.
(c)
4
t = ·0479 sec.
(d)
5
t = ·0504 sec.
(c)
6
t = ·0571 sec.
(d)
7
t = ·0571 sec.
(d)
8
t = ·1021 sec.
(c)
9

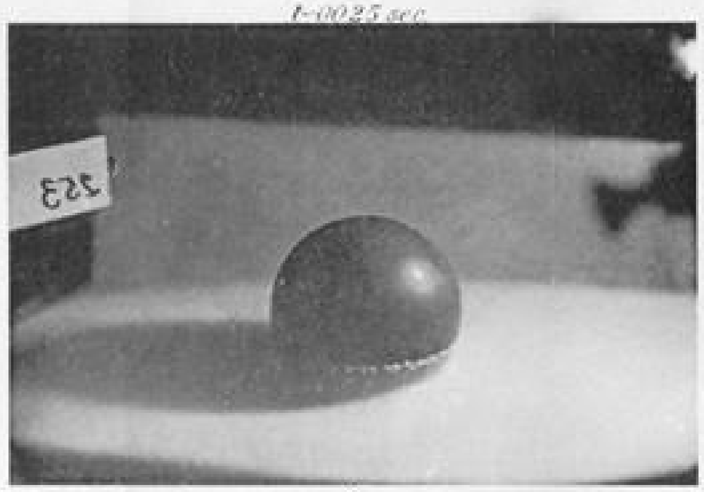
Series V

t = 0



1

t = ·0025 sec.

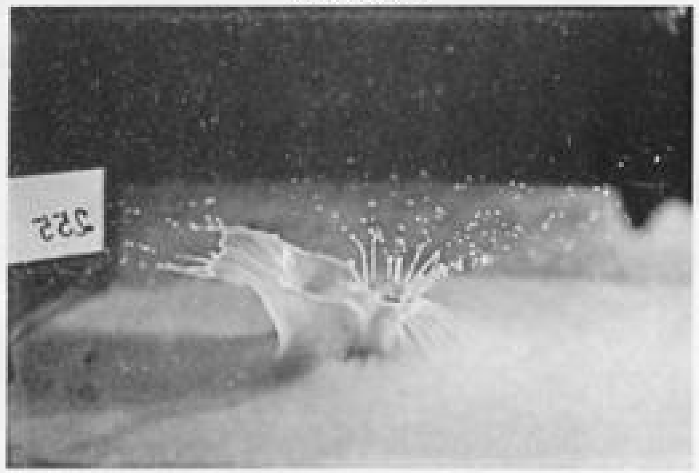


2

t = ·0080 sec.

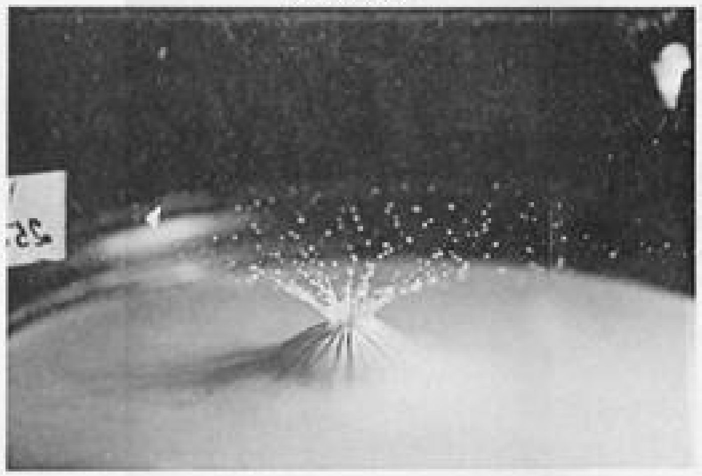
3

t = ·0110 sec.



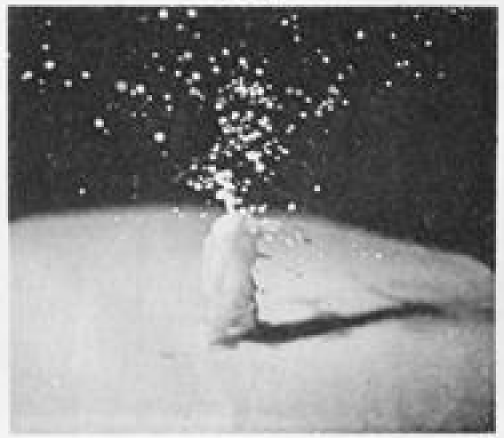
4

t = ·0174 sec.



5

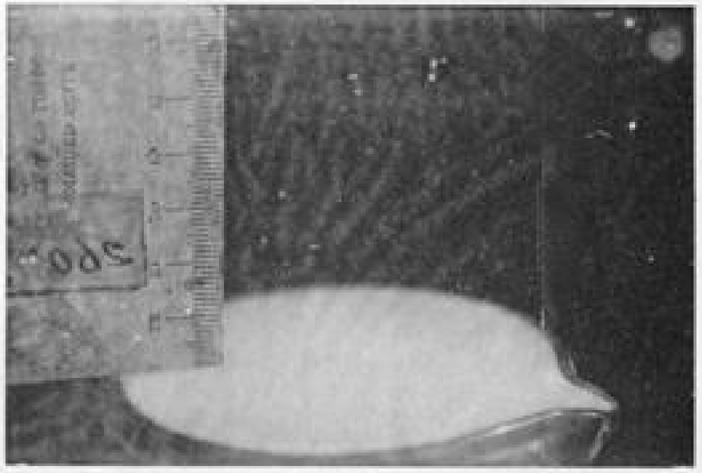
t = ·0242 sec.



6

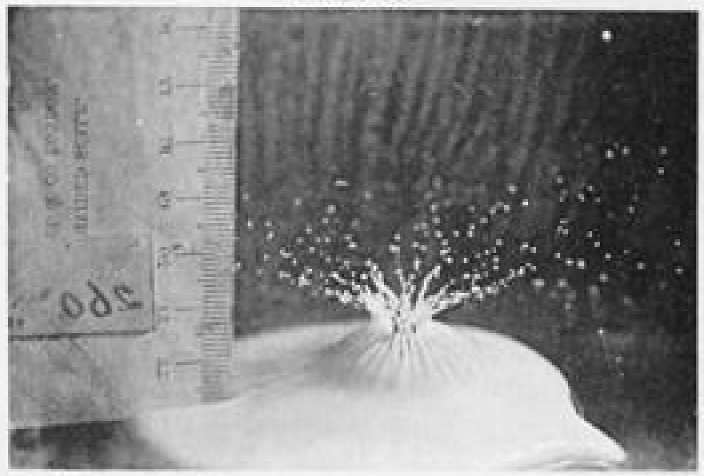
t = ·0391 sec.

7



8

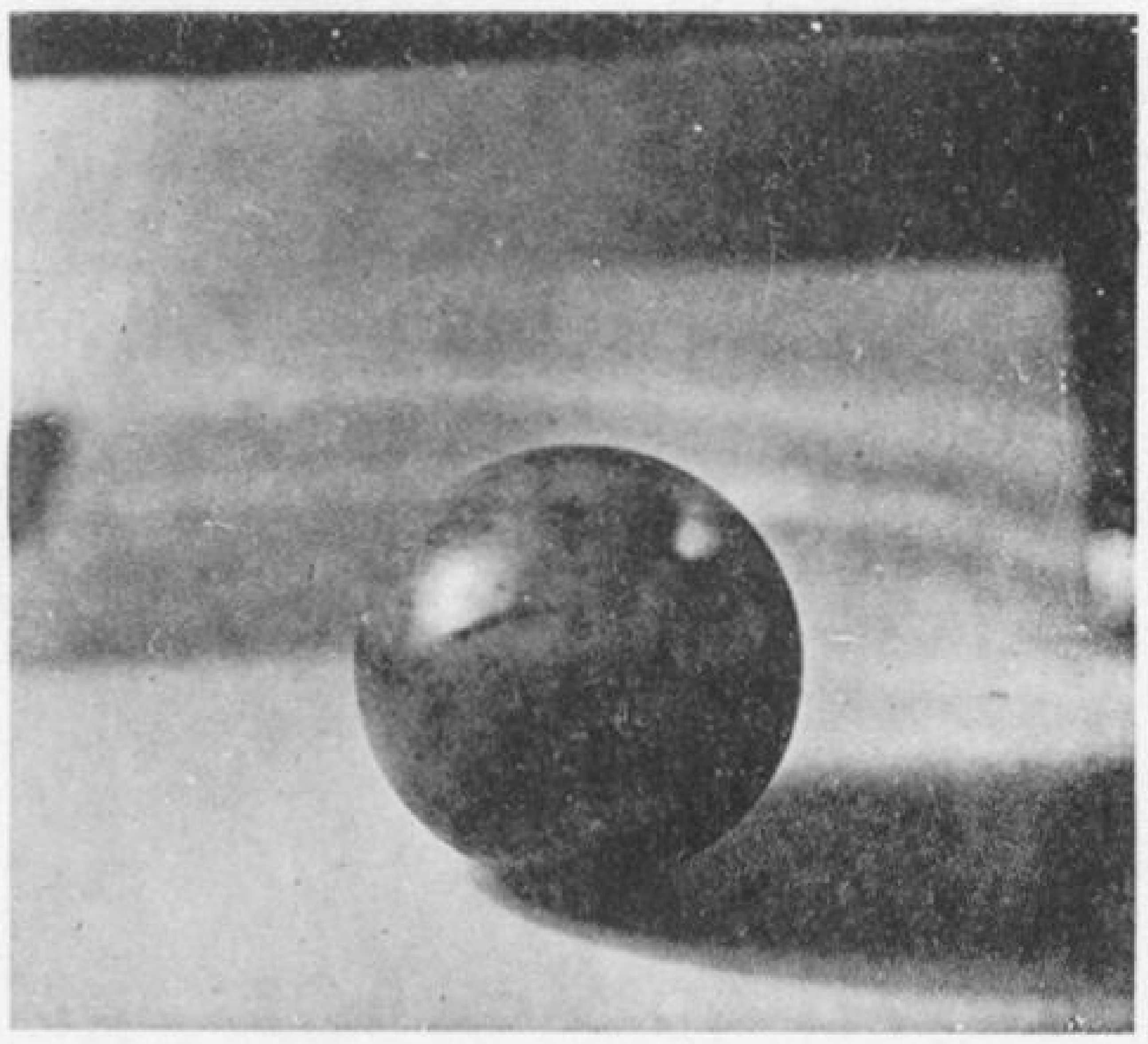
t = ·0110 sec.



9

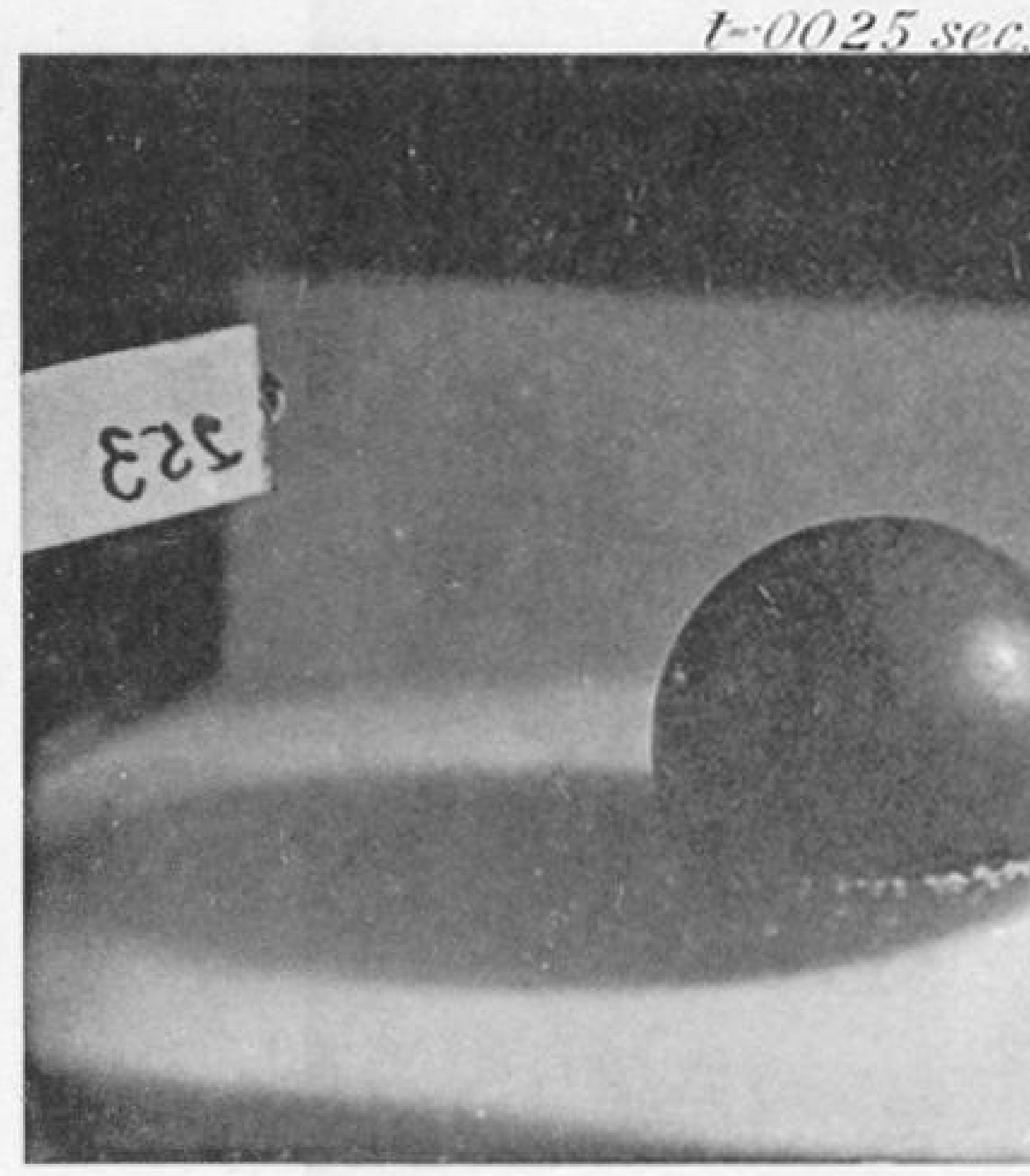
Series VI.

t=0



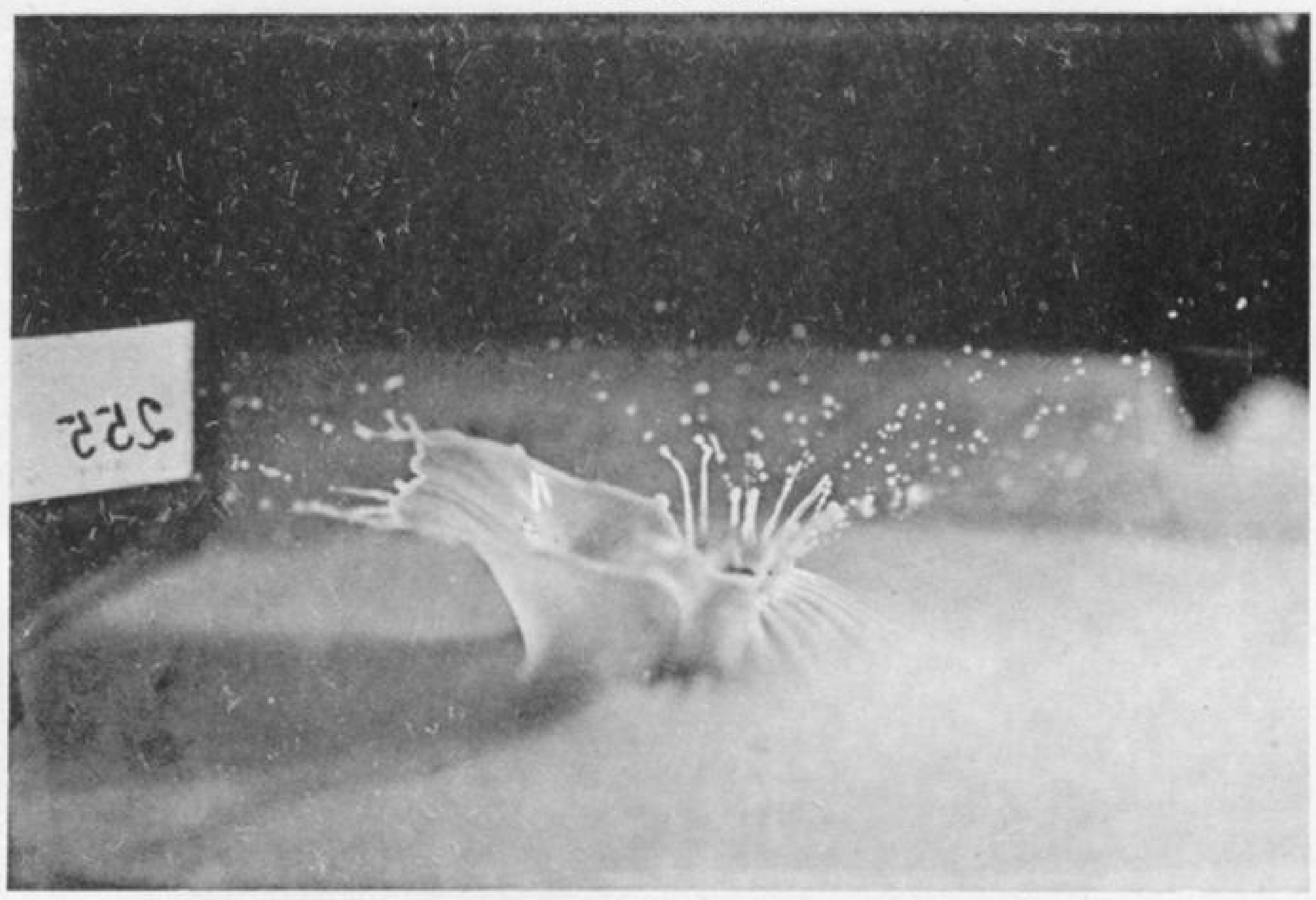
1

t=·0025 sec.



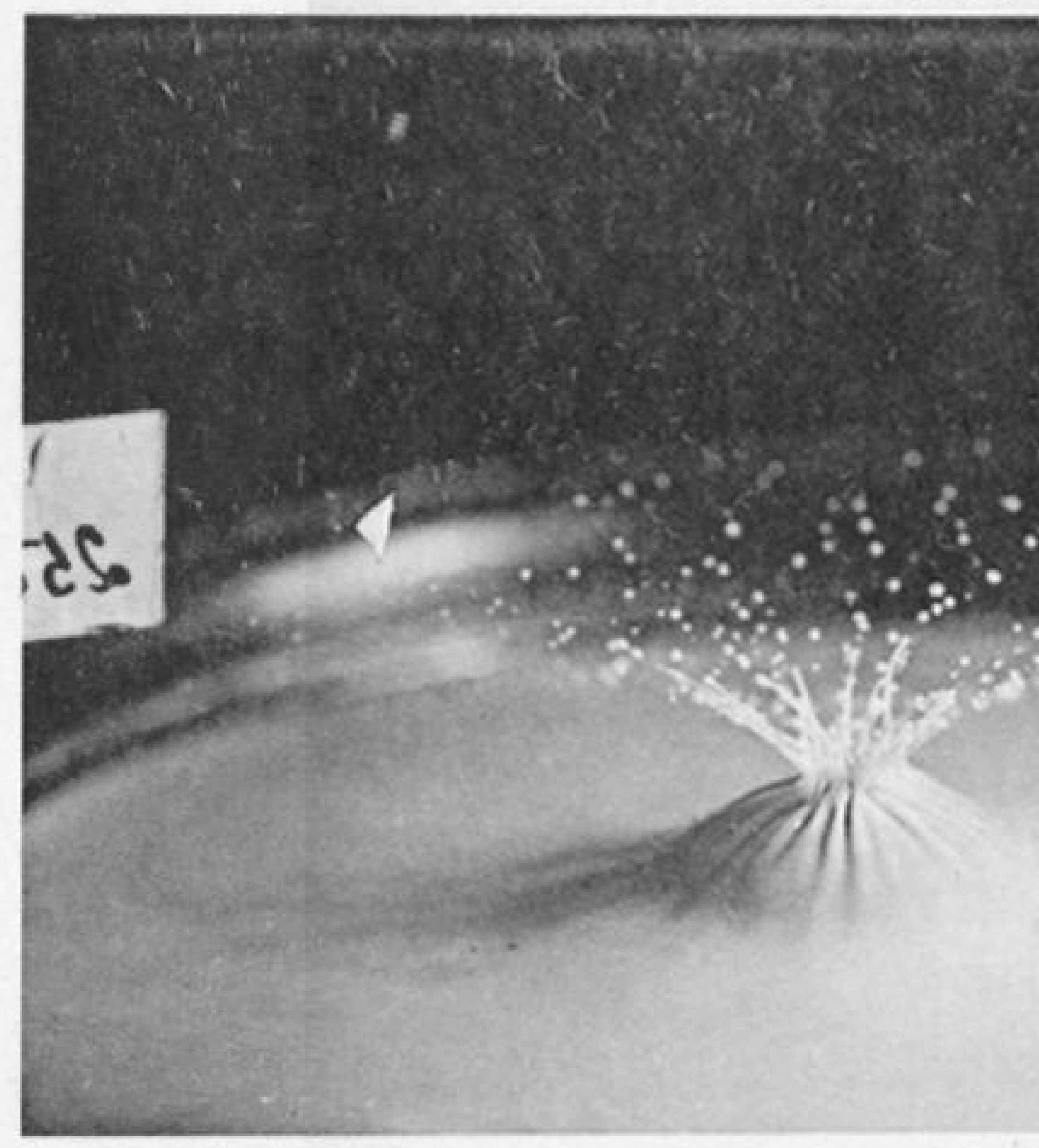
2

t=·0110 sec.



4

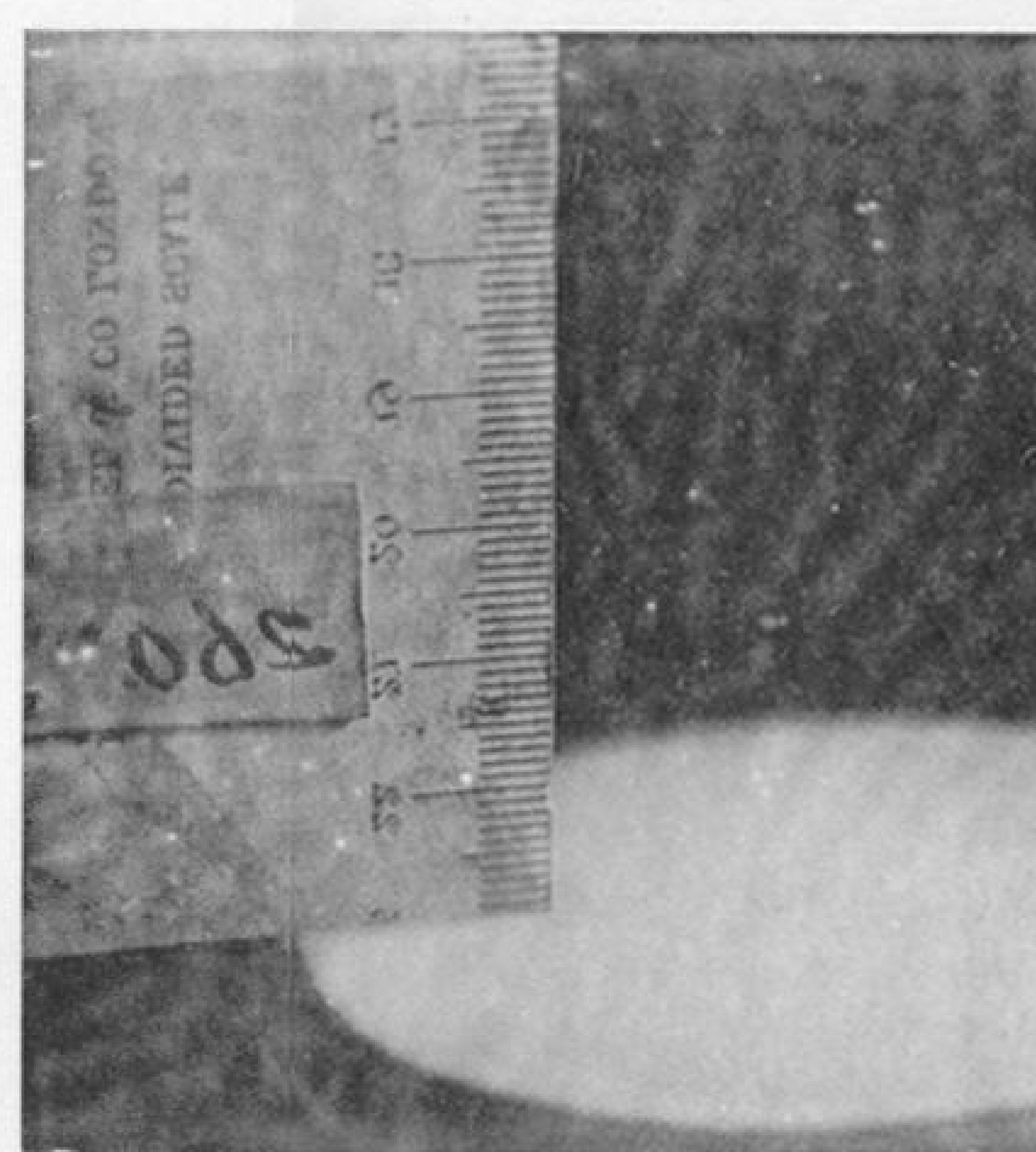
t=·0134 sec.



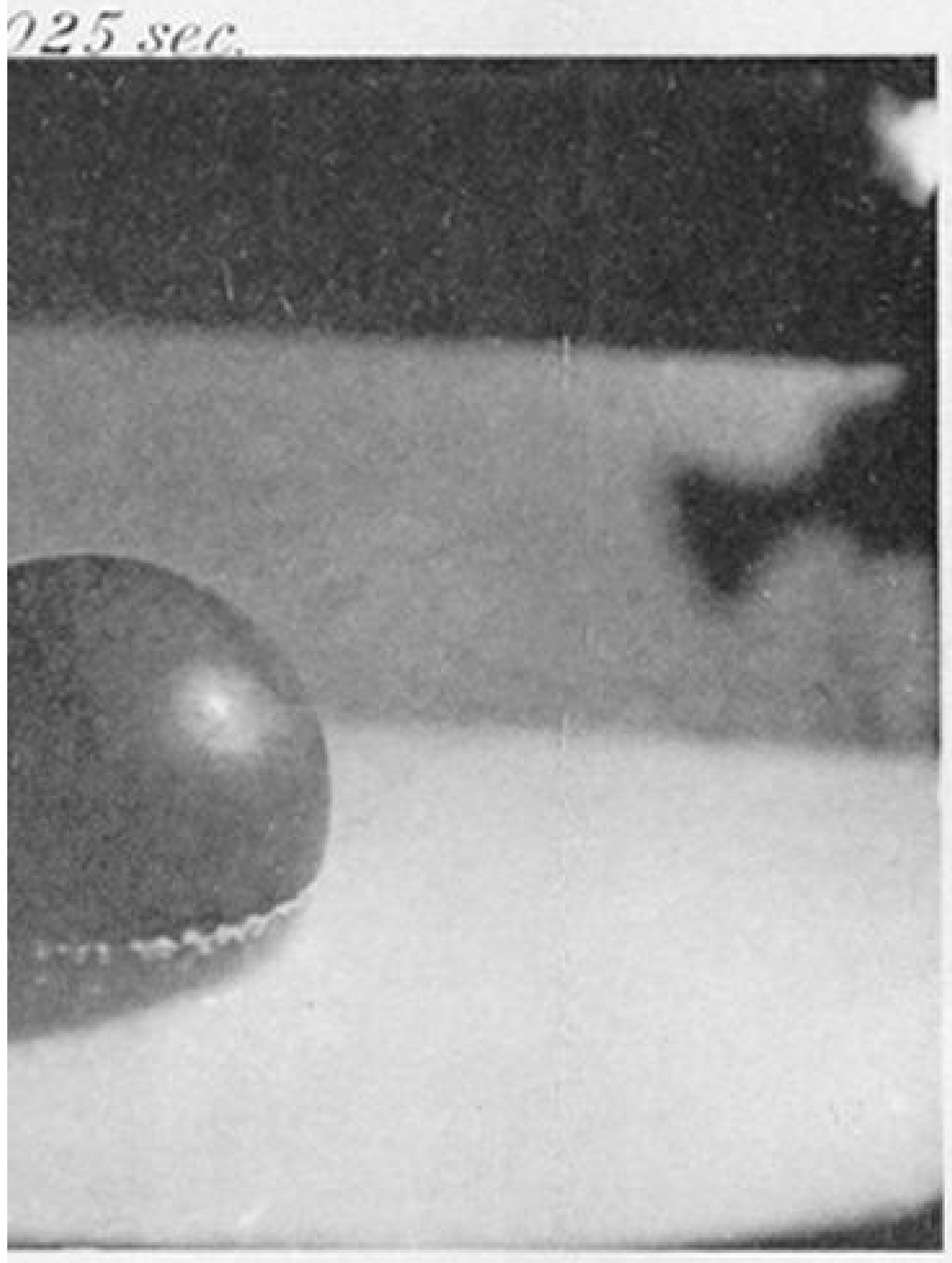
5

t=·0391 sec.

7

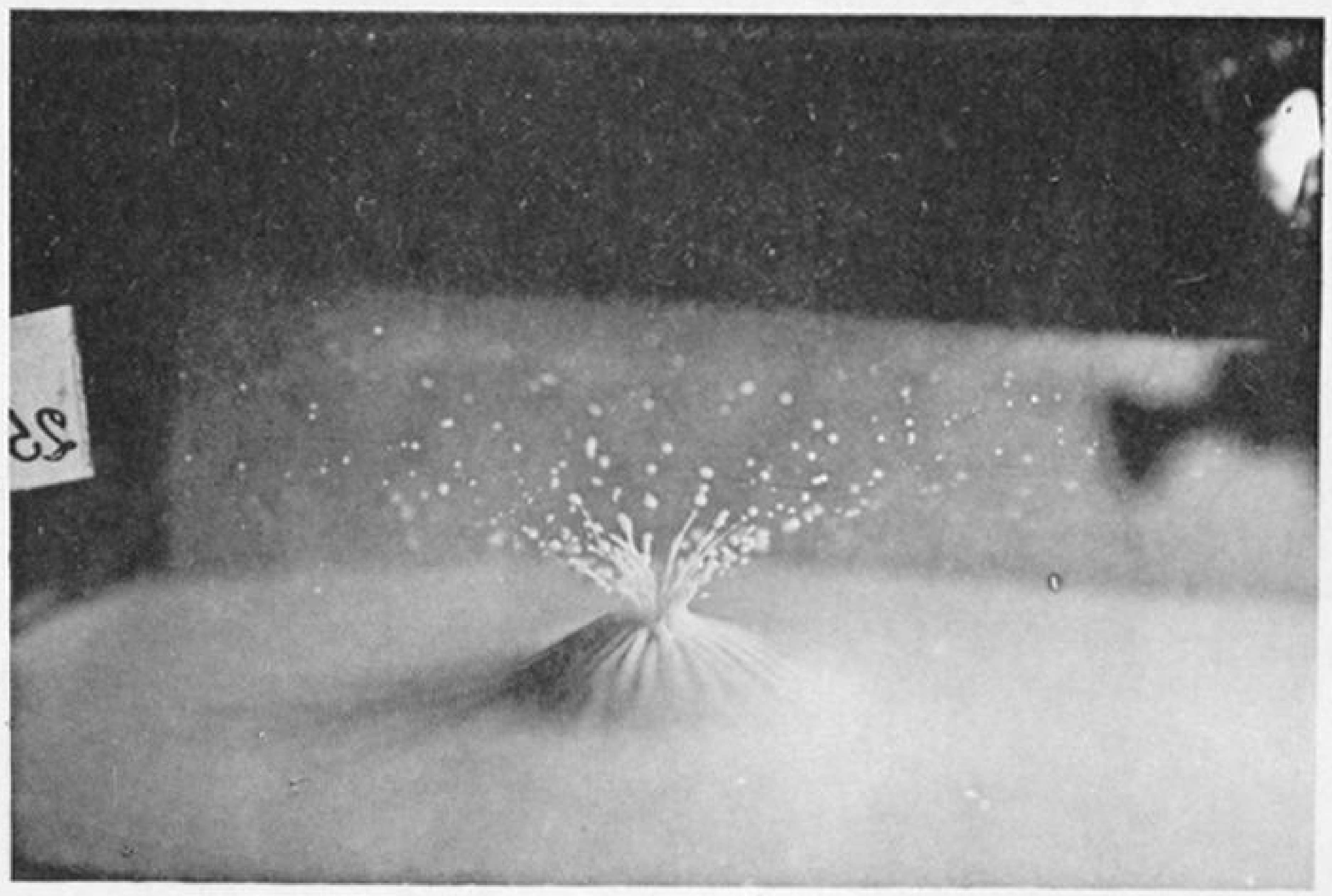


025 sec.



2

t = ·0080 sec

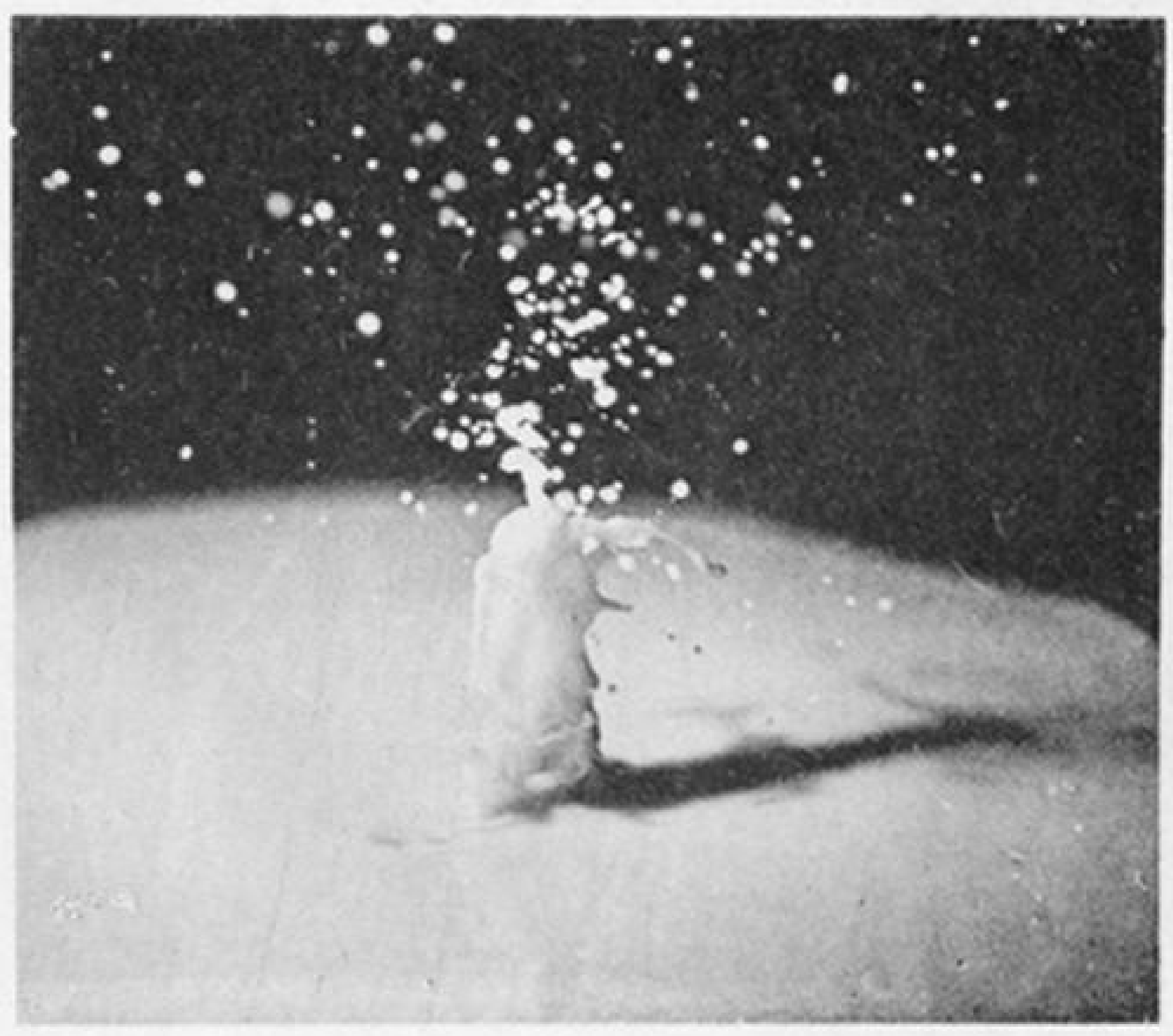


3

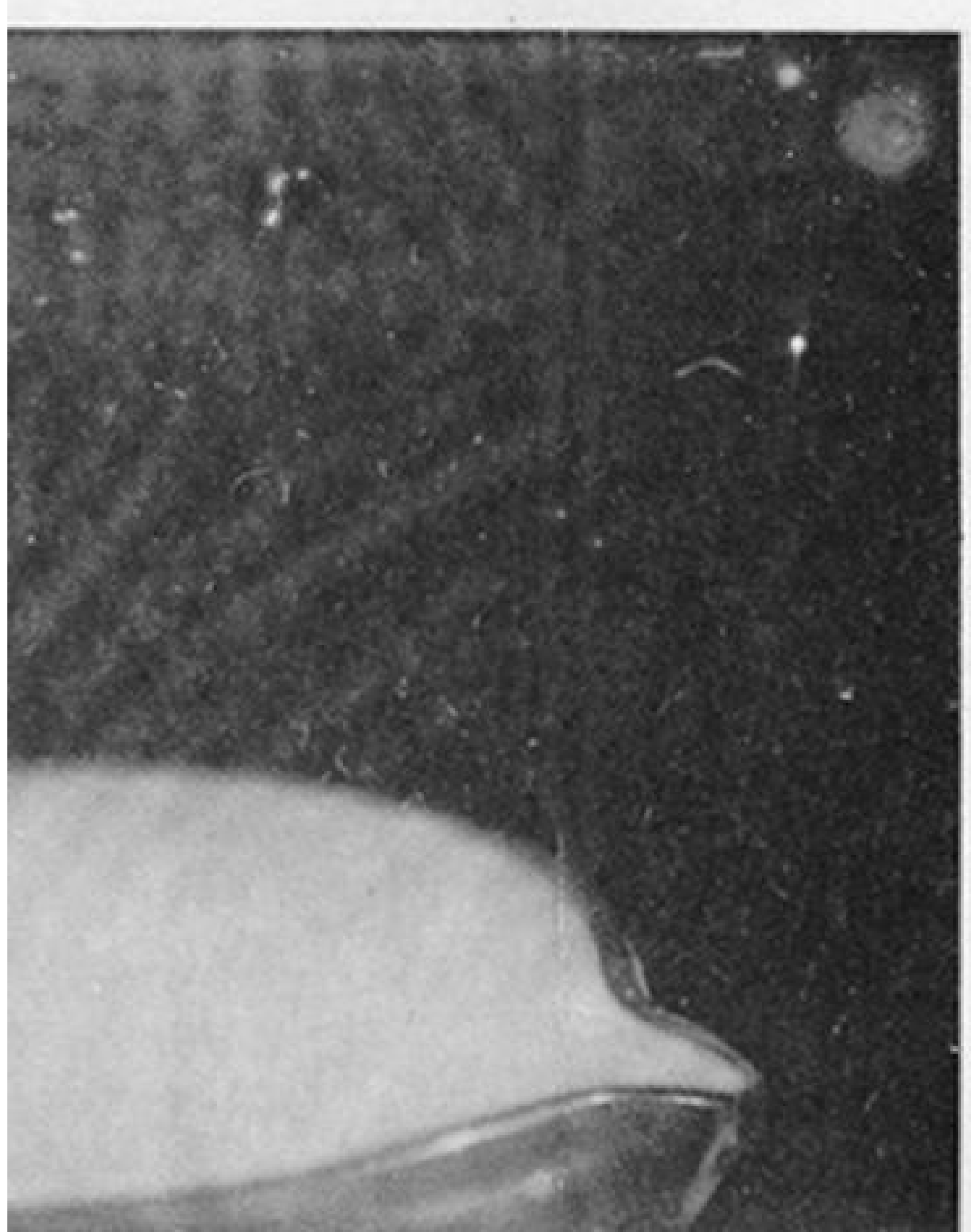
34 sec.

5

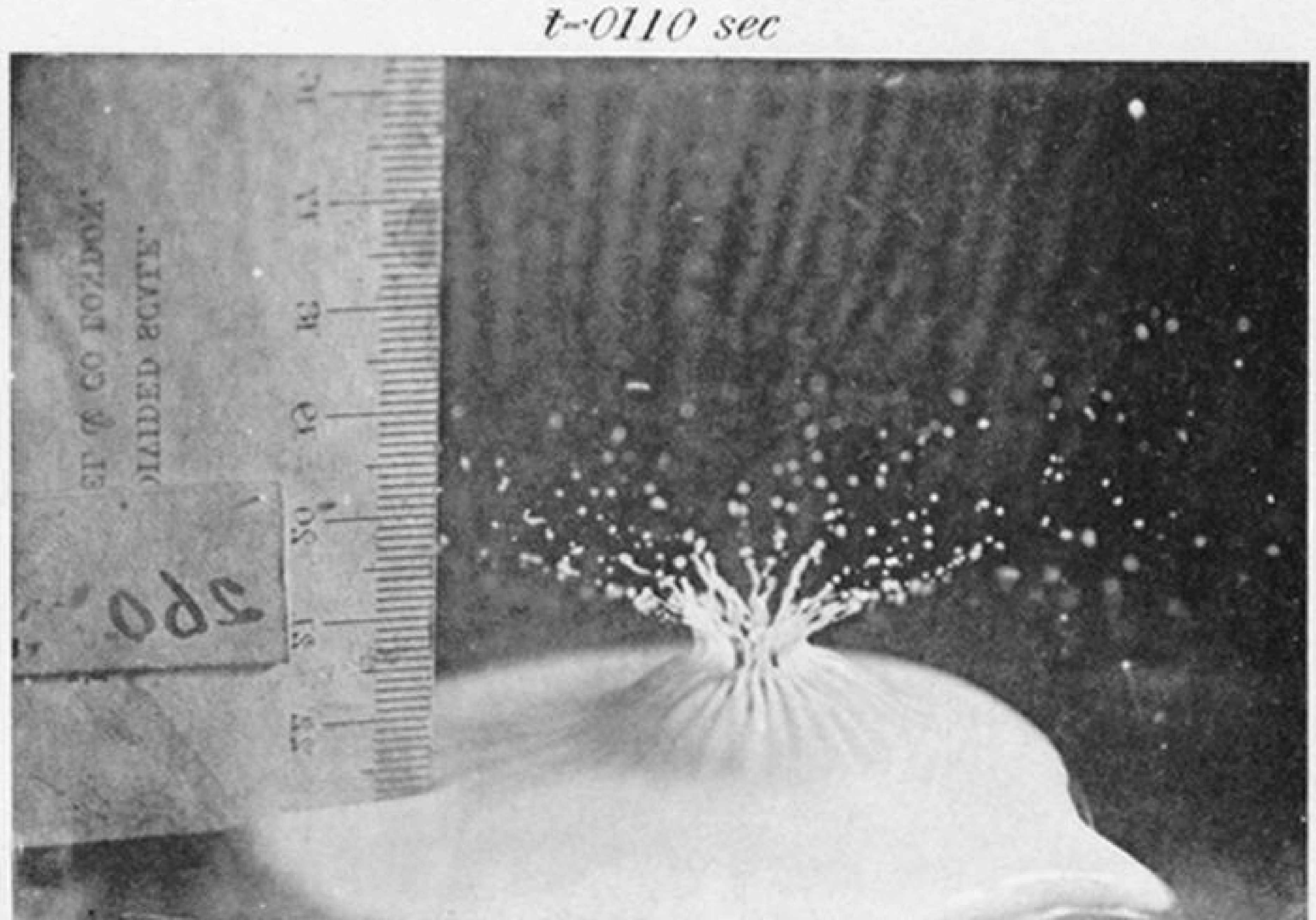
t = ·0242 sec.

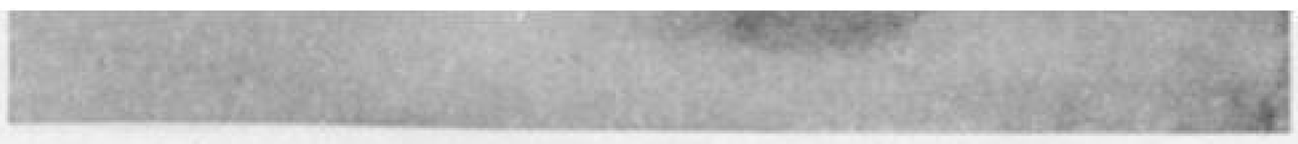


6

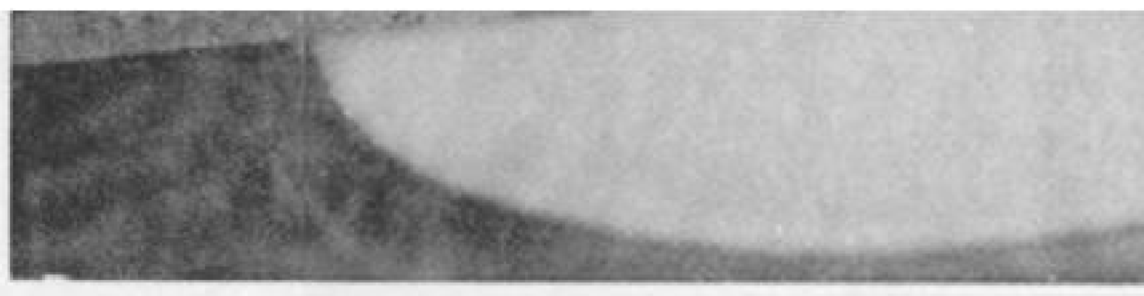


t = ·0110 sec



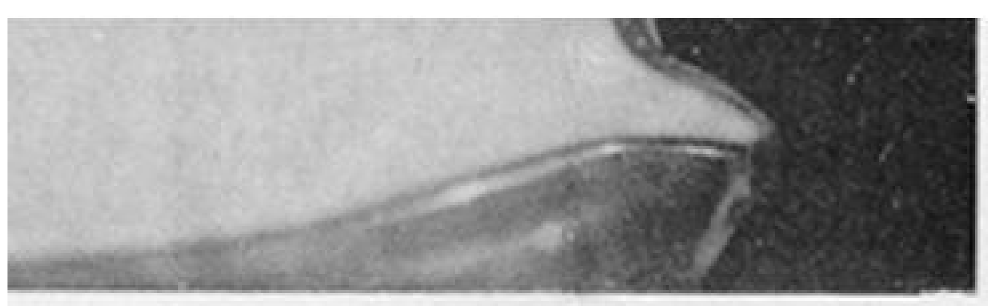


7

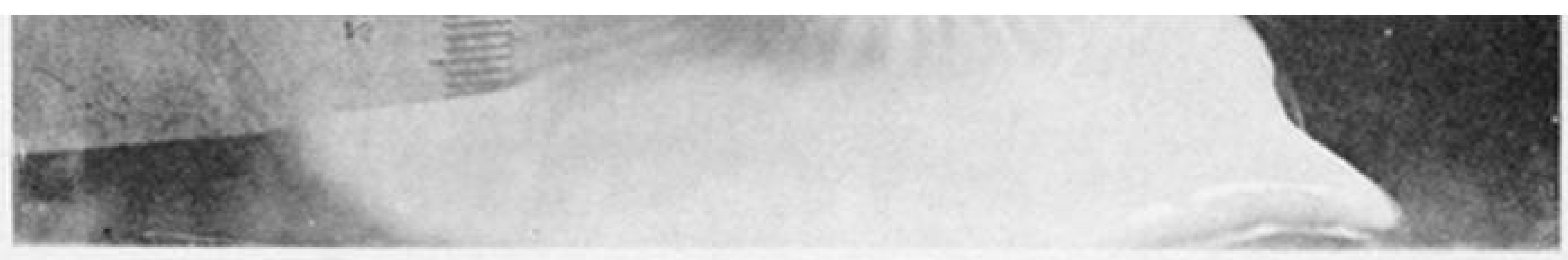


8

Series VI



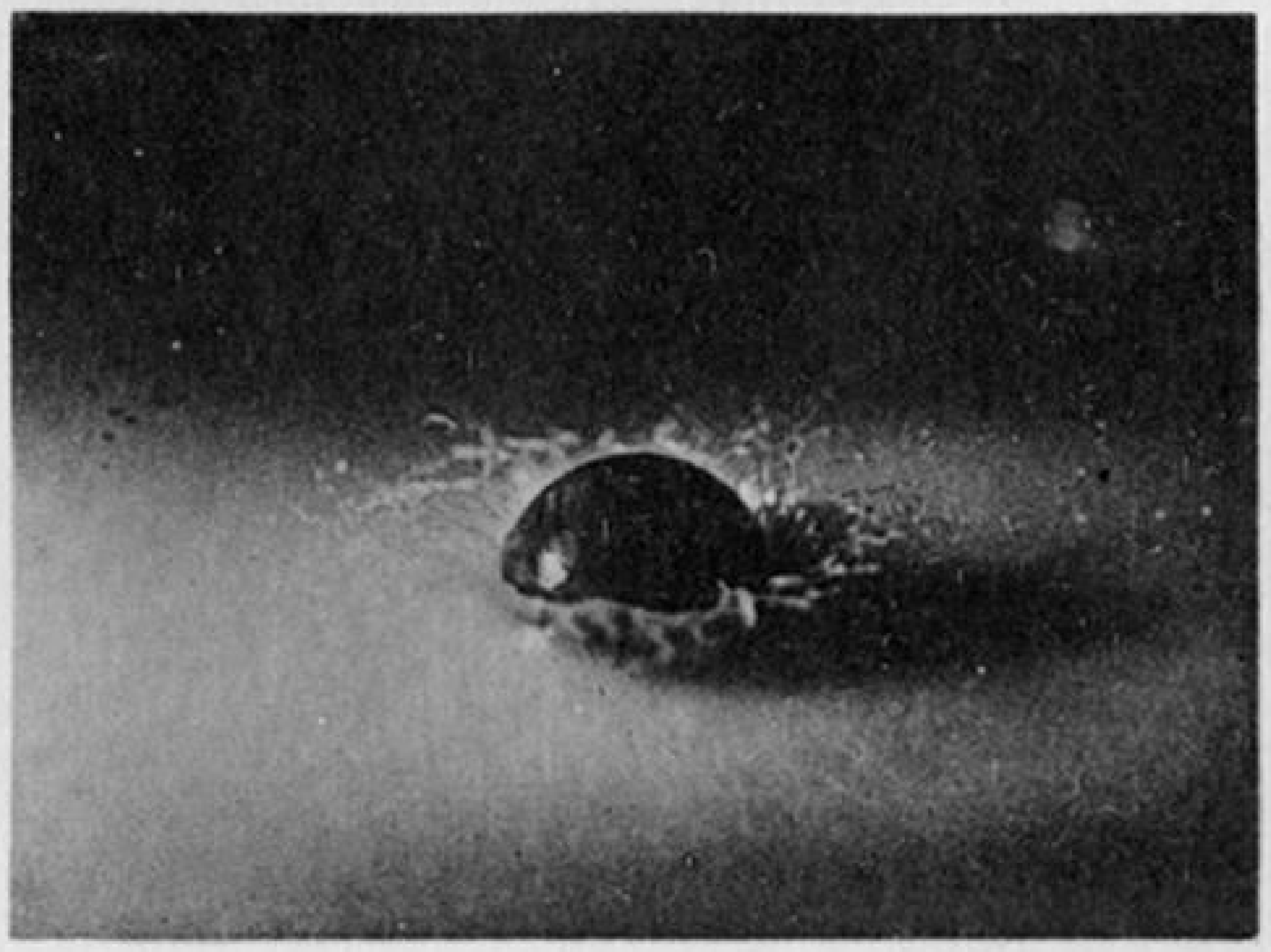
8



9

ies VI.

t=0



1

t=·0029 sec.

2

t=·0068 sec.

3

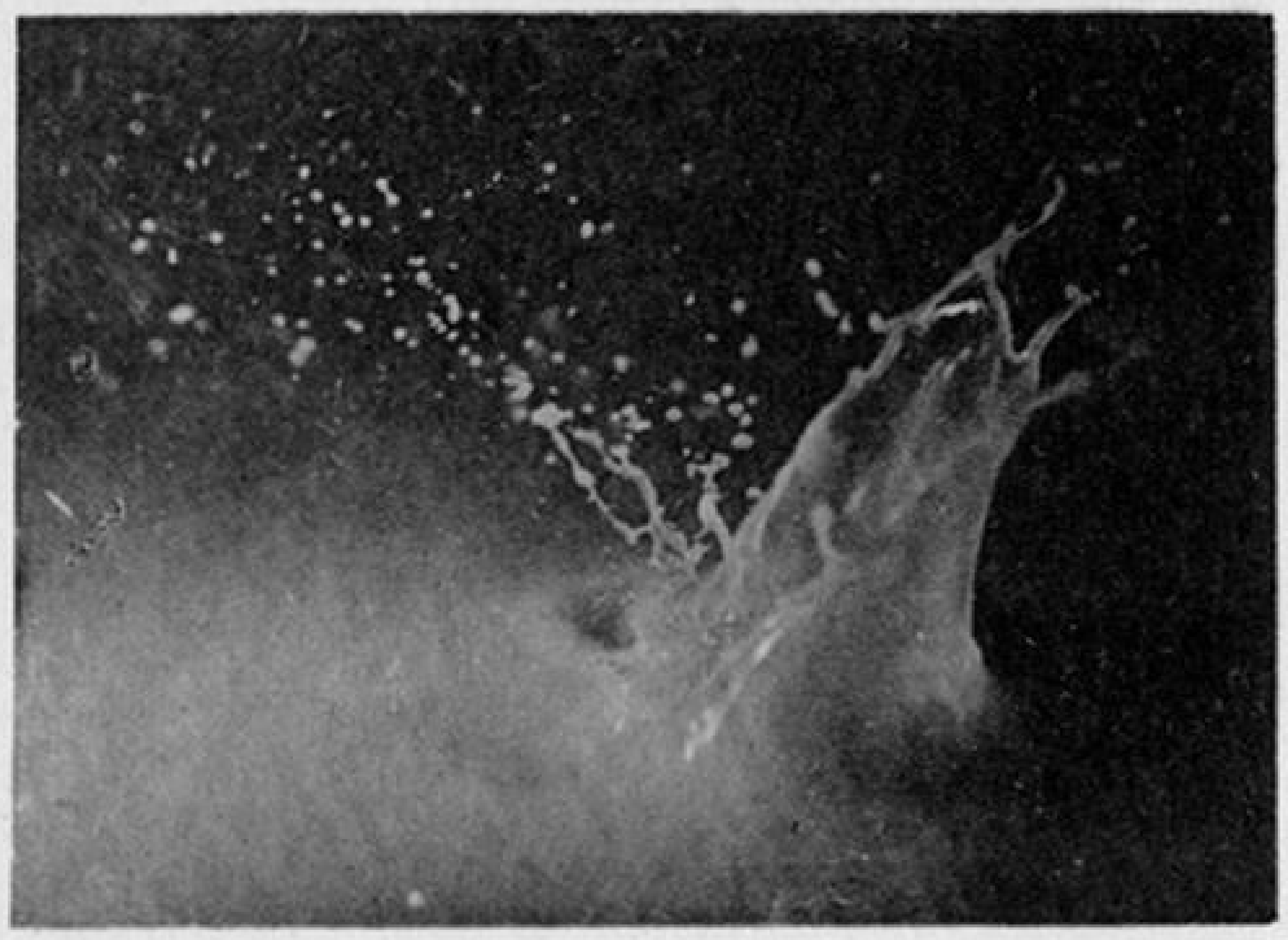
t=·0074 sec

4

t=·0103 sec.

5

t=·0147



6

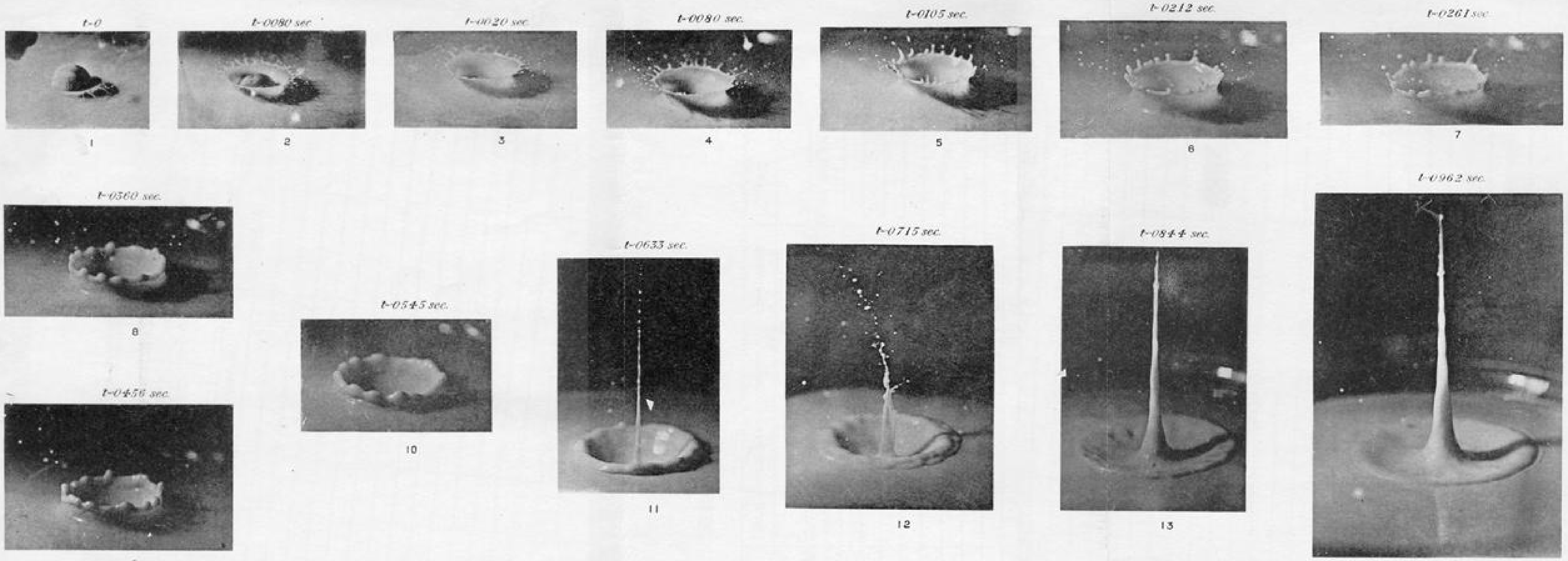
t=·0258

7

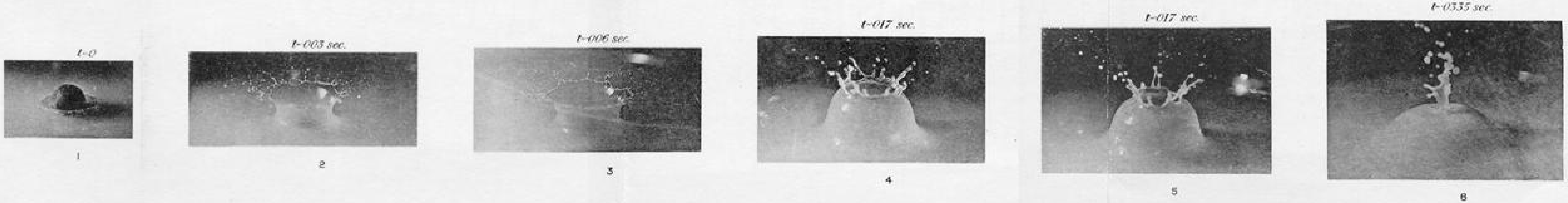
t=·0367

8

Series VII.



Series VIII.



Series IX.

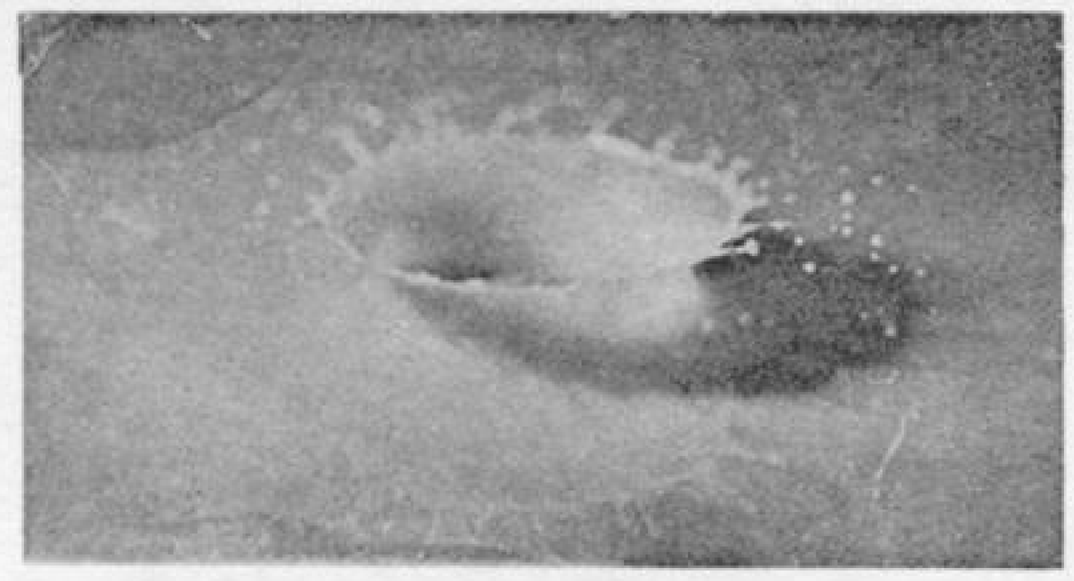
t=0

1

t=·0080 *sec.*

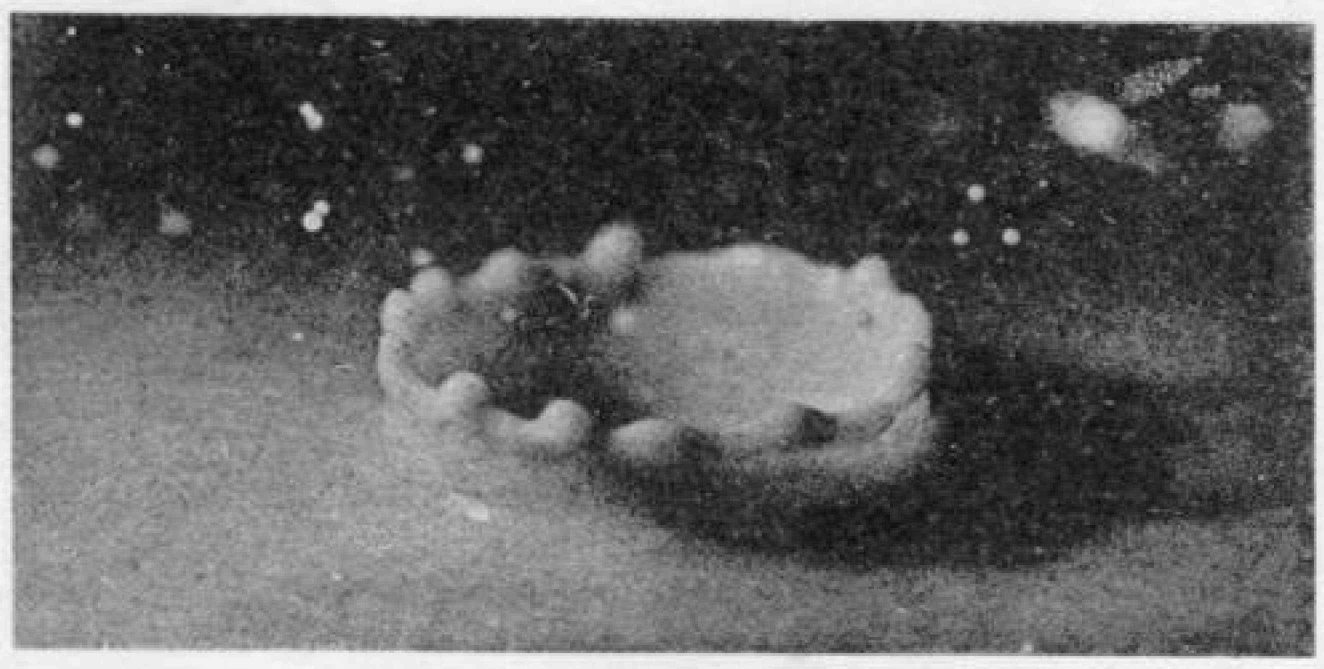
2

t=·0020 *sec.*



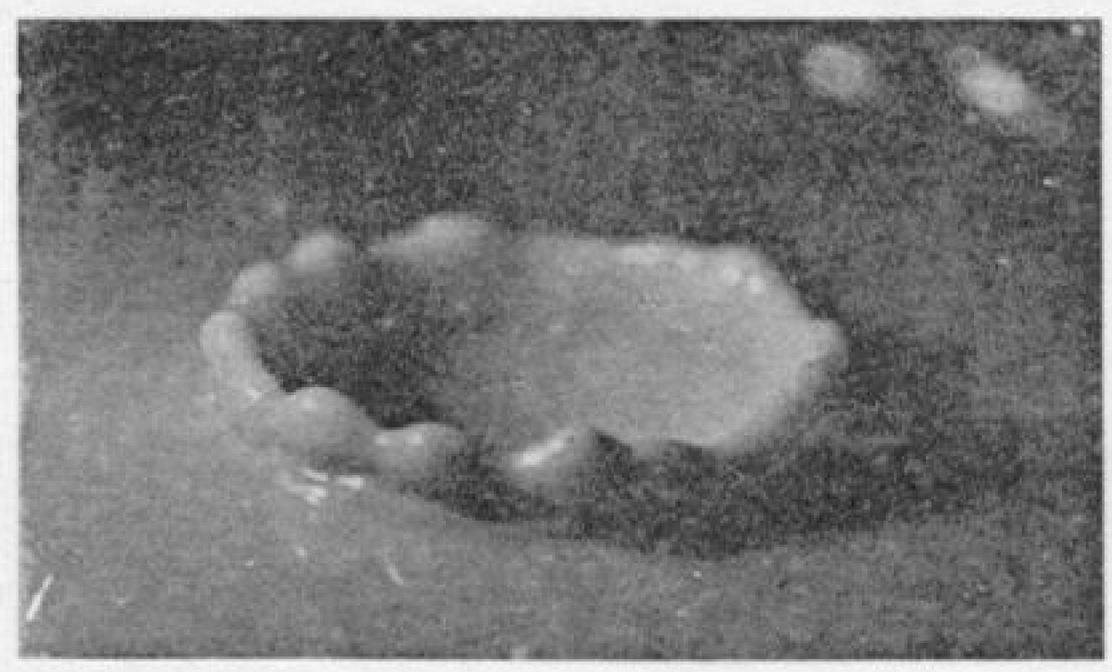
3

t=·0360 *sec.*



8

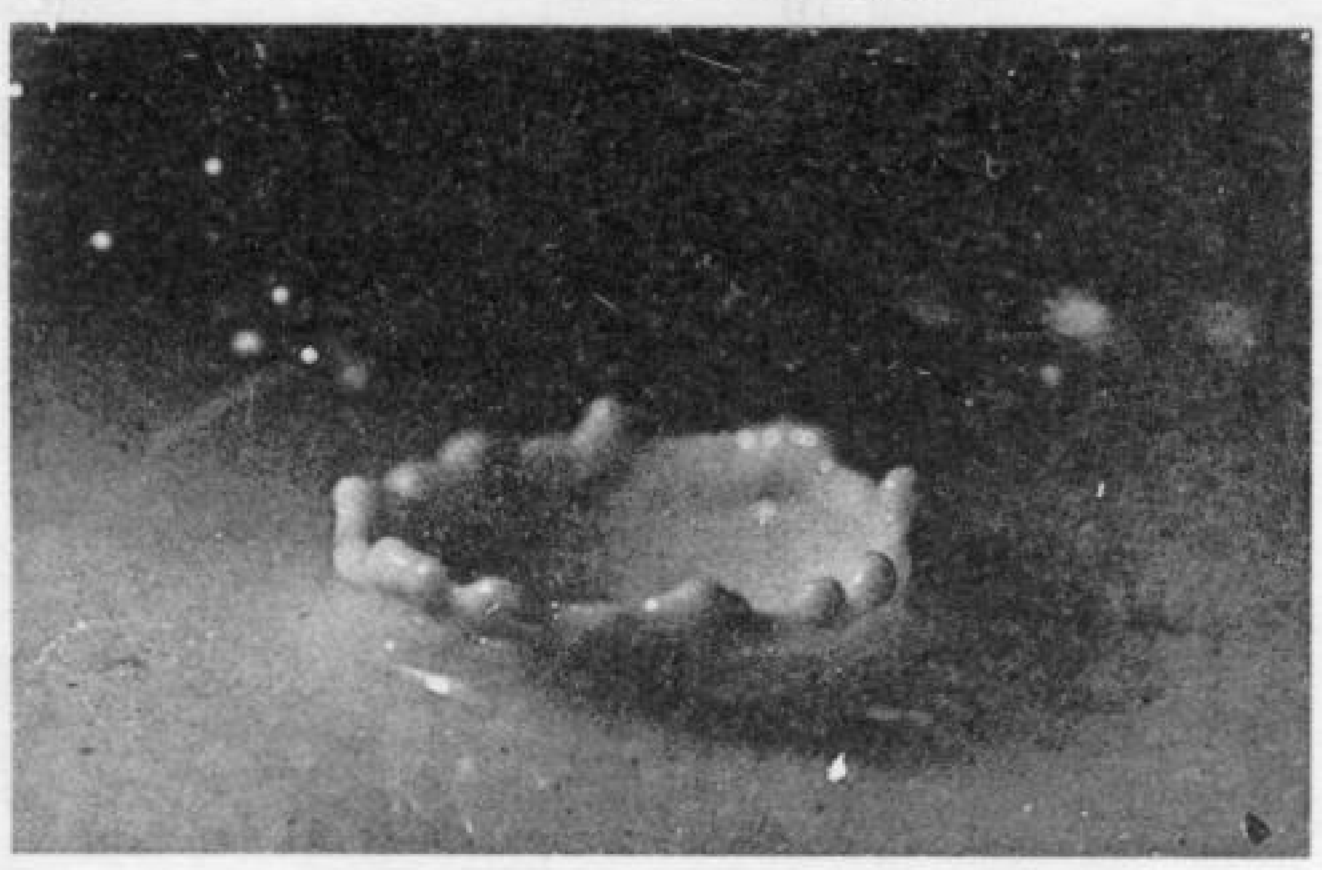
t=·0545 *sec.*



10

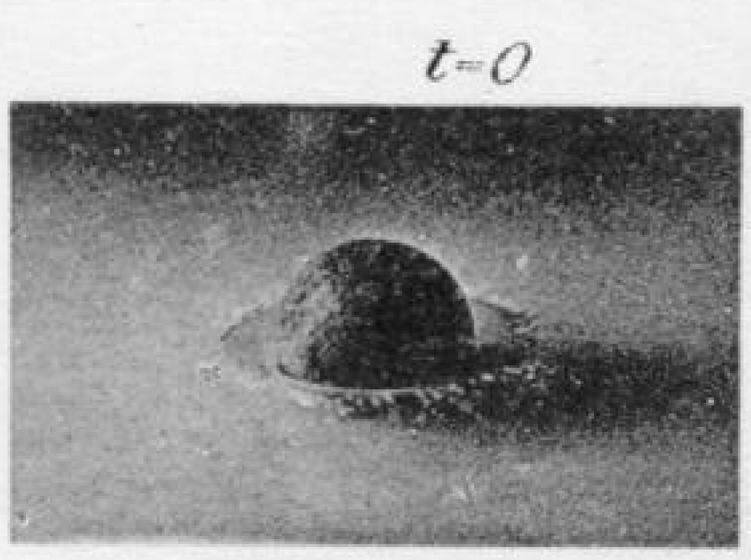
t=

t=·0456 *sec.*



9

t=0

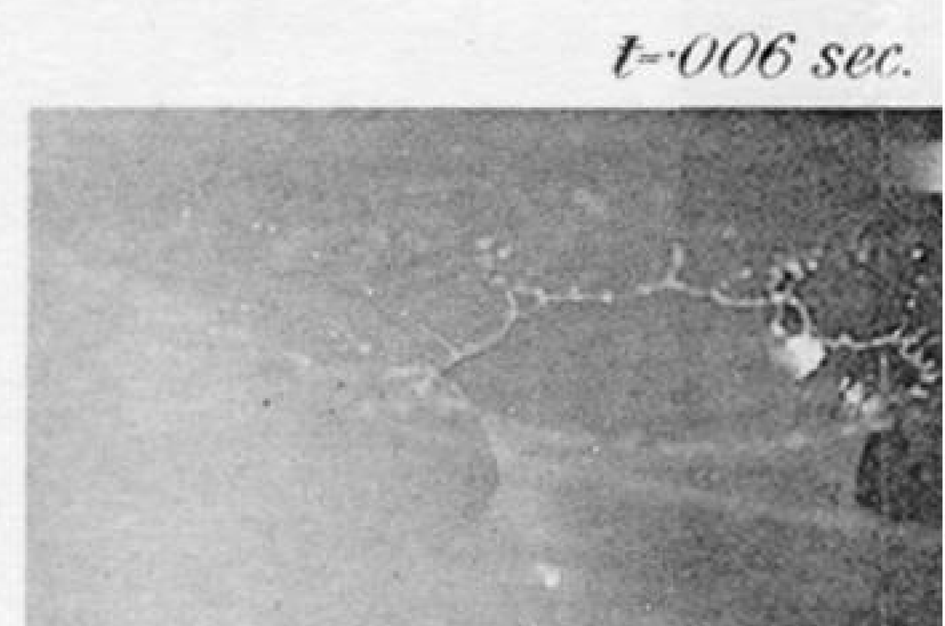


1

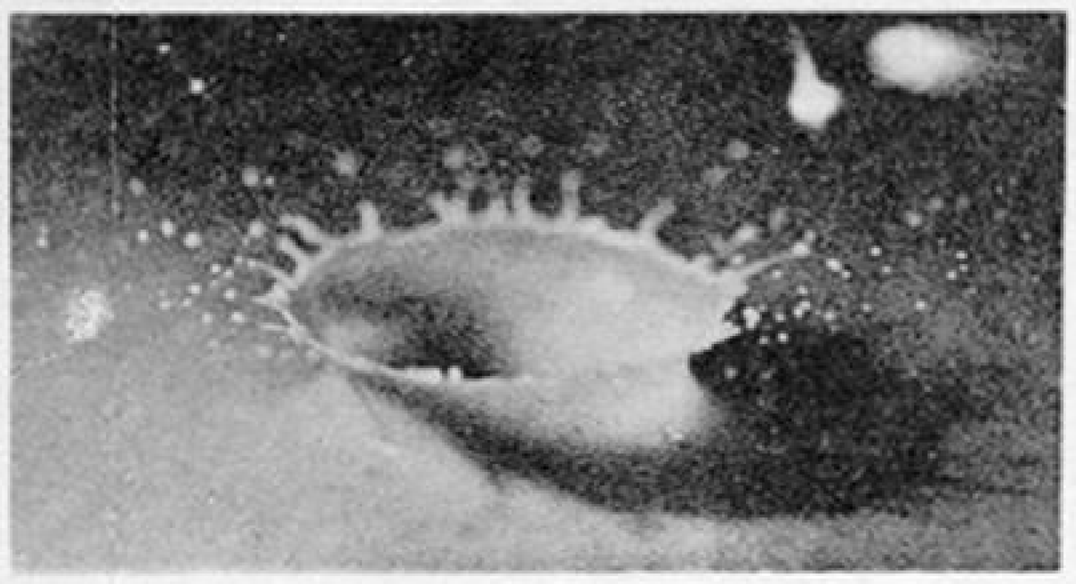
t=·003 *sec.*

2

t=·006 *sec.*

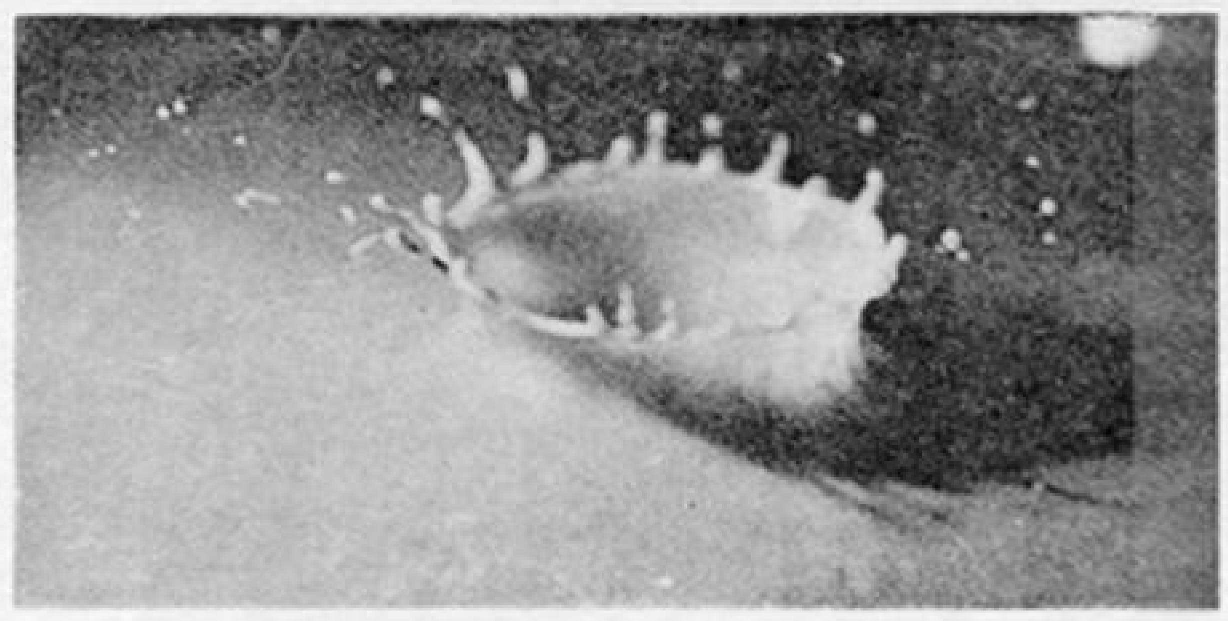


t-·0080 sec.



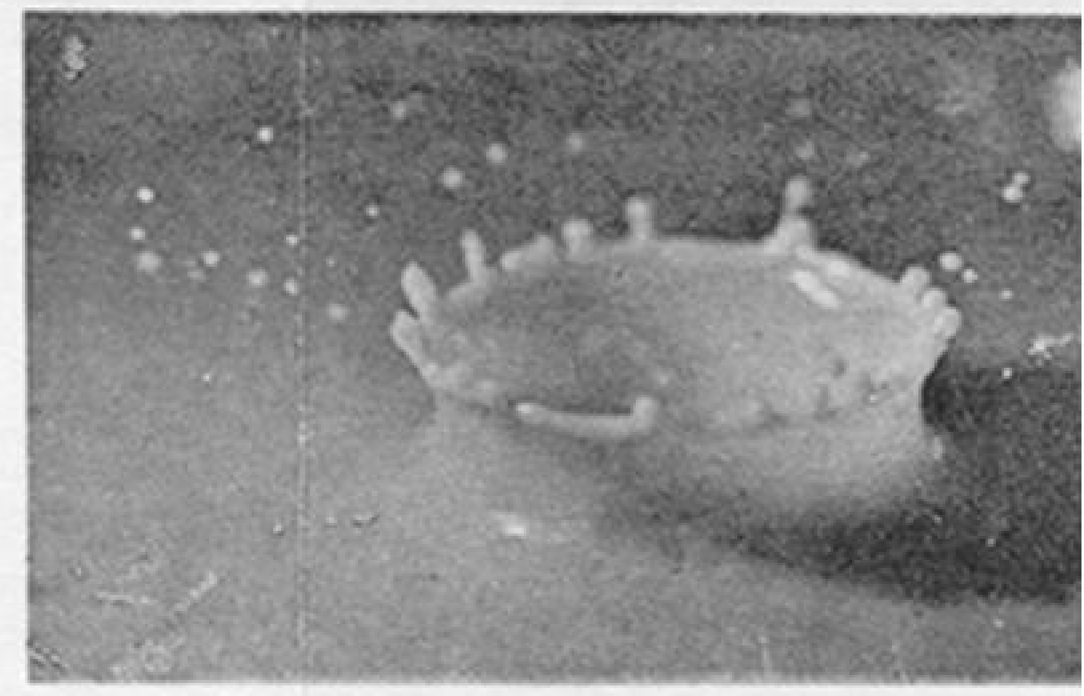
4

t-·0105 sec.



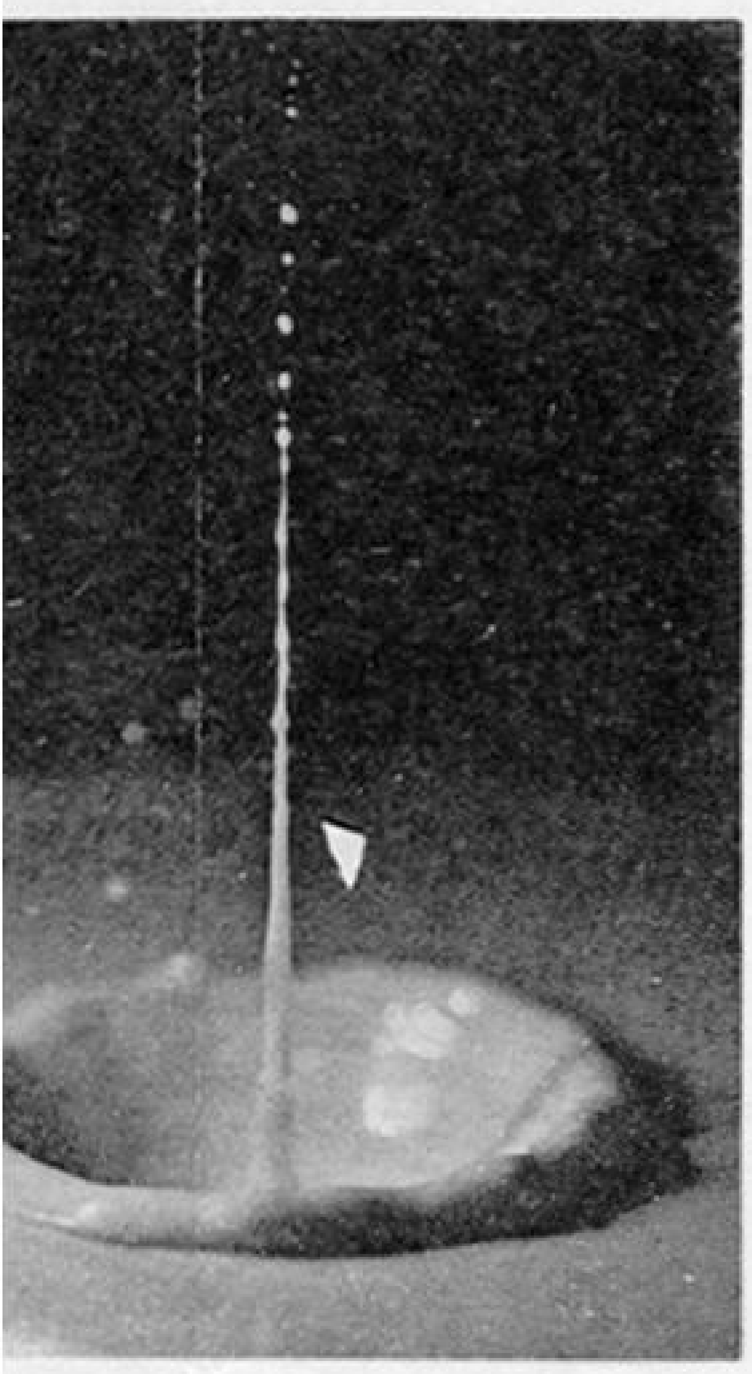
5

t-·0212 sec.



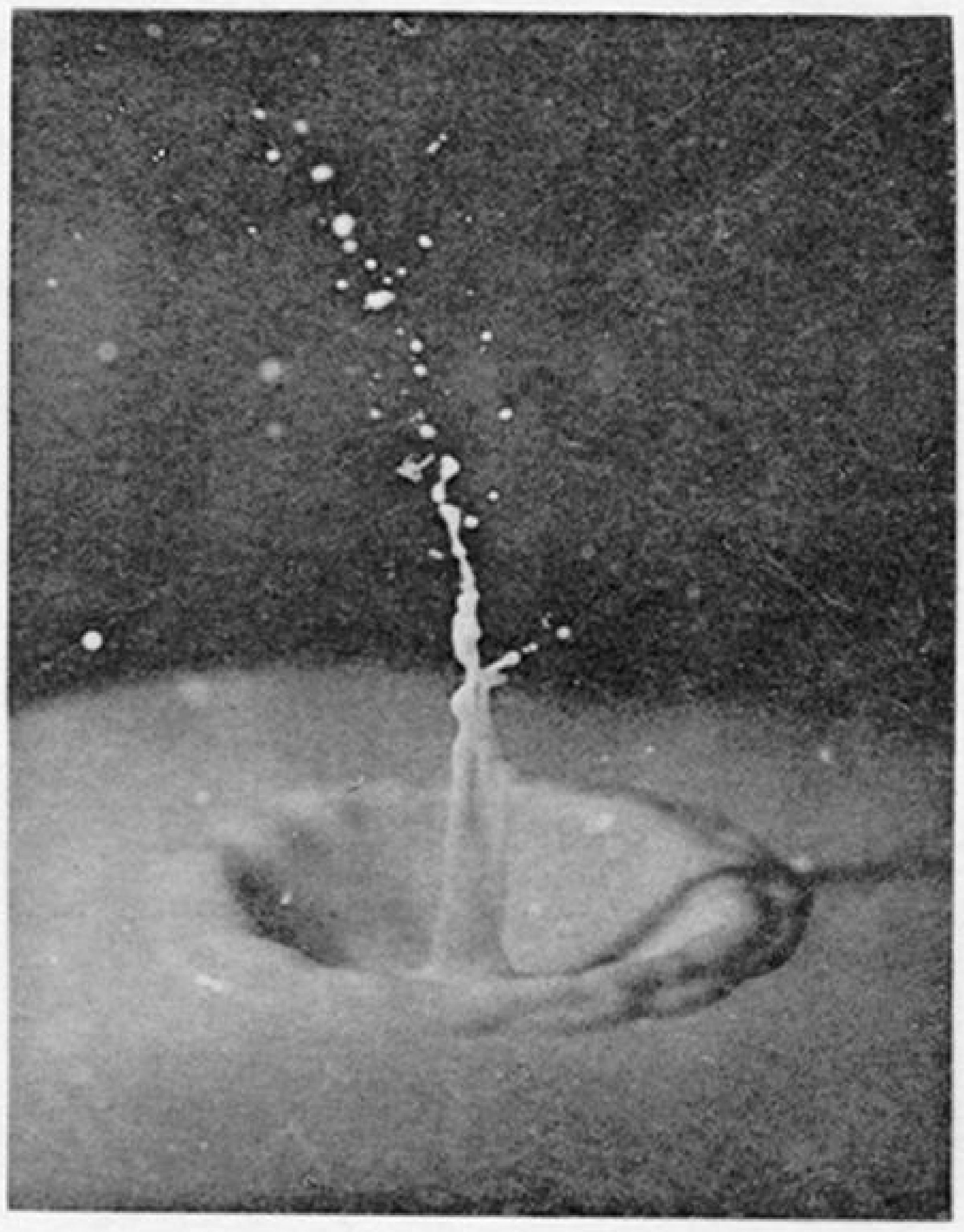
6

t-·0633 sec.



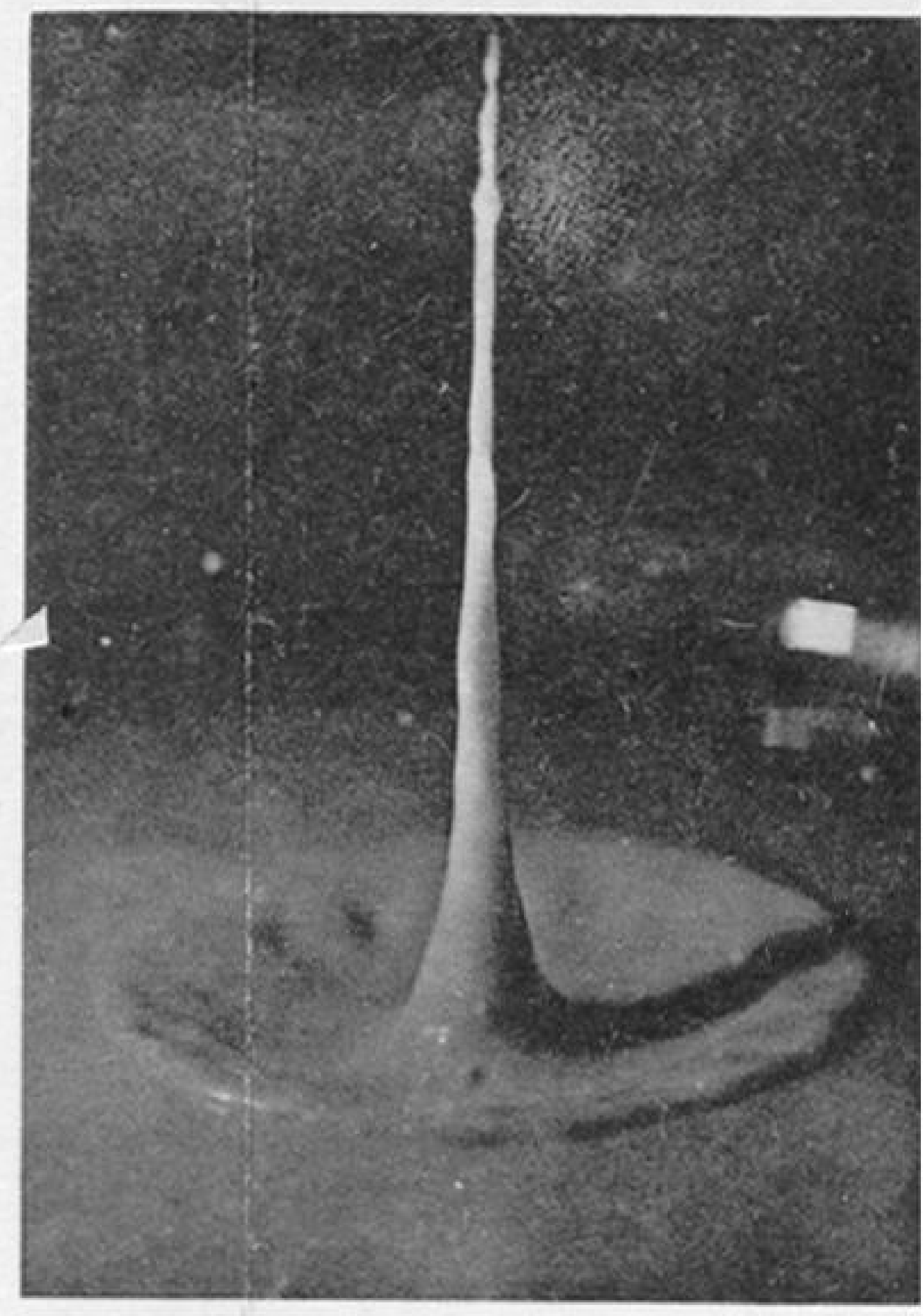
11

t-·0715 sec.



12

t-·0844 sec.



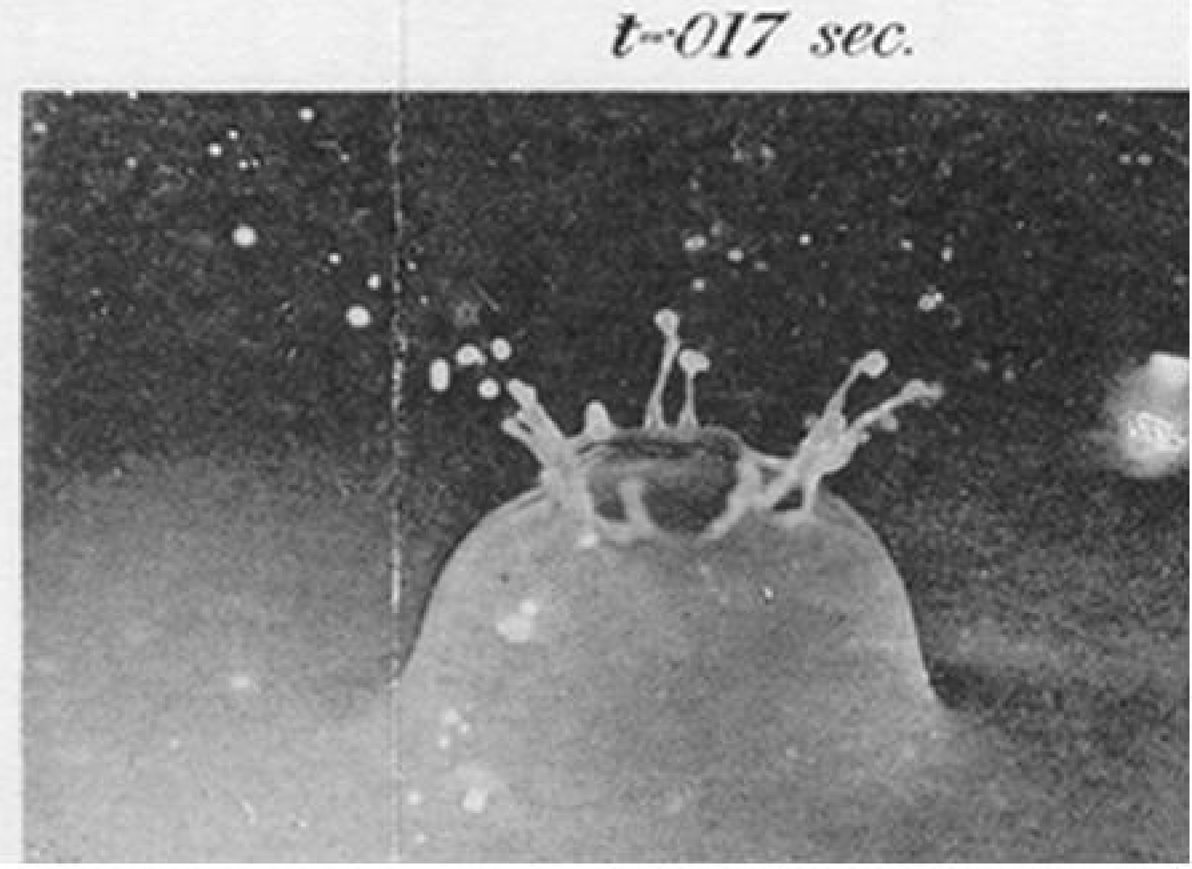
13

Series VIII.

·006 sec.

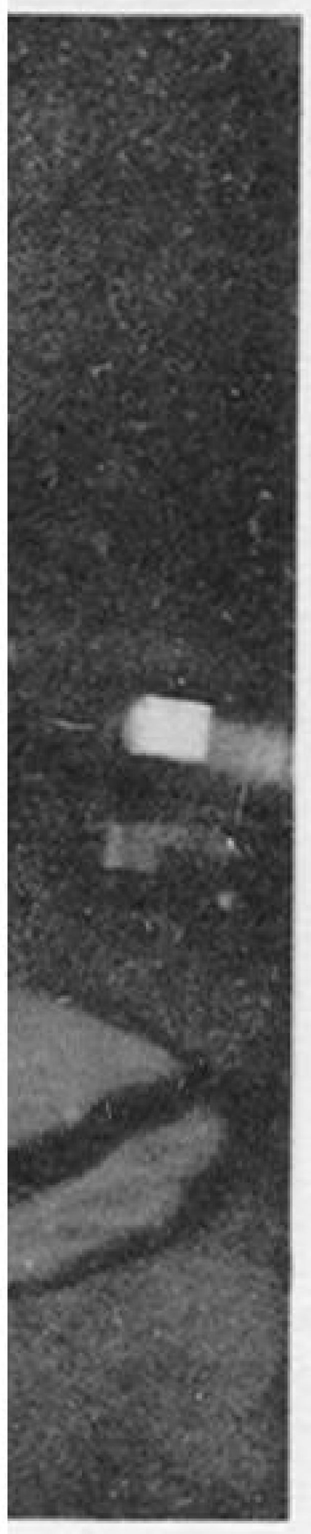
t-·017 sec.

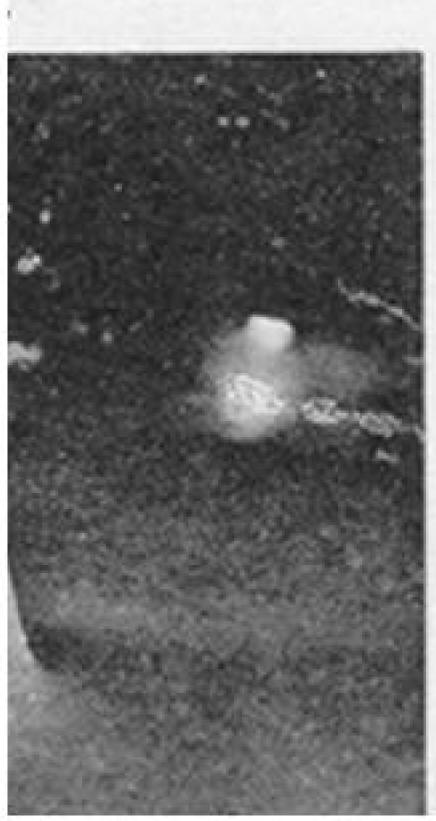
t-·017 sec.



sec.

ec.

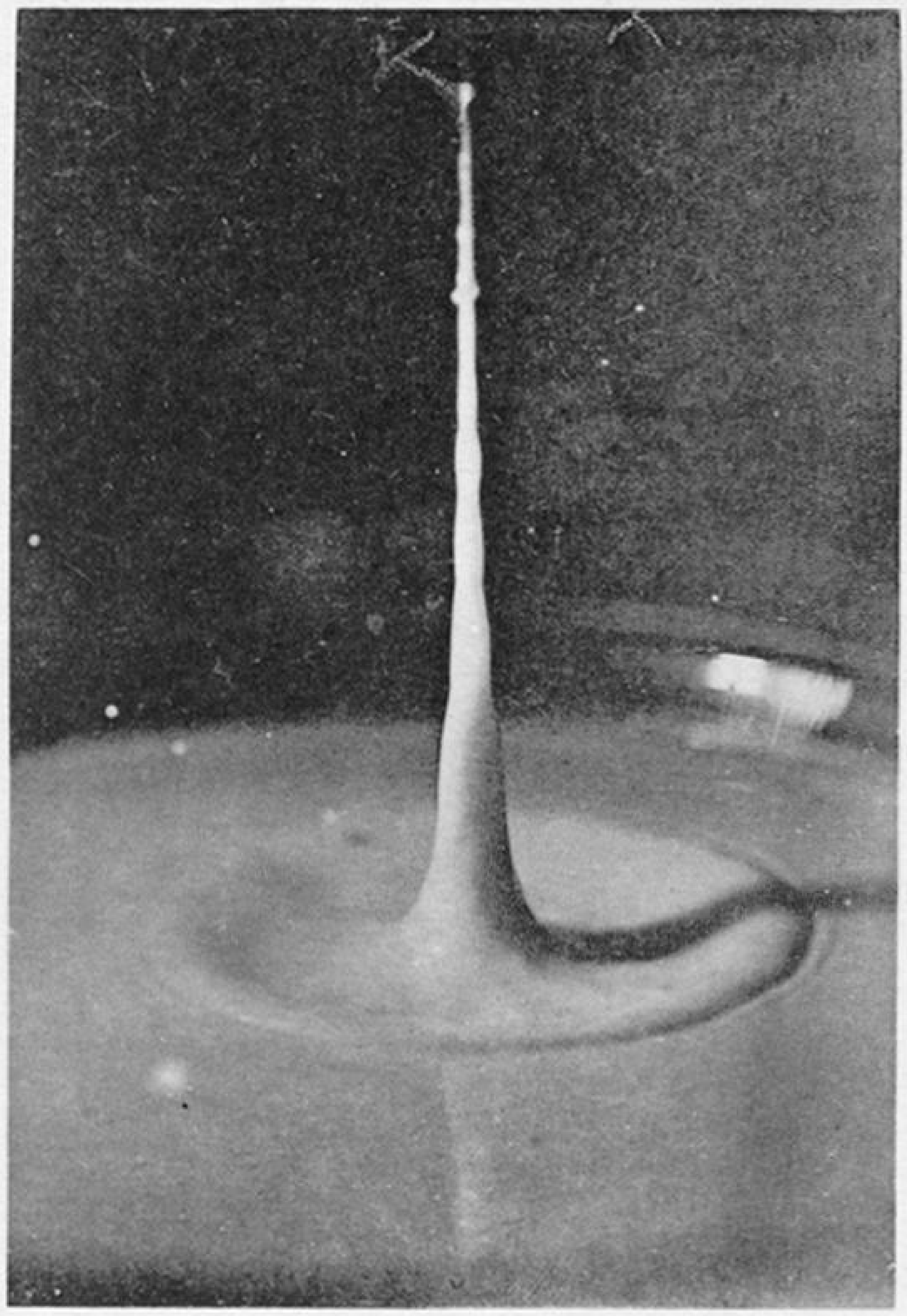




t-·0261 *sec.*

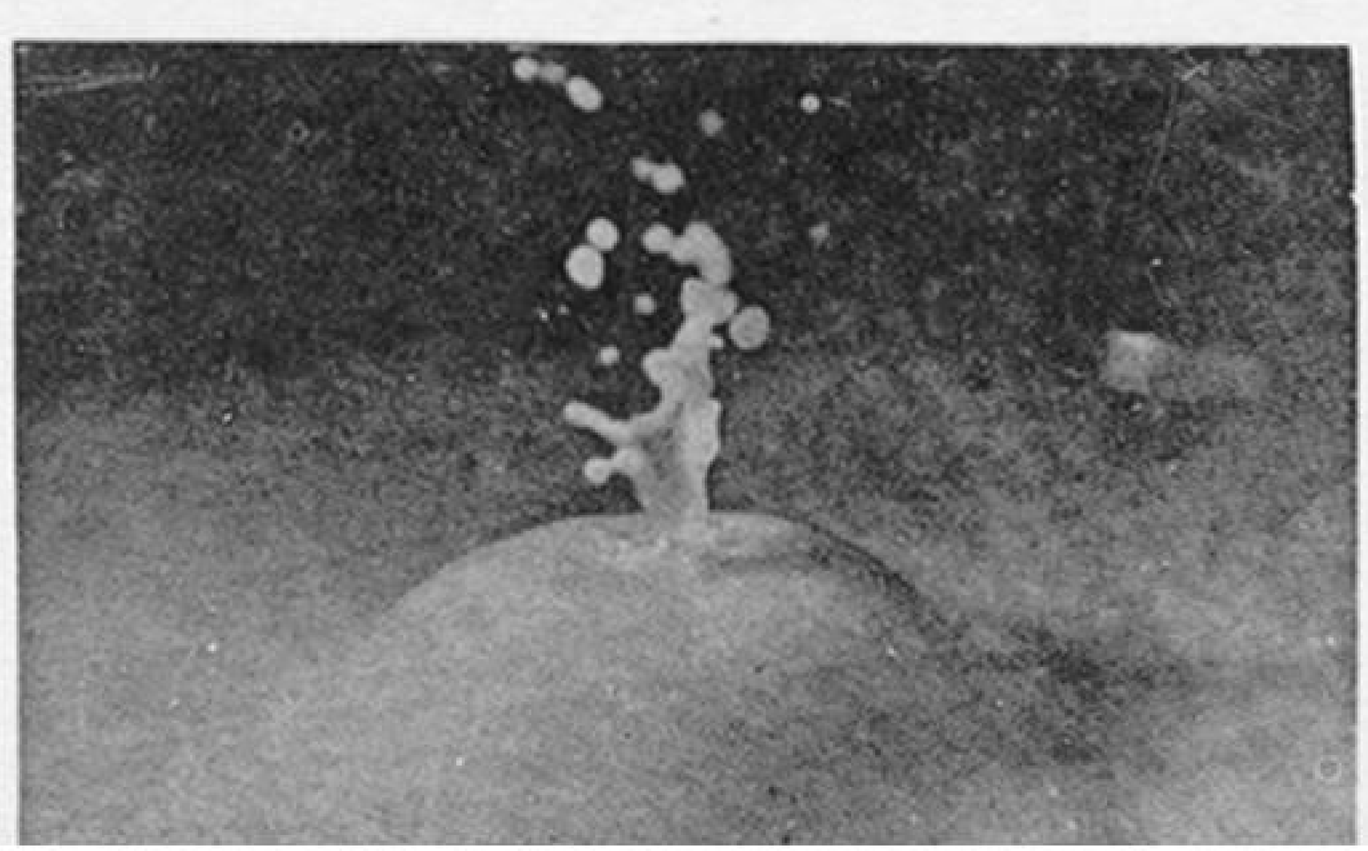
7

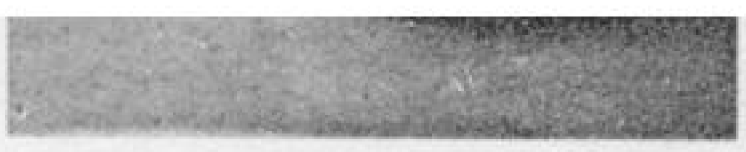
t-·0962 *sec.*



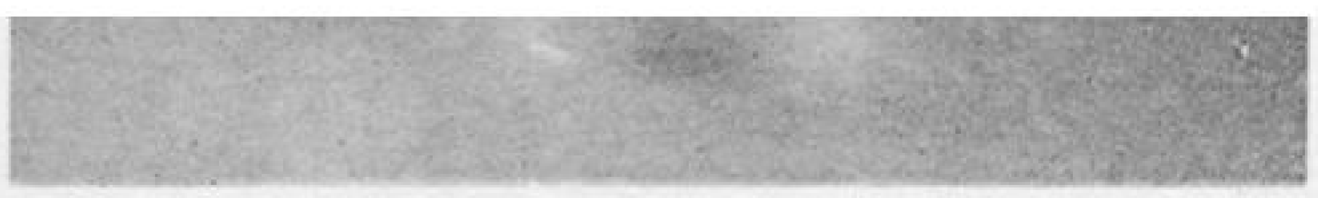
14

t-·0335 *sec.*

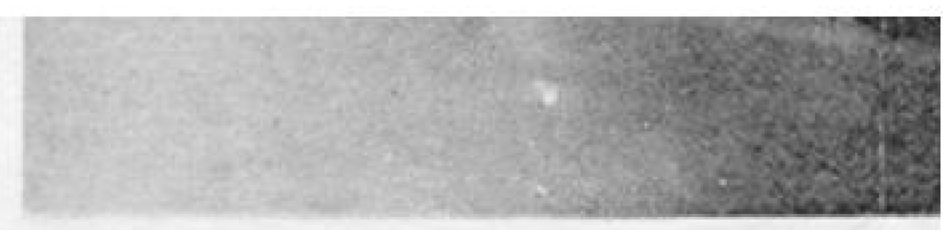




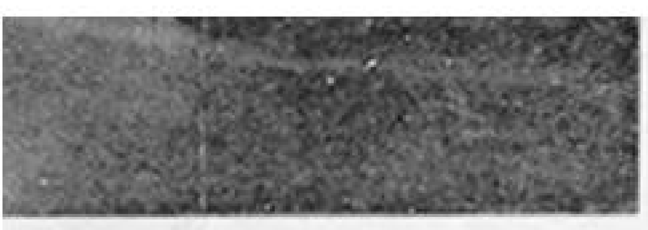
1



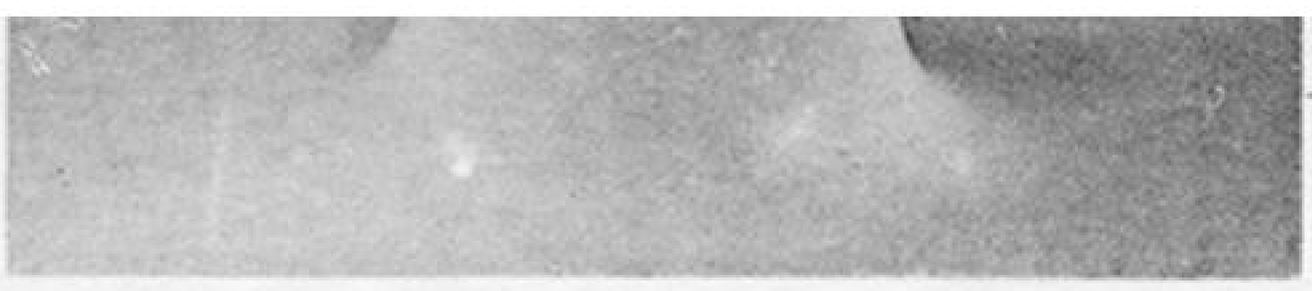
2



3



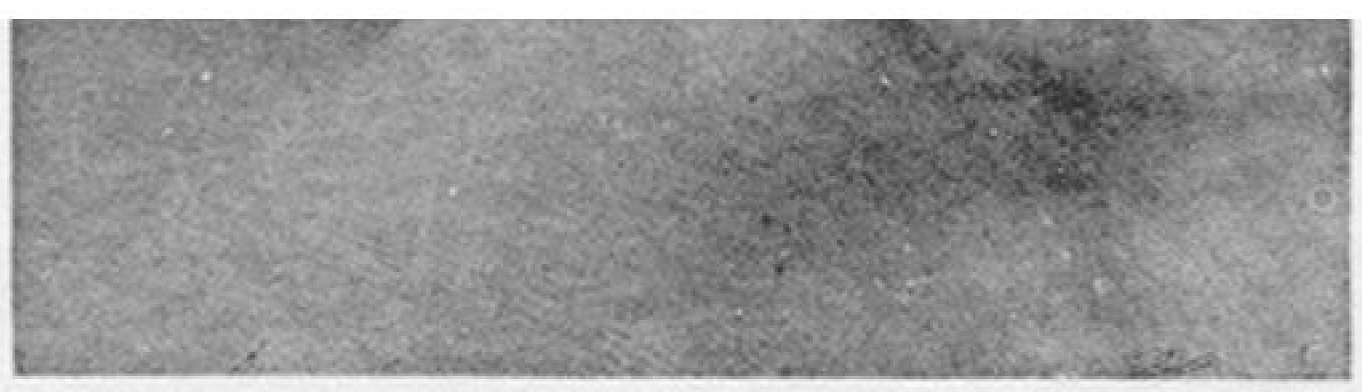
3



4

5

Series IX



6