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A Photographic Study of the Impact between Water Drops and a Surface moving at High Speed

by

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A PHOTOGRAPHIC STUDY OF THE IMPACT BETWEEN WATER DROPS AND A SURFACE MOVING AT HIGH SPEED

by

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and
J. D. Booker, A.F.R.Ae.S.

SUMMARY

The normal impact between 2 mm diameter water drops and a smooth, hard, surface moving at 1000 ft/sec has been studied photographically and the results discussed. The speed of the radial flow resulting from the impact has been measured and an estimate made of the corresponding pressure existing between the drop and the surface.

The case of impact of drops on rough, deformable and inclined surfaces has also been briefly considered.

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1 INTRODUCTION

An aircraft or missile in high speed flight through rain may suffer severe damage due to striking the rain drops[1,2]. A detailed knowledge of the way a drop breaks up in high speed impact may be of assistance in understanding the mechanism whereby the damage is caused and also may be of value in the wider study of droplet mechanics.

Descriptive and photographic work already published[3,4,5,6] shows that when a drop impinges on a surface at a low speed it spreads over the surface in a radially expanding disc. Break-down of the outer edge of the disc leads to flow along separate radial channels.

This Note gives results of a photographic investigation undertaken to obtain information on the manner of break-up of a drop impinging on a surface at high speed. The experimental method and results are described in paragraphs 2 and 3 and a more detailed discussion of the results given in paragraphs 4 to 7. As it was not possible in this limited investigation to study in detail all the points arising a list is given in paragraph 9 of some further work it is hoped to do in due course.

2 APPARATUS

To produce high speed impacts between the surface and drop an apparatus was used which had previously been developed for the study of single drop impacts[7]. In this apparatus the water drop is suspended on a very fine web and is struck by a projectile, one inch in diameter, fired by means of an air gun. The projectile is subsequently caught without damage in an arresting device. The impact was viewed in these tests by reflected and transmitted light using a Frungel spark gap, having an effective light duration in the order of 1 microsecond, or Arditron flash tube equipment.

A diagrammatic arrangement of the apparatus when using transmitted light from the spark gap is shown in Fig.1. The drop, supported on its web, was positioned on the axis of the gun so that it would be struck by the flat nose of the projectile which formed the impact surface. The camera and spark gap were positioned on either side of the drop as indicated with a ground glass screen placed between the drop and the light source to diffuse the illumination. The projectile velocity was measured by the projectile breaking two trip wires a known distance apart. Approximately 3 inches in front of the drop were positioned two crossed trigger wires 0.05 inches apart. On being struck by the projectile these wires touched and triggered the spark. It was possible to control the speed of the projectile closely by means of the air pressure used in the gun so that by using the variable delay unit built into the spark gap equipment it was possible to take a series of single pictures with the projectile and drop in successive stages of impact. The experiments were carried out in a darkened room with the camera shutter being operated manually before and after each shot.

By placing a mirror in front of the drop, as shown in Fig.1, and using a second camera it was possible to take oblique front and side view photographs simultaneously. For side views with reflected light the light source was placed immediately above the first camera and the ground glass screen replaced by a black flock paper screen. The oblique front views rely on reflected light irrespective of the method of illumination used for the side views.

3 RESULTS

3.1 Normal impacts

Figs.2a-2h are photographs using transmitted light from the Frungel spark showing various stages in the process of collision between a smooth surface travelling in the direction normal to its plane at approximately 1000 ft/sec and a 2mm diameter drop. Figs.3 and 4 are oblique front views taken simultaneously with Figs.2b and 2h respectively.

As can be seen in Fig.2a the web on which the drop is supported is blown away before impact leaving a small protuberance on the surface of the drop which is then unsupported at the moment of impact.

After impact the drop is seen to spread radially over the surface forming a disc, the perimeter of which breaks down first into radial filaments (see Fig.3) and then into a mist of small droplets which, in some preliminary sampling experiments with an oiled slide were found to range from 4 to 25 microns diameter. In Figs.5a and 5b, which are photographs of the collision using reflected light from the Frungel spark, there appears in addition a mist extending forward from the disc at an angle to the impacting surface. It is argued in paragraph 4 that this is a photographic effect associated with the lag in the spark illumination.

By taking the drop and projectile position of Fig.2a as datum and working to visually similar parts of the disc in successive transmitted light photographs the rate of radial increase of the disc can be estimated. This has been done in Fig.6 from which it can be seen that the maximum rate of increase occurs immediately after impact. Assuming constant projectile velocity of 1000 ft/sec the radial velocity of the disc periphery at this stage is found to be 3400 ft/sec. Fig.6 also shows disc radii based on another method, described in paragraph 4, in which reflected light photographs are used. This method gives the same initial radial velocity. In the later stages, when the disc extends beyond the edge of the projectile, this velocity is reduced probably by drag effects. The results in the transmitted light experiments show a greater reduction in speed than do those in reflected light. This is probably due to greater difficulty of estimating disc radius with the former method of illumination.

The effects of surface irregularities on this process appear to be negligible; changing the impact surface material from magnesium alloy D.T.D.259A, which is not permanently deformed under these impact conditions, to aluminium L.34, which is plastically depressed to a depth of 0.001 inches, has no apparent effect on the flow (Figs.2d and 2f); similarly a rough surface as used in Figs.7 and 8 still shows the same basic type of flow pattern after impact. Engel[5] found that upward splashing occurs when a drop falls onto a rough surface and that this is due to the surface irregularities. Whether the same effect is present under the high speed impact conditions is not clear.

The trailing web causes a distortion of the rear part of the drop which varies from shot to shot and this makes it difficult to assess the varying distortion of this part of the drop as the impact progresses. Also the shape of the drop near the impact surface is obscured by the thickness of the radial flow but the shape of the lower part of the drop seen in Fig.2e suggests that spreading of the drop in this region may occur. A comparison of the position of the rear portion of the drop in Figs.2b - 2e with that of Fig.2a suggests that movement of the drop in the direction of motion of the projectile during impact is small. In view of the comparatively low tensile strength of water the internal reflection of the initial impact pressure waves as tension waves at the rear face of the drop might have led to the expectation of signs of spalling from this region. The absence of signs of spalling in the photographs suggests a high degree of attenuation of the pressure waves. This aspect is discussed more fully in paragraph 5.

3.2 Oblique impacts

Figs.10a to 10d show various stages in the impact of 2mm diameter drops on the conical nose of the projectile having an included angle of 60°. The corresponding projectile speeds are given on the figure. These are shadowgraph pictures using as point source illumination an Arditron flash tube focussed onto a small hole in a screen. Fig.10a shows the drop suspended on the web just prior to impact whilst the remaining figures show the drop in various stages of radial flow parallel to the inclined surface.

With oblique impacts the drop has two velocity components relative to the surface, (a) a component normal to the surface; this component causes the impact pressure which induces the radial flow and (b) a component parallel to the surface; the effect of this component is to reduce the relative velocity between the flow and the surface on one side and increase it on the other. Figs.10b to 10d show the flow to be thicker on the side remote from the cone apex (where the relative surface velocity is increased) than on the side towards the cone apex (where the relative surface velocity is reduced).

4 POSSIBLE PHOTOGRAPHIC EFFECTS

Figs.5a and 5b, which are photographs of the impact taken with reflected light, show a fine mist appearing ahead of the surface. It is debatable whether this mist represents a cloud of droplets or whether it is due to a photographic effect. It is evident from Fig.5b, where the outer edge of the disc is beyond the projectile that the presence of the mist cannot be explained by splashing from the impact surface.

On the whole the most likely explanation of the mist seems to be that it is caused by the lag or "tail" of the spark illumination. This "tail" would record the progress of the highly reflective edge of the disc of droplets after it had ceased to record the black and much less reflective projectile. Evidence of a "tail" in the spark illumination can in fact be found in Fig.5b where drawn out highlights from parts of the broken trigger wires in front of the projectile are visible.

Droplets in the outermost edge of the disc have two velocity components (a) their radial velocity and (b) a forward velocity which equals that of the impact surface in the initial stages. The edge of the disc will thus trace out in space a cone whose half section will be given by the shape of the curve in Fig.6. If the disc were illuminated for a short interval of time, say by the "tail" of the spark illumination, this cone would be recorded on photographs taken by reflected light. It can be seen that the angle forming the boundary of the mist area ahead of the disc in Figs.5a and 5b is approximately the same as the angle given by the curve of disc growth of Fig.6.

If the apparent cone formation is caused by the "tail" of the illumination it would be expected that using illumination having a longer and brighter tail would result in the recorded cone being correspondingly increased. This has been shown to be the case using an Arditron flash tube which is known to have a much longer "tail" than the Frungel spark by means of which Figs.5a and 5b were taken. Typical results are shown in Figs.9a and 9b. In Fig.9b the flash was triggered to occur well before the projectile had reached the drop, yet a cone formation spreading from the drop is clearly seen. A highly polished projectile was used for these tests and drawn out "highlights" on the surface of the projectile extend forward through the length of the cone confirming that photographic recording was still taking place during the time taken for the projectile to move through that distance. The cone radii for successive time intervals measured from the front face of the drop in Fig.9a have been plotted in Fig.6. It is seen that agreement between corresponding cone and disc radii is very good in the initial stages but in the later stages, when the disc extends beyond the edge of the projectile, the disc radii are smaller. This may be explained by the dispersal of the droplets at the outer edge of the disc so that their density is insufficient to be recorded in transmitted light, whereas they could reflect sufficient light to be recorded.

In the transmitted light pictures the apparent volume of the disc is far greater than the volume of water displaced; further, from considerations of the energy involved in the impact it can be shown that at any stage of the impact only a small fraction of the water displaced by the surface can be accelerated to the measured radial velocity of 3400 ft/sec. This suggests that either the disc is comprised of a cloud of droplets or that the excessive thickness of the disc is due, in part at least, to a photographic effect. In the photographs it can be faintly discerned that the outer edge of the disc makes approximately the same angle with the impact surface as does the mist in Fig.5 This strengthens the view that a photographic effect caused by the duration of the illumination is also present in the transmitted light pictures. The disc must have some thickness so that light reaching the photographic plate within the area traced out by the radially expanding disc will be cut-off before light outside the area is cut-off by the projectile. Consequently the area traced out by the expanding disc would appear darker. The effect is also present in Fig.7, impact on a rough surface, although in this case splashing of the flow is more likely to occur.

To prove this point finally it will be necessary to use a very short duration spark from which all trace of "tail" is eliminated.

5 EFFECT OF INTERNAL PRESSURES IN THE DROP

Pressure waves in the drop radiating from the site of impact will be reflected internally as tension waves from the back of the drop. In view of the large impact pressures estimated in paragraph 6 and the comparatively low tensile strength of water, some evidence of spalling from the back face of the drop might have been expected. Engel[8] has discussed this effect as a possible mechanism for the fragmentation of drops when struck by an air blast. No evidence of spalling from the back of the drop is visible in the photographs so that either (a), the photographic technique used is inadequate for this purpose or (b) rapid attenuation of the pressure waves occurs. The latter alternative seems the more likely.

In the case of the spherically expanding pressure waves from an underwater explosion Cole[9] shows that the pressure, theoretically, varies as $x \times a/R$ for values of R/a greater than about 25, where a is the radius of the initial charge, R the radius at the point considered and x is a dissipation factor which depends on a/R for a given charge. There is some experimental evidence that the pressure varies at a rate greater than $1/R$. For a charge of TNT and $R/a = 100$ Cole quotes figures of x in the region 0.2 (Ref.9).

These figures are not directly applicable to this impact case but they suggest that if the area of contact with the drop is small at the point of maximum pressure giving a low equivalent value of a/R with a corresponding low value of x then a high degree of attenuation of pressure could be achieved. Spalling may occur, however, at higher impact speeds.

6 IMPACT PRESSURES

It is clear that processes going on in the drop immediately after impact with the projectile are very complex and it may well be that they are not amenable to treatment by simple mathematical techniques.

Nevertheless it is worthwhile to apply the steady incompressible flow Bernoulli equation to the flow in order to get some idea of the order of pressures produced after the impact. This shows that a pressure of 78,000 p.s.i. is necessary to produce the measured radial velocity of 3400 ft/sec.

This estimate of pressure is probably conservative as the following terms have been ignored:-

(a) compressibility effects

(b) drag losses

(c) time dependent terms for unsteady flow

A rough estimate using available data[10] shows that compressibility effects may increase the estimated pressure from 78,000 p.s.i. to 86,000 p.s.i. (38 ton/in^2).

The correction required for drag losses is unknown but would increase the estimated pressure. In order to allow for the time dependent terms in unsteady motion a complete theoretical analysis of the flow would be required. Engel[5] assumes that the time dependent terms are negligible at the instant the maximum pressure is reached.

Engel[5] has developed a theoretical expression for the maximum impact pressure between the drop and an infinitely rigid surface which is given by:-

$$p = \frac{\alpha}{2} \cdot \rho CV \qquad (1)$$

where p is the maximum pressure (lb/ft^2)

C is the speed of sound in water (ft/sec)

ρ is the density of water (slug/ft^3)

V is the impact speed (ft/sec)

α is a flow factor, less than unity, which is stated to approach unity at high speeds.

Applying the steady incompressible flow Bernoulli equation the radial speed in the disc just outside the drop is given by[5]:-

$$W = (\alpha CV)^{\frac{1}{2}} \text{ ft/sec} . \qquad (2)$$

Taking $\alpha = 1$ and C = 4900 ft/sec equations (1) and (2) give p = 33,000 p.s.i. and W = 2200 ft/sec for an impact speed of 1000 ft/sec.

In the "hammer blow" pressure (= ρ CV) which appears in equation (1) C is the speed of sound in water. For large pressures when shock waves are initiated, the higher shock wave velocity should be used instead of C. Using data by Cole[9] for the propagation of plane shock waves in water equation (1) gives 40,000 p.s.i. In the impact of a flat ended column of water on a column of incompressible material of the same cross-section at 1000 ft/sec the "hammer blow" pressure is 94,000 p.s.i., assuming a plane shock wave is initiated. If the material is compressible this pressure is reduced due to the movement of the particles of the column of material. If the material is magnesium alloy, in which the speed of sound is taken as 15,000 ft/sec, the pressure is reduced to 70,000 p.s.i.

The impact of a spherical drop on a comparatively large surface differs from the impact of the columns in that the shock waves are not plane and the average movement of the surface particles is reduced. It may be, however, that a part of the shock wave radiating from the impact area in the water drop could, in the initial stages, be regarded as nearly plane with the appropriate water particle velocity behind it. In this case the pressure would lie between 70,000 - 94,000 p.s.i. The fact that the impact pressure estimated from the measured radial speed is 86,000 p.s.i. suggests that this does represent the maximum impact pressure with the effects of drag losses and time dependent terms being negligible at this speed.

It would be of interest to compare these estimated pressures for a series of impact speeds and to determine the effect of air drag on the radial flow velocity by repeating this experiment in an altitude chamber under conditions of low ambient air density.

7 STRENGTH OF IMPACT SURFACE

As noted in paragraph 3.1 the impacts produced no noticeable plastic deformation on a magnesium alloy (DTD.259A) surface. The static 0.2% compressive proof stress of this material is approximately 9.4 ton/in^2 so that a ratio of dynamic to static proof stress of at least 4 is achieved if the estimated impact pressure of 38 ton/in^2 is correct. There is no data available for the strength of DTD.259A under high rates of loading, however, with which to judge if this ratio is reasonable. In the case of mild steel, having a compressive proof stress of about 10 ton/in^2, Taylor[11] has collected data to show that the dynamic yield strength increases with increasing rates of loading with the highest ratio of dynamic to static strength being 3.4. The form of the plotted results suggests that ratios higher than 3.4 might be expected. In view of this it is considered that the estimated impact pressure of 38 ton/in^2 does not imply an unreasonably high value of dynamic proof strength for the DTD.259A impact surface.

8 CONCLUSIONS

The following points emerge from a photographic study of the impact of 2mm diameter water drops on surface moving at high speed:-

A Normal impact at 1000 ft/sec

(1) When viewed along a smooth hard surface using transmitted light, impacting drops were seen to spread over the surface in radially expanding flow having, initially, a radial speed of approximately 3400 ft/sec.

(2) When viewed with reflected light the radial flow was again seen but in addition a fine mist could be seen preceding the impact surface. The presence of this mist is explained as a photographic effect.

(3) Oblique front views of the impacts using reflected light show that the radial flow develops into flow along separate radial channels.

(4) In the impact on a smooth deformable surface, which suffered local plastic deformation to a depth of approximately 0.001 inches during impact, the radial flow was still along the surface.

(5) In the impact on a rough surface the radial flow over the impact surface was still evident but in side view the outer edge of the flow appeared irregular compared with impact on a smooth surface.

(6) The movement of the rear of the drop in the direction of motion of the impacting surface during impact appeared small and no evidence could be seen of spalling from the back face of the drop due to internal reflection of pressure waves as tension waves.

(7) By applying the Bernoulli equation for steady compressible flow to the measured radial speed of 3400 ft/sec a maximum stagnation pressure in the radial flow of 86,000 p.s.i. is calculated. This is compared with a hammer blow pressure of 94,000 p.s.i. for the impact of a column of water on an infinitely rigid surface and 70,000 p.s.i. for impact on a bar of magnesium alloy which was the impact surface material in these tests.

B Oblique impact at various speeds

(1) In the impact of 2mm drops on cones of 60° included angle radial flow parallel to the inclined impact surface was found.

(2) A thickening of the flow occurred where the relative velocity over the surface was increased due to the resolved component of the impact velocity parallel to the surface.

9 FURTHER WORK

Further work envisaged on this aspect of water drop impact includes the following:-

(1) Further photographic study and measurement of radial flow velocities over a range of impact speeds for both normal and oblique impacts.

(2) Comparison of impact pressures deduced from the measured radial velocities in (1) above with the corresponding shock wave pressures.

(3) Check of flow pattern under conditions of low ambient air density.

(4) Measurement of droplets formed during impacts.

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Acknowledgement is made to Mr. W. J. J. Sexton of R.A.E. for helpful discussions on photographic interpretation and to Mr. E. J. Cuff and Staff of C.D.E.E. Porton for photographic work with the Frungel spark equipment.

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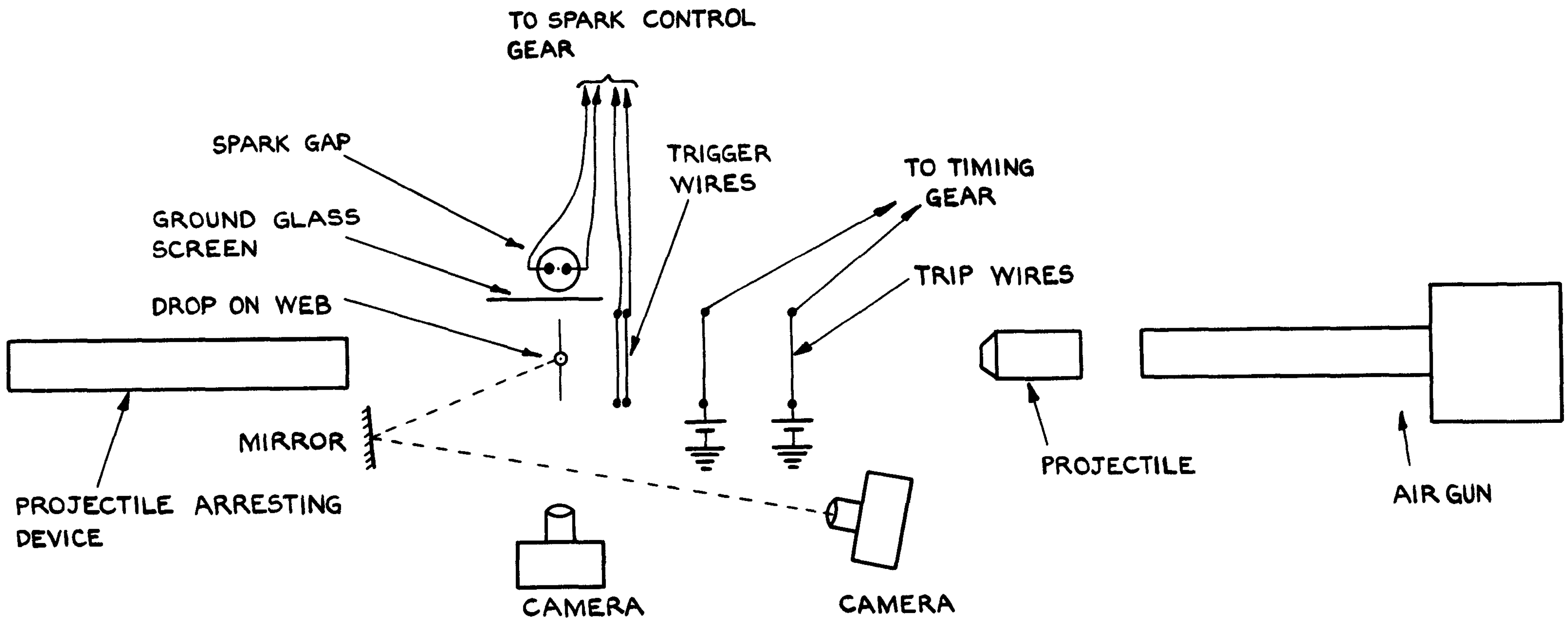

FIG.1. DIAGRAMMATIC ARRANGEMENT OF APPARATUS.

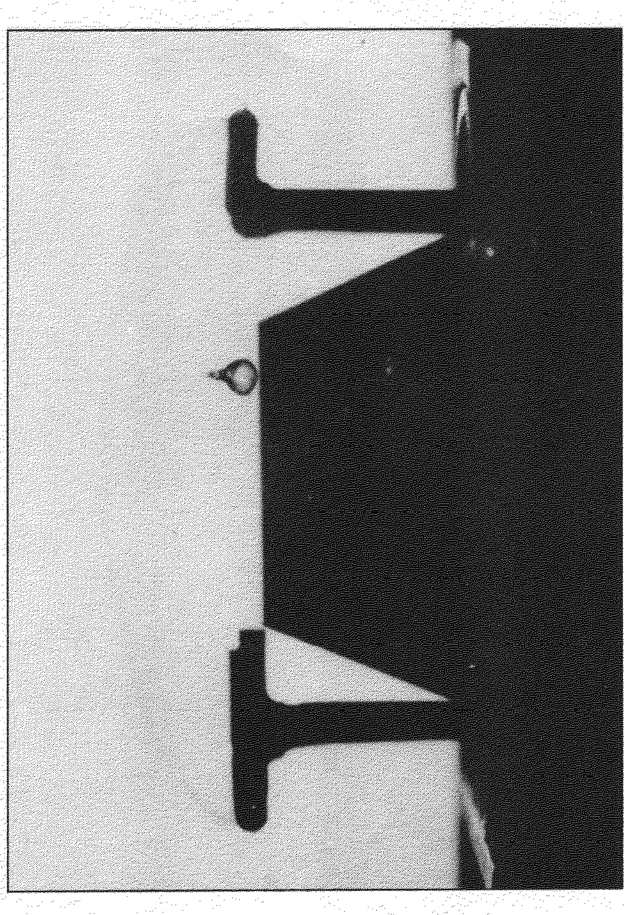

FIG.2a

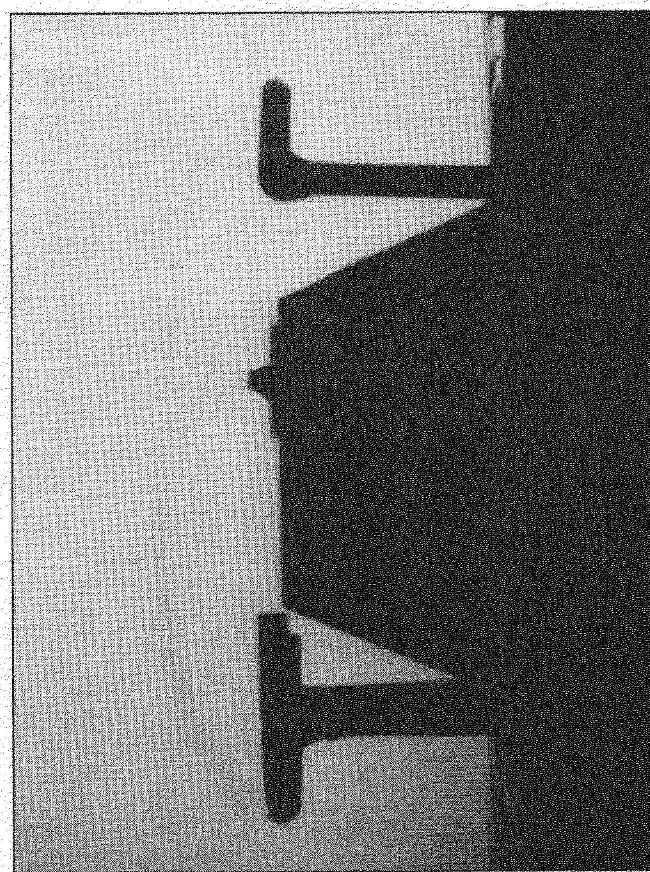

FIG.2b

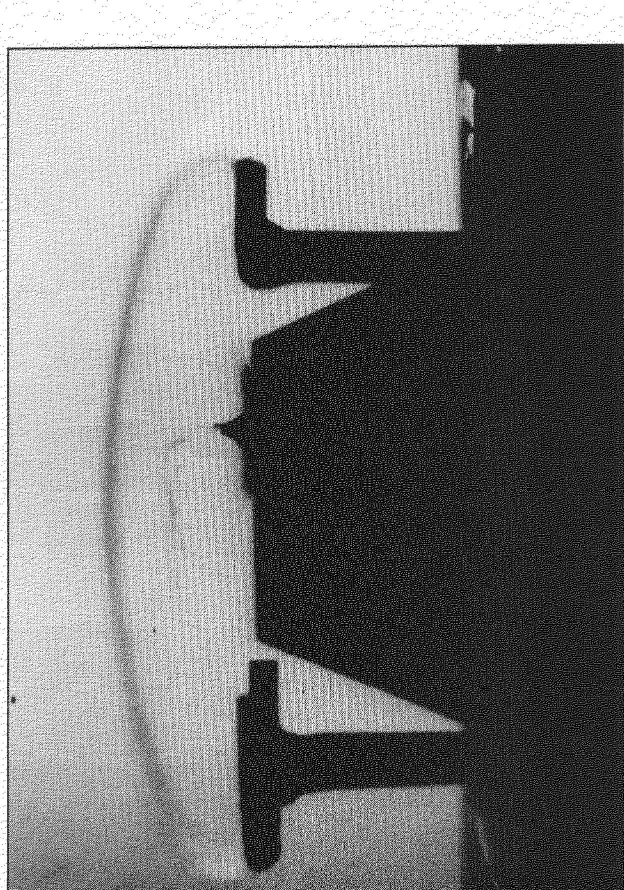

FIG.2c

SCALE: X2.5

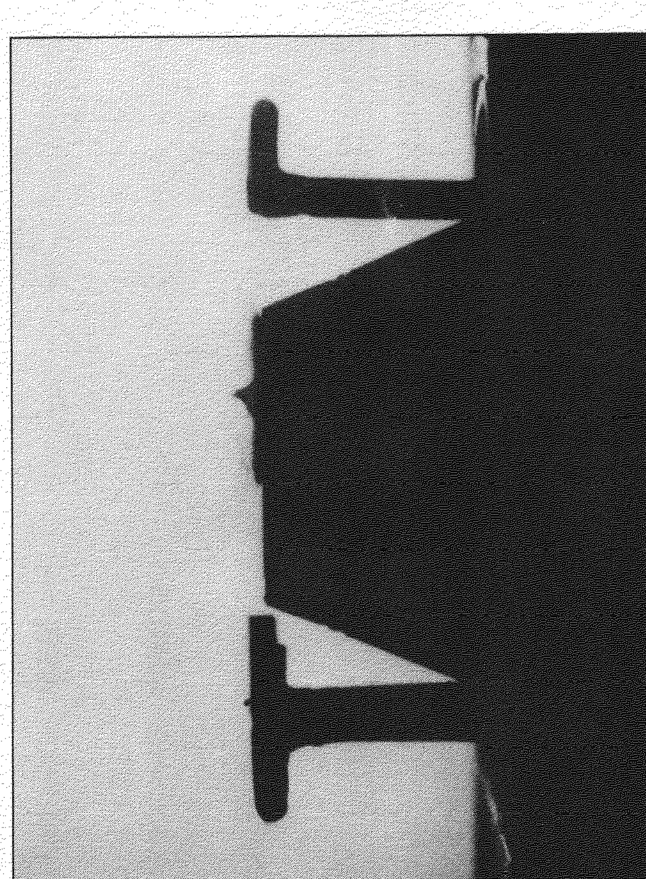

FIG.2d

FIG.2a-d. SUCCESSIVE STAGES OF THE NORMAL IMPACT BETWEEN 2 mm. DIAMETER WATER DROPS AND A SMOOTH SURFACE MOVING AT 1000 ft./sec.
(SIDE VIEWS USING TRANSMITTED LIGHT)

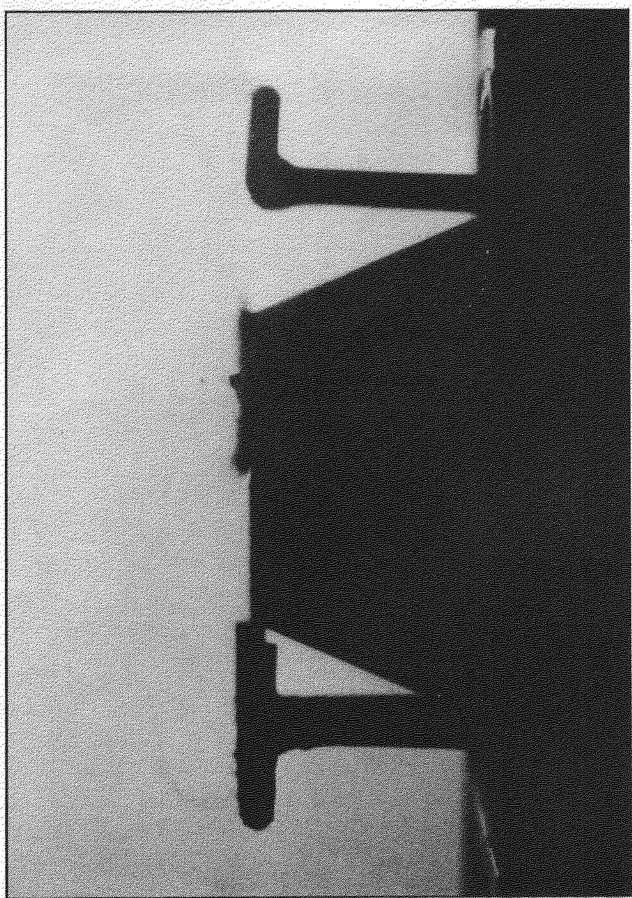

FIG.2e

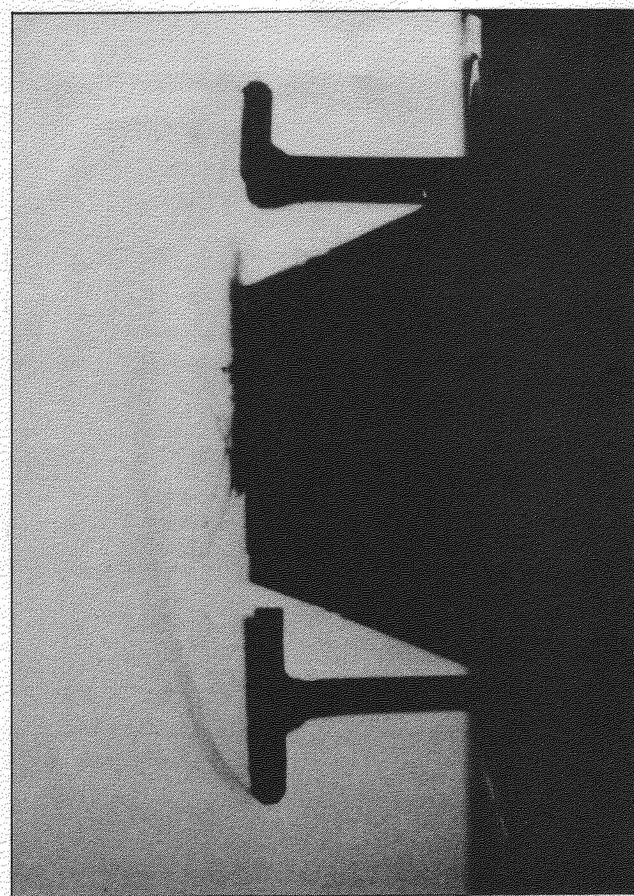

FIG.2f

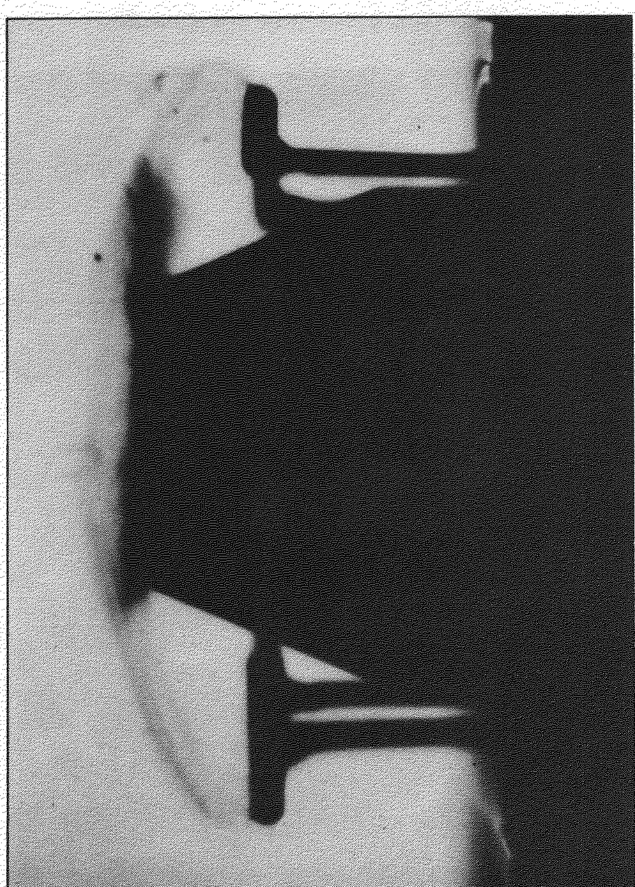

FIG.2g

SCALE: X2.5

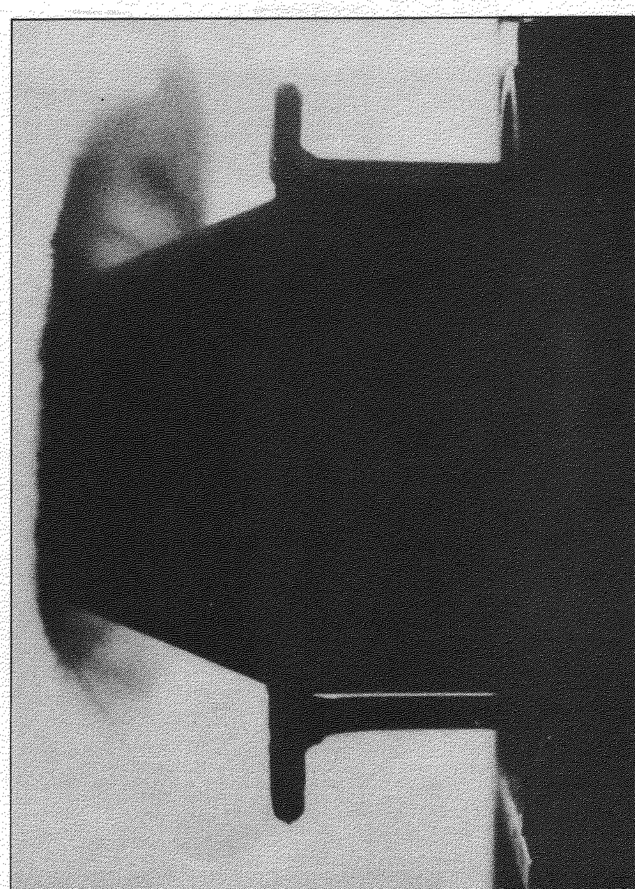

FIG.2h

FIG.2e-h. SUCCESSIVE STAGES OF THE NORMAL IMPACT BETWEEN 2 mm. DIAMETER WATER DROPS AND A SMOOTH SURFACE MOVING AT A 1000 ft./sec.
(SIDE VIEWS USING TRANSMITTED LIGHT)

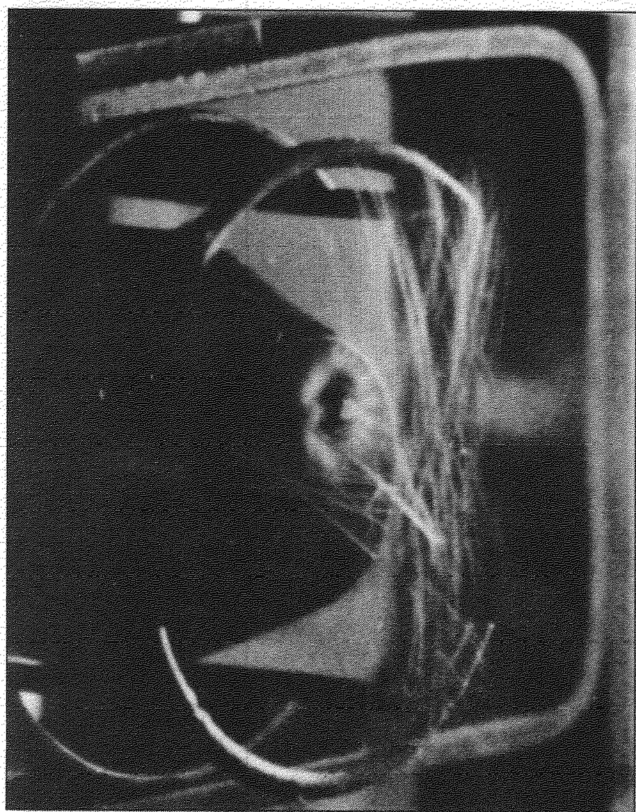

FIG.3. OBLIQUE FRONT VIEW, USING REFLECTED LIGHT, OF THE IMPACT SHOWN IN FIG.2b

FIG.4. OBLIQUE FRONT VIEW, USING REFLECTED LIGHT, OF THE IMPACT SHOWN IN FIG.2h

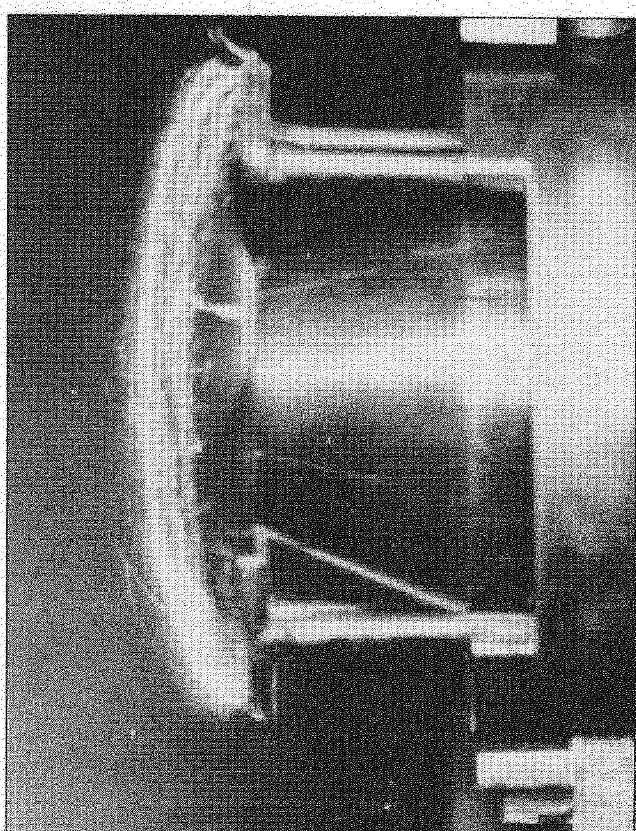

FIG.5a

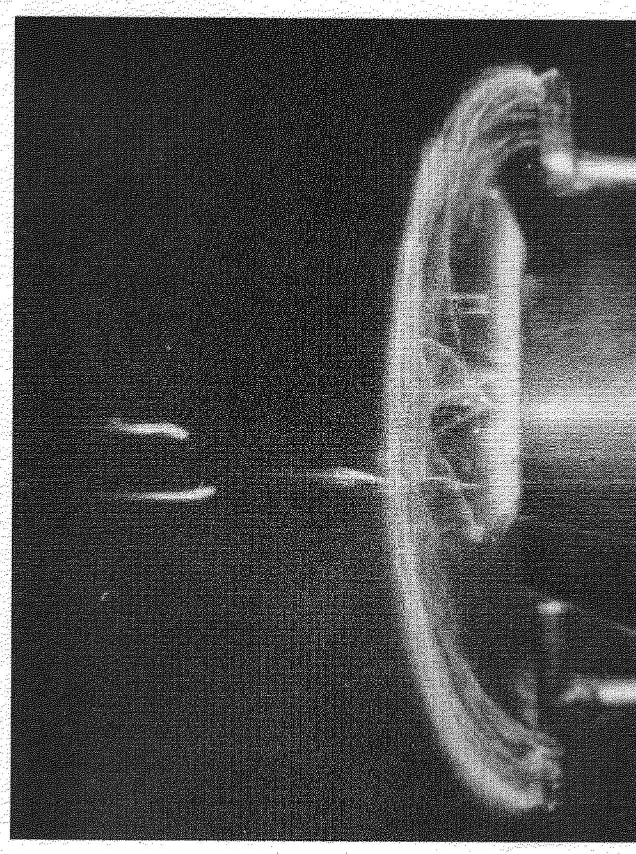

FIG.5b

FIG.5. TWO STAGES OF THE NORMAL IMPACT BETWEEN 2 mm. DIAMETER WATER DROPS AND A SMOOTH SURFACE MOVING AT 1000 ft./sec.
(SIDE VIEWS USING REFLECTED LIGHT)

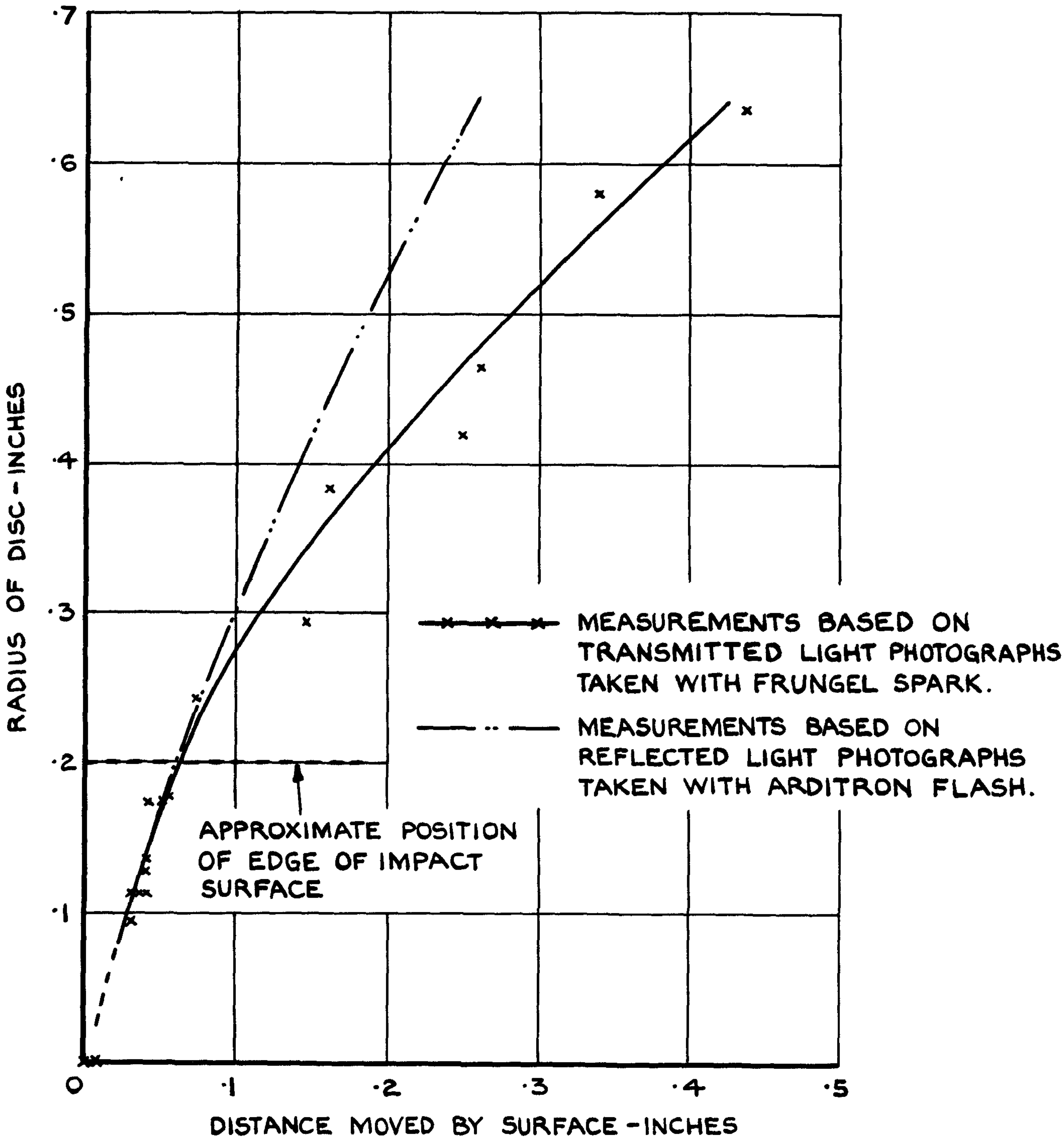

FIG.6. SPREAD OF DISC FLOW FOR THE NORMAL IMPACT OF A 2 m.m. DIAMETER WATER DROP ON A SURFACE AT 1,000 FT / SEC.

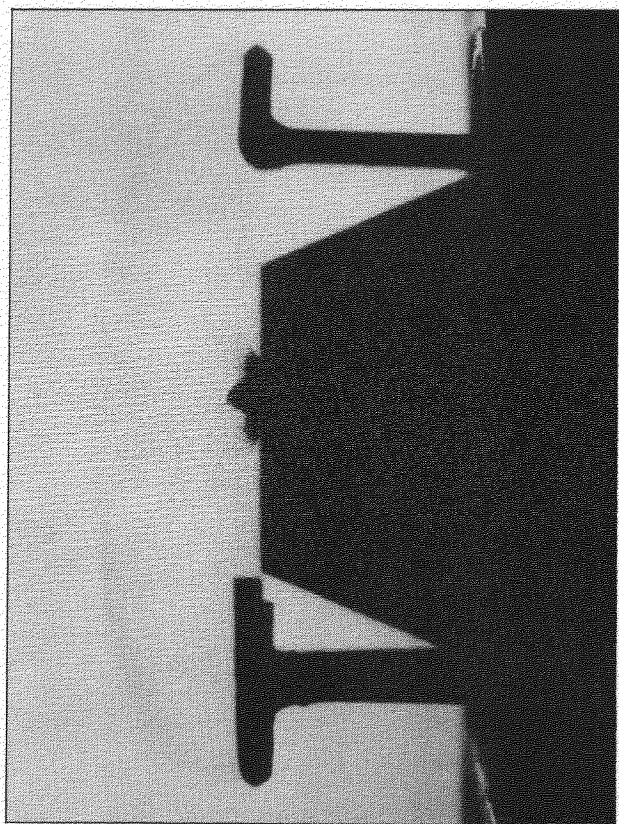

FIG.7. NORMAL IMPACT OF A 2 mm. DIA. WATER DROP ON A ROUGH SURFACE AT 1000 ft./sec.
(SIDE VIEW USING TRANSMITTED LIGHT)

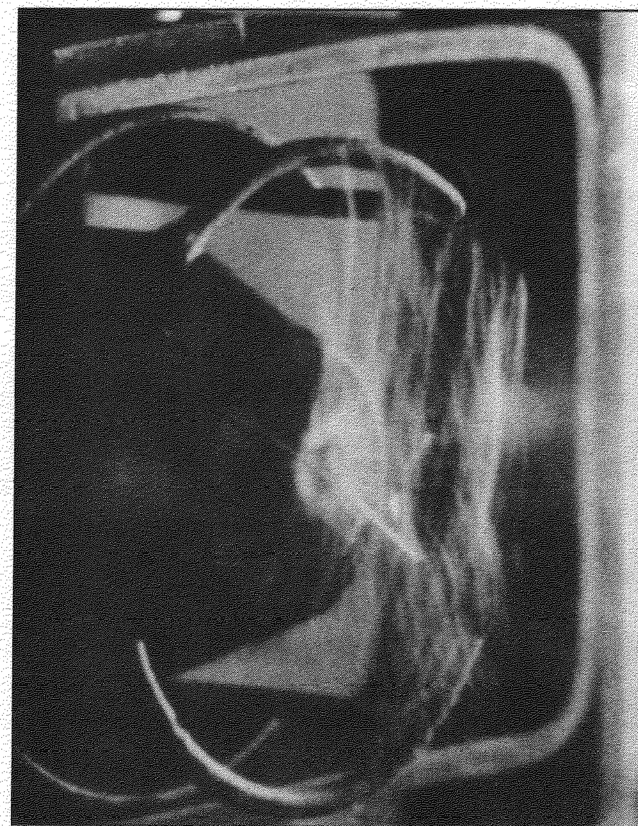

FIG.8. OBLIQUE FRONT VIEW, USING REFLECTED LIGHT, OF THE IMPACT SHOWN IN FIG.7

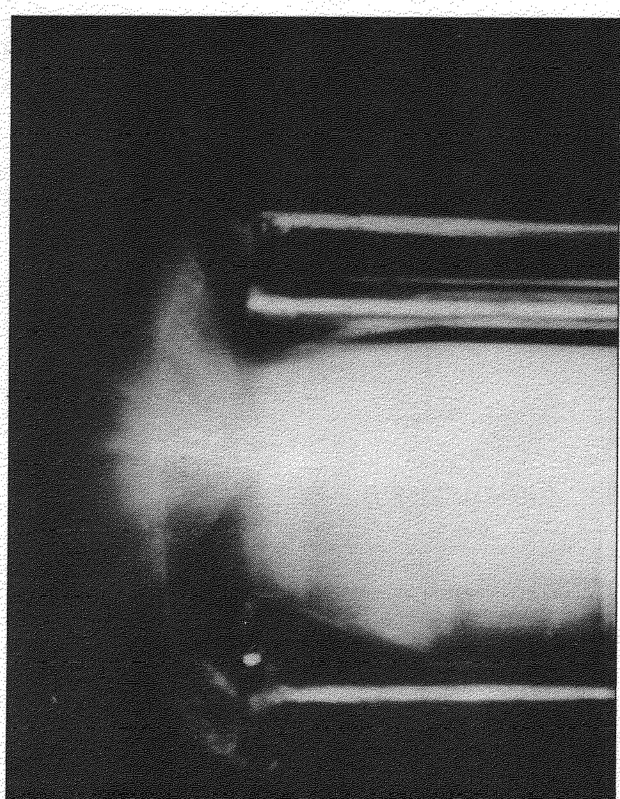

FIG.9a

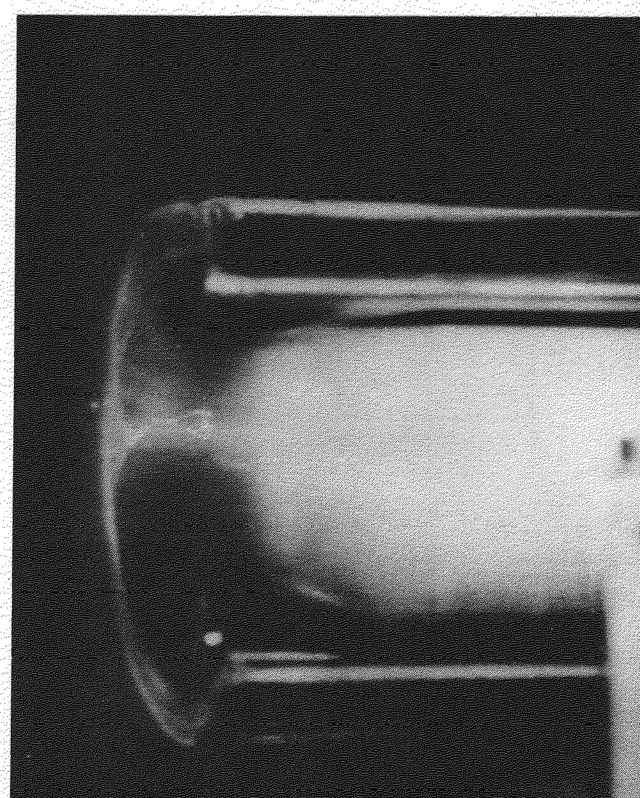

FIG.9b

FIG.9. NORMAL IMPACT OF 2 mm. DIAMETER WATER DROPS ON A SMOOTH SURFACE MOVING AT 1000 ft./sec. APPARENT SPRAY FORMATION OBTAINED WHEN USING ARDITRON FLASH TUBE ILLUMINATION
(SIDE VIEWS USING REFLECTED LIGHT)

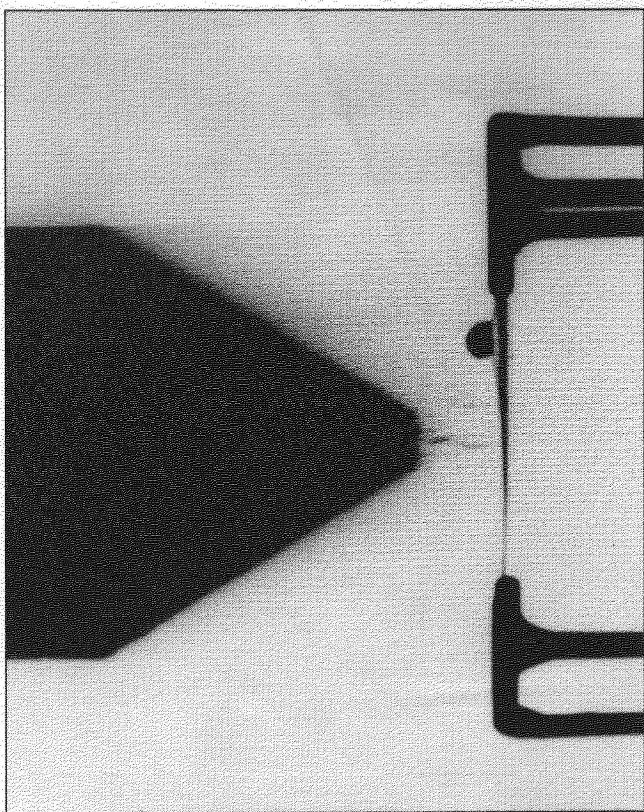
FIG.10a. (1750 ft./sec.)

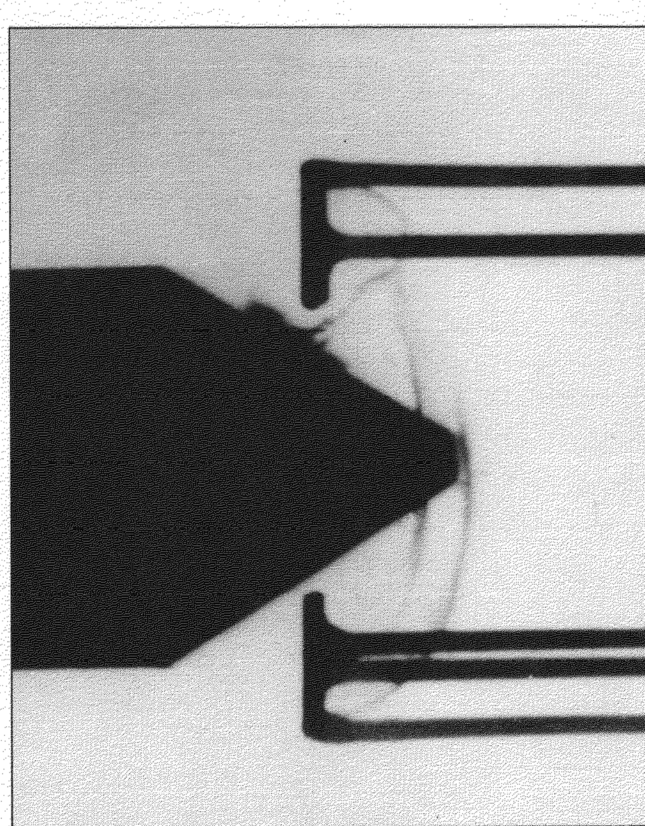
FIG.10b. (1580 ft./sec.)

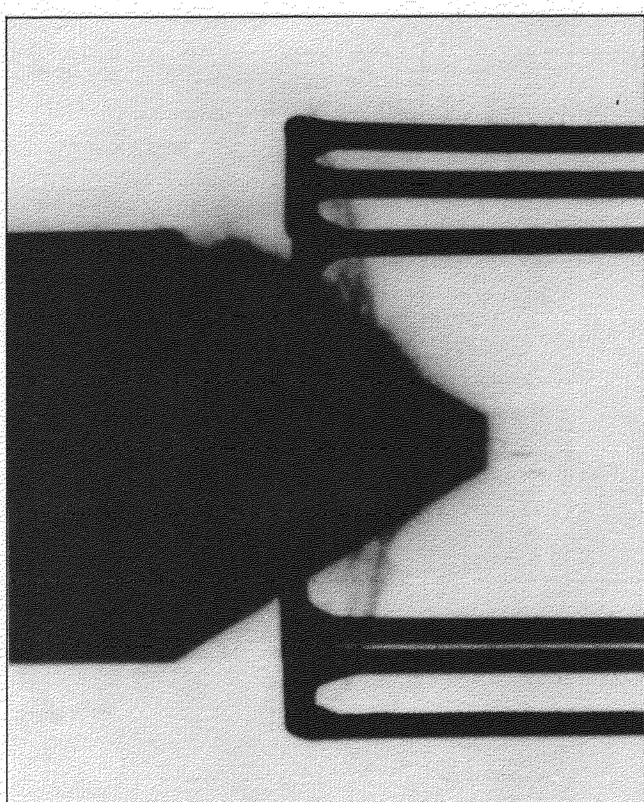
FIG.10c. (1360 ft./sec.)

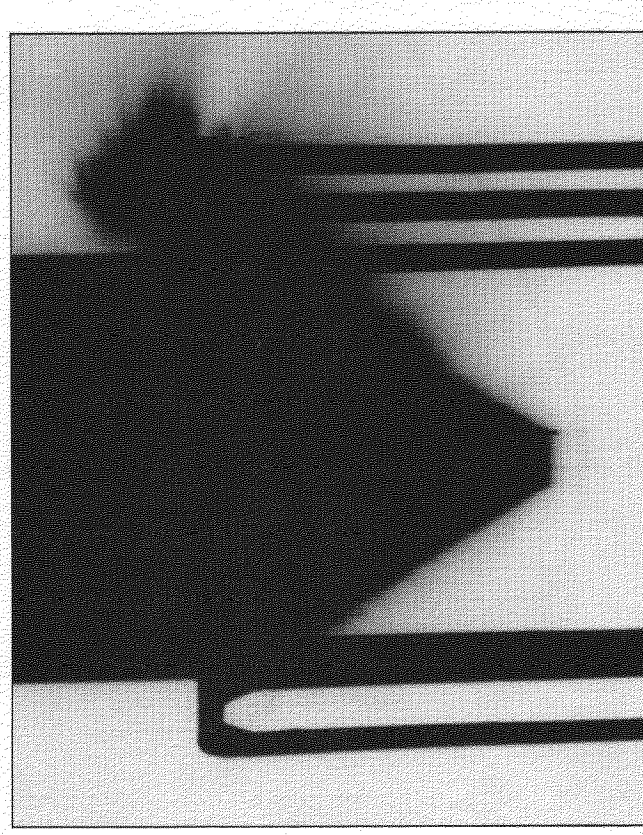
FIG.10d. (1750 ft./sec.)

FIG.10a-d. IMPACT OF 2 mm. DIAMETER WATER DROPS ON A CONICAL SURFACE OF 60° INCLUDED ANGLE AT VARIOUS SPEEDS
(SIDE VIEWS USING TRANSMITTED LIGHT)

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