PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Disintegration of Raindrops by Shockwaves ahead of Conical Bodies

D. C. Jenkins

Phil. Trans. R. Soc. Lond. A 1966 **260**, 153-160
doi: 10.1098/rsta.1966.0039

C. RAIN EROSION OF AIRCRAFT

XI. Disintegration of raindrops by shockwaves ahead of conical bodies

By D. C. Jenkins

Royal Aircraft Establishment, Farnborough, Hants

[Plates 28 and 29]

When an aircraft flies at high speed through rain the impact of raindrops on the forward facing surfaces of the aircraft may cause severe erosion damage depending on the size and number of the drops, the speed of the aircraft and the time of flight in the rain. However, before the raindrops reach the aircraft surface they have to pass through a region where they are subjected to relative air velocities caused by the airflow round the aircraft surface. This is particularly applicable to supersonic flight when, in the region between the shockwaves and the aircraft surface, the raindrops may be exposed to air velocities large enough to disintegrate them. The raindrop disintegration is not an instantaneous event; it takes short but finite time and appears to be an erosion process whereby droplets are torn off the surface of the main drop until it is completely reduced to a fine mist. The degree of disintegration of a drop by the time it reaches the aircraft surface will depend on the magnitude of, and the exposure time to, the air velocity. For supersonic flight this time depends on the distance travelled by the drop between the shockwave and the aircraft surface.

The experiments described had the object of determining the time required for high speed airstreams completely to disintegrate water drops. An empirical relation is postulated between D, the drop diameter, V, the airstream velocity and t, the time for complete disintegration. The paper considers a conical body at supersonic velocity in a raindrop environment, the body being of a shape typical of that envisaged for supersonic aircraft design. From the derived empirical relation for the time of disintegration of water drops the size of drops to be completely disintegrated when approaching the surface of cones of different vertex angles has been calculated for a range of flight Mach numbers. An experiment giving partial justification for computed results is described.

1. Introduction

When a raindrop approaches the surface of a fast-moving aircraft it is subjected to relative air velocities caused by the airflow round the aircraft surface. This is particularly applicable to supersonic flight when, in the region between shockwaves and the aircraft surface, the raindrop may be exposed to air velocities large enough to disintegrate it. The resulting disintegration of raindrops could lead to a reduction of the amount of rain erosion damage that would otherwise occur. The object of this paper is to use experimental data on the disintegration of water drops in an airstream and theoretical estimates of the air velocity in the region between cones and attached shockwaves in supersonic flight to calculate the size of the largest drops that are completely disintegrated in approaching the surface of cones of different vertex angles for a range of flight Mach number.

2. General

Essential information required in estimating the survival of a raindrop as it approaches the surface of a moving body, in this case a cone, is first the magnitude of the air velocities experienced by the drop, and secondly, the rate of disintegration of the drop under these air velocities so that the total time of survival can be calculated. In the case of supersonic cones the value of the components of the air velocity in the region between the attached shockwave and the cone surface are available in tabulated form (M.I.T. 1947). These have been used to calculate air velocities.

3. Tests on drop disintegration

There did not appear to be any reliable theoretical or extensive experimental data available on the survival time of waterdrops in airstreams so it was necessary to do some preliminary experimental work on this subject. The laboratory apparatus used for this work consisted of an airgun (Jenkins, Booker & Sweed 1958) already developed for studying the impact of water drops on a fast moving surface. The method of producing a short duration air blast consisted of using a long tubular projectile open at the front and closed at the rear, a diagrammatic arrangement of which is shown in figure 1. The projectile carries along with it a column of air moving at the same speed as the projectile.

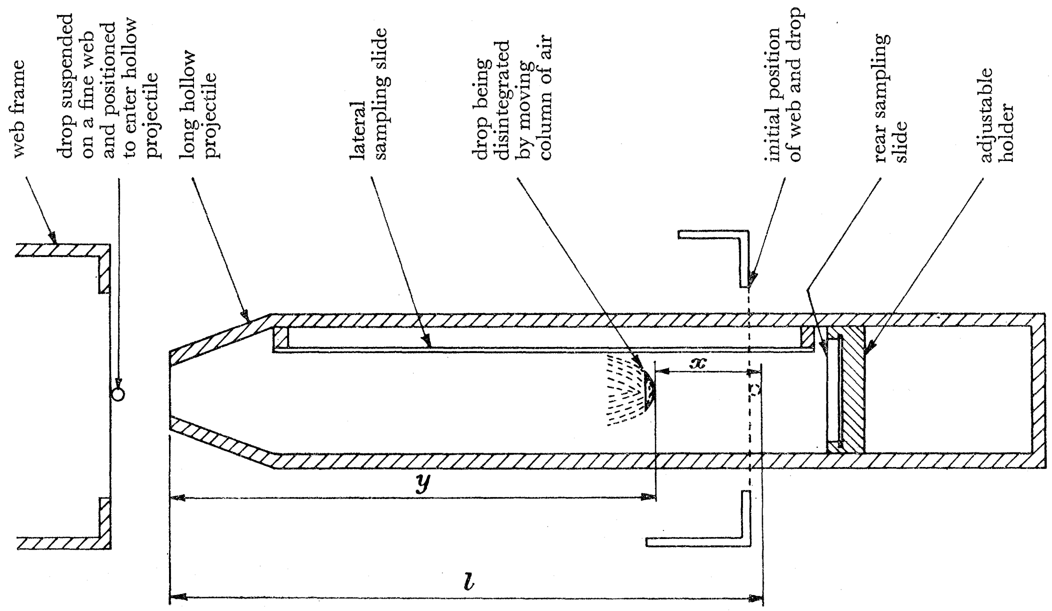

Figure 1. Diagrammatic representation of the hollow projectile method. x indicates the movement of the drop from the initial position on the web; y the penetration of the drop into the projectile and l is the movement of the projectile while the drop is inside.

The velocity can be measured by standard timing methods; in this case by the projectile breaking two timing wires placed a known distance apart. A water drop of known size is placed on an artificial web (figure 2, plate 28) positioned so that it will enter the open nose of the hollow projectile (figure 3, plate 28). On entering the projectile the drop is subjected to an air blast having a velocity equal to that of the projectile. The projectile can be caught without damage in an arresting device. By making the projectile of a transparent material it is possible to study the disintegration of the drop photographically as it is subject to the air blast (figure 4, plate 28). Alternatively, if the projectile is made of metal, droplet sampling slides can be carried inside and thus the progress of disintegration with depth of penetration into the projectile can be ascertained. In particular if a sampling slide is

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

placed across the inside of the projectile (figure 1) and positioned near the open nose at a depth of penetration where disintegration is only partial, then some very small droplets from the disintegration process will be collected on the slide, together with some large droplets from the residue of the undisintegrated drop. If successive shots are made of drops of the same size and projectile velocity and with the sampling slide placed inside the projectile at successively increasing distances from the entry point the number and size of the residue droplets decreases as the disintegration standard is increased. At the point where disintegration is complete only very fine droplets from the disintegration process are collected on the sampling slide. Complete disintegration has been arbitrarily taken to be the condition where no droplets greater than 150 μm are collected. For each case considered the movement l in feet of the projectile while the water drop is inside has been found (see figure 1) and the time in seconds that the drop has been exposed to the airstream is then given by

$$t = l/V,$$

where V (ft./s) is the speed of the projectile.

4. Time to disintegrate drops

A number of cases with different drop sizes and projectile speeds were considered and the time for complete disintegration was found in each case. From the results an empirical relation was found (Jenkins & Booker 1964) connecting t (s), the time for complete disintegration, D (ft.) the drop diameter and V (ft./s) the air blast velocity in the form

$$t = 20D/V^{0\cdot72}. \tag{1}$$

In deriving this empirical formula two sets of cases were considered, first with D constant and different values of V, and secondly, with V constant and different values of D. In both sets of cases the other liquid and airstream parameters were constant with the exception of a small variation of air density in the projectile due to ram effect.

5. Discussion of results

Equation (1) at first sight does not appear dimensionally consistent, this is because not all the parameters possibly connected with the disintegration process are present. In particular the effect of airstream density, temperature and viscosity is not given. However, a comparison of times predicted by the use of the above formula with disintegration times measured photographically by Engel (1958) suggests that the effect of these parameters on the disintegration time is small. The case quoted by Engel is of 1·4 mm diameter water drops disintegrated by the airstream following plane shockwaves where fairly high temperatures and densities exist. In calculations in this paper on disintegration times, no special allowance has been made for variations in the value of these parameters.

Table 1 gives a comparison between disintegration times for 1·4 mm diameter water drops found by the use of the empirical formula and those found by Engel by judging photographically when the drops had been completely reduced to a fine mist.

It is seen that quite close agreement is given. The experimental test conditions on which the empirical results were based did not have the high airstream temperatures or densities associated with shockwave conditions as used by Engel, but in view of the close agreement in the results it is assumed that the effect of the higher values of these parameters on the disintegration process is small.

TABLE 1

V (ft./s)	disintegration time (ms) Engel	empirical
498	0·90	1·05
777	0·70	0·76
1036	0·58	0·62

6. Analytical method

6·1. *Basic formula*

From equation (1) the diameter of drop D that is disintegrated when acted on by an airstream of constant velocity V for time t is given by

$$D = tV^{0\cdot72}/20. \tag{2}$$

When t and V are known for a particular case D can be calculated. It is found experimentally (Green & Lane 1956), however, that there is a minimum value of V for each drop size below which the drop does not disintegrate.

6·2. *Assumptions*

In applying equation (2) to calculate the size of drop that is disintegrated by the non-constant air flows experienced by a drop in the region between a cone surface and the attached shock wave it has been assumed that the average value of $V^{0\cdot72}$ along the trajectory can be used. For convenience in making calculations the cone has been considered stationary with the airstream and raindrop approaching it at speed U_0. In order to simplify the calculation of t and V it has been assumed that after passing through the shockwave the raindrop is not decelerated or deflected but continues to move in a straight line at its original speed U_0 up to the cone surface (see figure 5). It has been further assumed that the shockwave itself does not play a part in disintegrating the drop, but that disintegration is due only to the relative air velocities experienced by the drop. As the drop starts to move along the trajectory AB the resultant air flow is inclined at a small angle to the trajectory. The component at right angles to the line of flight will cause the drop to follow a path such as AD (shown dotted in figure 5). The resultant component of air velocity along the trajectory will tend to decelerate the drop. This causes it to take a longer time to travel between the shockwave and the cone surface and reduces the relative air velocity causing disintegration. It can be seen from equation (2) that the consequent changes in these two parameters have opposite effects in determining the size of drop that is disintegrated. To calculate accurately the true velocities and the time that the drop is in the airstream it would be necessary to make a complicated step by step calculation of the trajectory of a disintegrating drop. The assumption of zero deceleration and deflexion of the drop seems

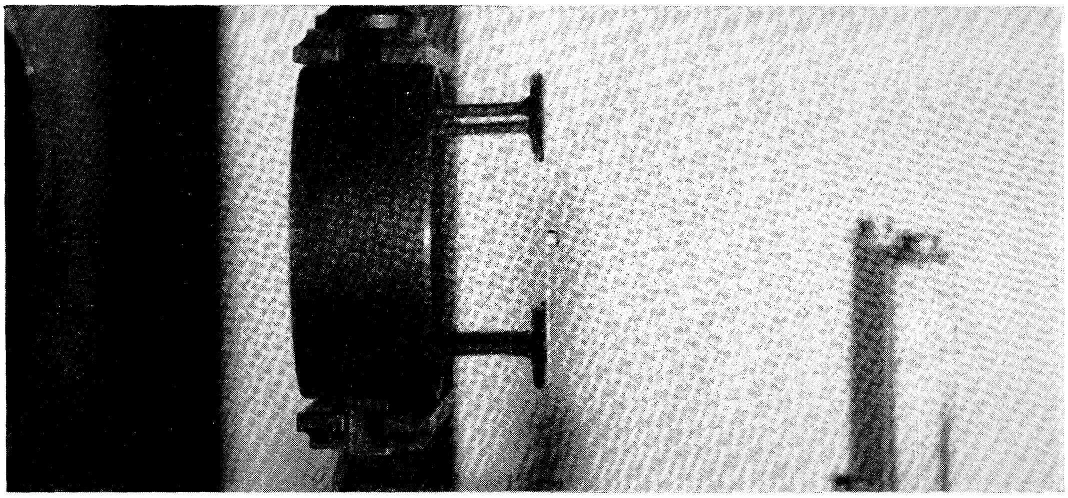

FIGURE 2. Water drop (2 mm diameter) suspended on a fine web.

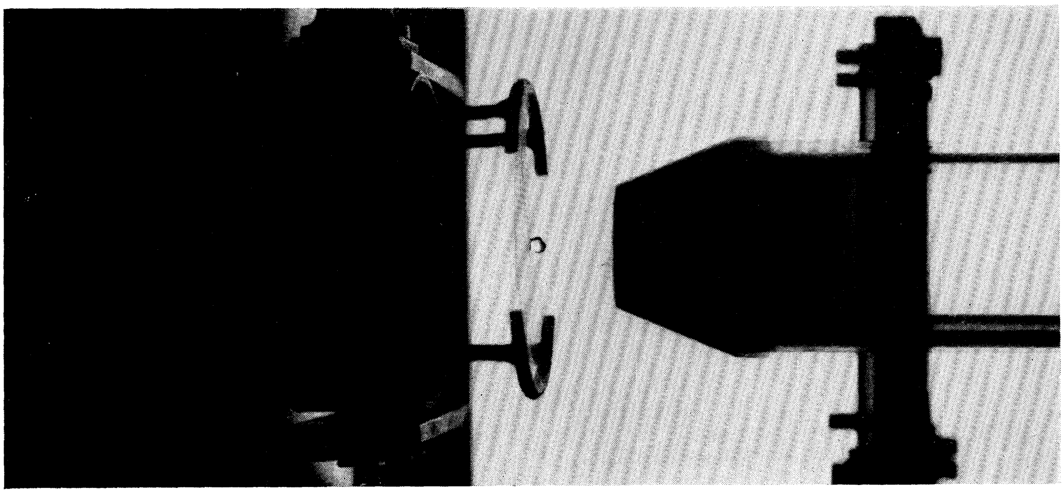

FIGURE 3. Water drop (2 mm diameter) about to enter a hollow projectile moving at 560 ft./s.

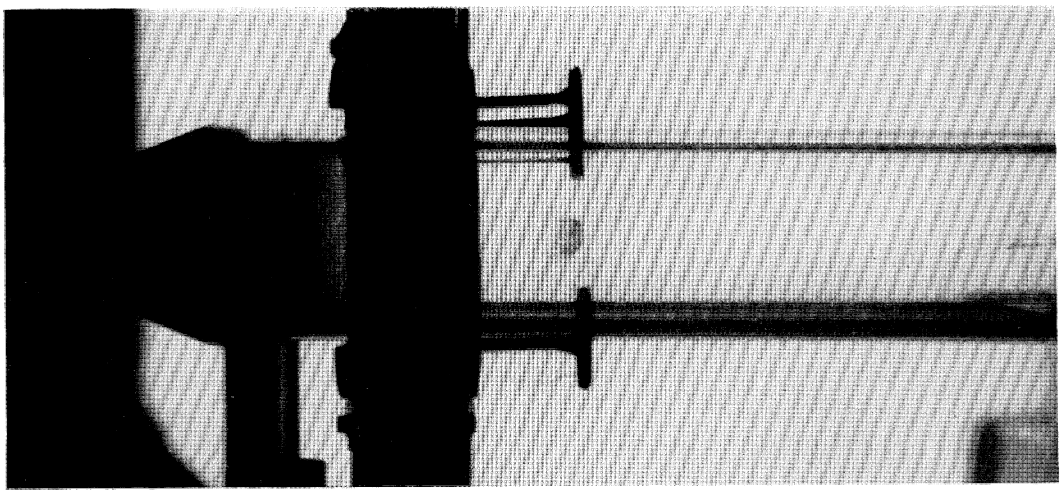

FIGURE 4. Breakup of a 2 mm diameter water drop inside a hollow projectile moving at 560 ft./s.

(*Facing p.* 156)

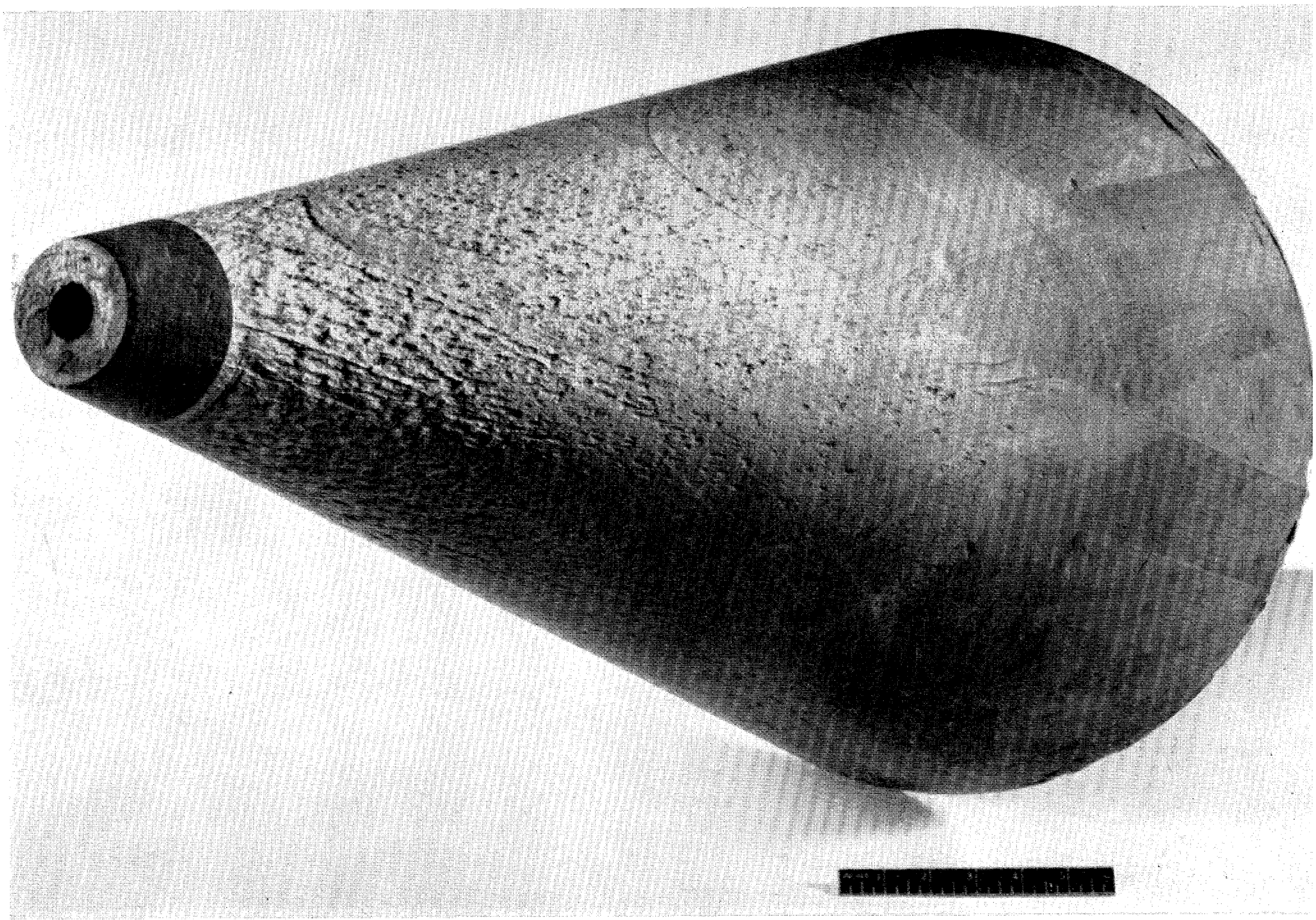

FIGURE 7. Balsa wood cone (semi-angle 30°) after traversing a 500 ft. belt of artificial rain of intensity 6·0 in./h at an average speed of $M = 1{\cdot}03$.

a reasonable compromise to avoid this complication. With this assumption the air velocity relative to the drop at a point C on the trajectory AB is given by (Jenkins 1957):

$$V = M_0 a_0 \left[1+\left(\frac{U_1}{U_0}\right)^2 - 2\left(\frac{U_1}{U_0}\right)\cos(\theta-\omega)\right]^{\frac{1}{2}}, \tag{3}$$

where
$$\left(\frac{U_1}{U_0}\right)^2 = \left[1+\left(\frac{2}{\gamma-1}\frac{1}{M_0^2}\right)\right]\left[\left(\frac{u}{c}\right)^2+\left(\frac{v}{c}\right)^2\right]. \tag{4}$$

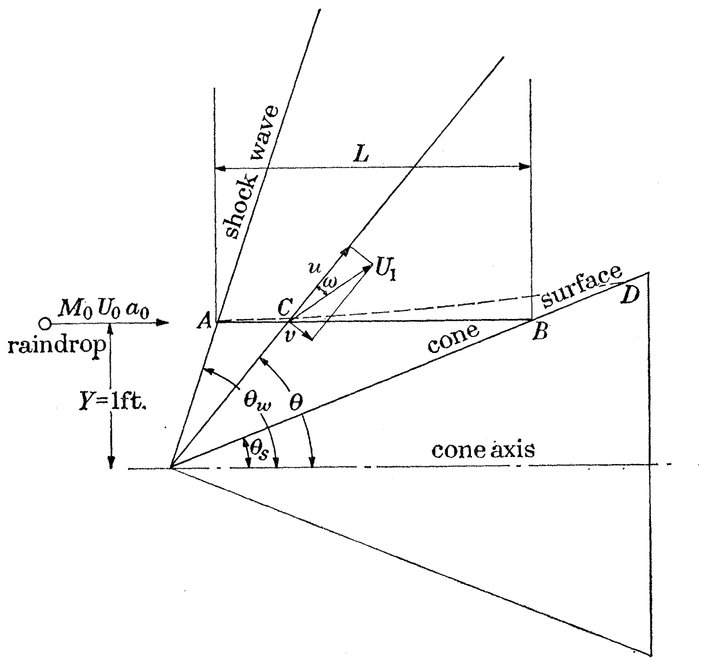

FIGURE 5. Geometry of the cone-shockwave system.

M_0 is the speed of the raindrop and the airstream approaching the cone expressed as a Mach number ($M_0 = U_0/a_0$); (u/c) and (v/c) are the nondimensional velocity components of the airstream at a point C on the path AB and depend on θ only. The symbol c stands for the speed the air would have if allowed to expand adiabatically into a vacuum and is related to the conditions ahead of the shockwave by the equation

$$c^2 = U_0^2\left[1+\frac{2}{\gamma-1}\frac{1}{M_0^2}\right]. \tag{5}$$

From these formulae and tabulated values of u/c and v/c the average value of $V^{0.72}$ along the path AB has been calculated for a number of cases of cone angle and flight Mach number. The path length AB ($=L$) can be calculated from the cone semi-angle θ_s the shockwave angle θ_w and the distance y of the drop from the cone axis. Taking y to be 1 ft. then

$$L = (\cot\theta_s - \cot\theta_w). \tag{6}$$

In view of the assumption made that the drop is not decelerated or deflected, the time for the drop to move the distance L is given by

$$t = \frac{L}{U_0} = \frac{L}{M_0 a_0}; \tag{7}$$

hence from equation (2)
$$D = \frac{L(V^{0.72})_{\text{av.}}}{20 M_0 a_0}. \tag{8}$$

7. Drop disintegration

The size of drop disintegrated has been calculated from equation (8) for cone angles of 10°, 20°, 30° and 40° and for flight Mach numbers up to a maximum of about 2·5 and the results plotted in figure 6. This figure shows the variation with Mach number of the diameter of the drop that is completely disintegrated on approaching cones of different vertex angles at a distance of 1 ft. from the axis. By the nature of the assumptions made

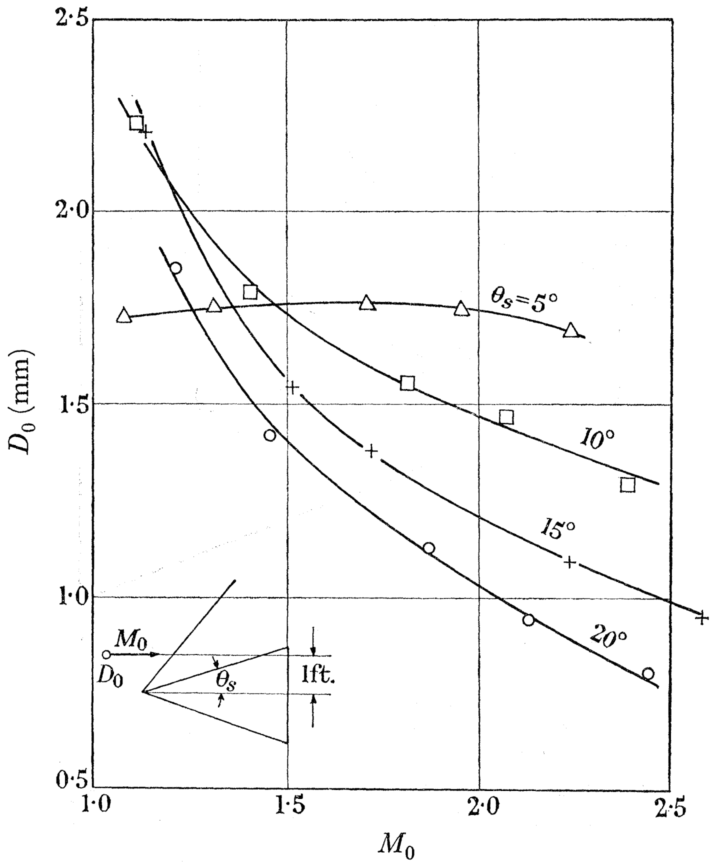

Figure 6. Variation with Mach number of the diameter of the drop that is disintegrated on approaching a cone of semivertex angle θ_s at a distance of 1 ft. from the axis.

and the theoretical solution used to calculate the flow velocities in this analysis the values of V are constant for all drop trajectories such as AB, for a given flight case irrespective of the distance y of the trajectory from the axis; also the time t to traverse the distance from the shockwave to the cone surface varies linearly with the distance from the cone axis. Hence, from the results of figure 6 the size of drop that is disintegrated on approaching the cone at any distance from the axis can be found by simple proportion. Thus if a drop of diameter D is completely disintegrated on approaching the cone at a distance of 12 in. from the axis then under the same flight conditions a drop of diameter $\frac{1}{2}D$ will be completely disintegrated on approaching the cone at a distance of 6 in. from the axis.

In figure 6 it is seen that above a Mach number of about 1·5 the size of the drop that is disintegrated increases with decreasing cone angle and decreases with increasing Mach number. These are presumably effects due to variations in L the trajectory length with cone angle and Mach number. From equation (1) the 'dwell' time t (which depends on L) is more important than the velocity V.

8. Tests on cones

An attempt has been made by Mr R. B. King to prove experimentally predictions of drop disintegration from this analysis. A cone of vertex angle 30° and base radius 9 in. was made in balsa wood, fixed to a rocket sled and thereby driven at high speed through an artificial rain belt. Balsa wood was chosen as it is readily marked by high speed raindrop impacts and any regions not marked can be taken to correspond to regions where the raindrops have been disintegrated. The rain belt was 500 ft. long and the rain was of an average intensity of about 6 in./h with 79 % of the raindrops lying in the size range 1·2 to 2·8 mm diameter. The average speed through the rain belt was at a Mach number of 1·03 with a maximum Mach number of 1·09 and a minimum value of 0·945. It is to be noted that for a cone of 30° vertex angle the minimum Mach number for which a conical flow type of solution is possible is $M = 1{\cdot}119$. Above this speed the velocity components are constant along a radius vector through the apex and depend only on the angle of the vector. At Mach numbers below this minimum value a conical flow solution does not exist and the shockwave may become detached from the cone. There is thus no obvious justification for extrapolating the 30° cone results of figure 6 down to Mach numbers below 1·119, but if this is done it is seen that the results would suggest that drops up to about 1·9 mm diameter would be disintegrated in approaching the cone at a distance of 9 in. from the axis at a Mach number of $M = 1{\cdot}03$ and also that drops larger than 1·9 mm diameter would experience a considerable reduction in size due to partial disintegration. As 79 % of drops of the artificial rain used were in the size range 1·2 to 2·8 mm diameter it is clear that a considerable reduction in rain erosion damage should occur at the base region if this degree of disintegration did in fact occur. The erosion damage would also steadily increase as the apex region of the cone is approached. This, in general, is the result achieved as can be seen in figure 7, plate 29, which shows the cone after being driven through the rain belt. In order to establish if the reduction in rain erosion damage achieved is in agreement with what could be predicted it would be necessary to make calculations of the flow velocities experienced by the drops in the region of the 30° cone at the appropriate Mach number of 1·03 using linearized flow theory, which is the best that can be done in the absence of a transonic theory. In figure 7 the cone is shown truncated but during tests a metal retaining head completed the full solid of revolution.

9. Conclusions

In conclusion it does appear that the analysis presented here can be used to predict the degree of reduction in rain erosion damage to be expected for a cone in supersonic flight through rain due to disintegration of raindrops by shockwaves. The experimental attempt to prove predictions made by this method was only partially successful in that the speed achieved in the tests was too low. It is hoped at a future date to make further proving tests by using a high speed rocket sled that is at present being developed.

References (Jenkins)

Engel, O. G. 1958 Fragmentation of water drops in the zone behind an air shock. *J. Res. Natn. Bur. Stand.* vol. 61, no. 3.

Green, H. L. & Lane, W. R. 1956 Mechanics of drops and bubbles. From *Surveys in mechanics*. Cambridge University Press.

Jenkins, D. C. 1957 Note on the possibility of raindrops being shattered by the air disturbances caused by a moving body. *Tech. Notes R. Aircr. Establ.* (*Mech. Engng*), no. 239.

Jenkins, D. C. & Booker, J. D. 1964 The time required for high speed airstreams to disintegrate waterdrops. *Tech. Notes R. Aircr. Establ.* (*Mech. Engng*), no. 401.

Jenkins, D. C., Booker J. D. & Sweed, J. W. 1958 An experimental method for the study of the impact between a liquid drop and a surface moving at high speed. *Rep. Memo. aeronaut. Res. Coun.* no. 3203.

M.I.T. 1947 Tables of supersonic flow round cones. *M.I.T. Tech. Rep.* no. 1.

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF

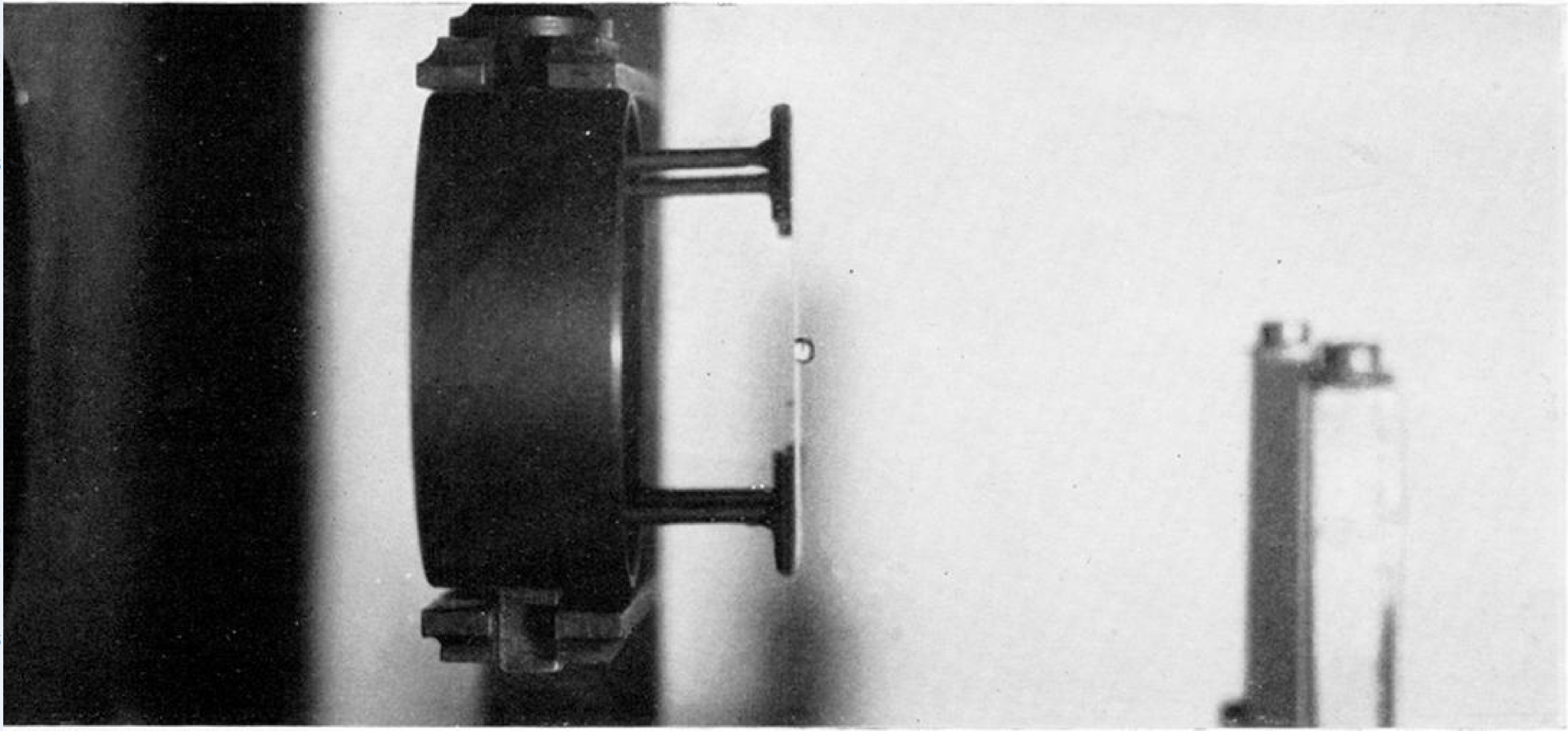

FIGURE 2. Water drop (2 mm diameter) suspended on a fine web.

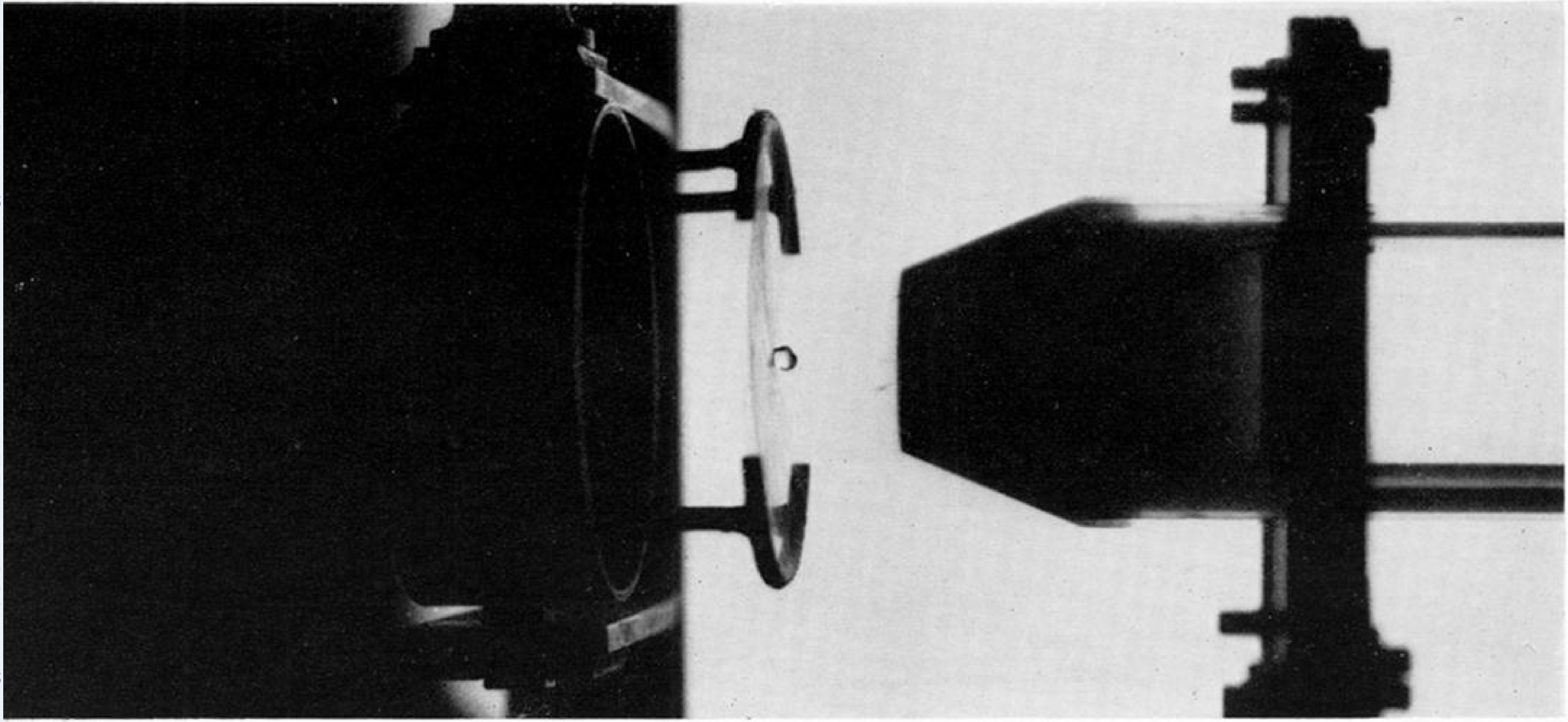

FIGURE 3. Water drop (2 mm diameter) about to enter a hollow projectile moving at 560 ft./s.

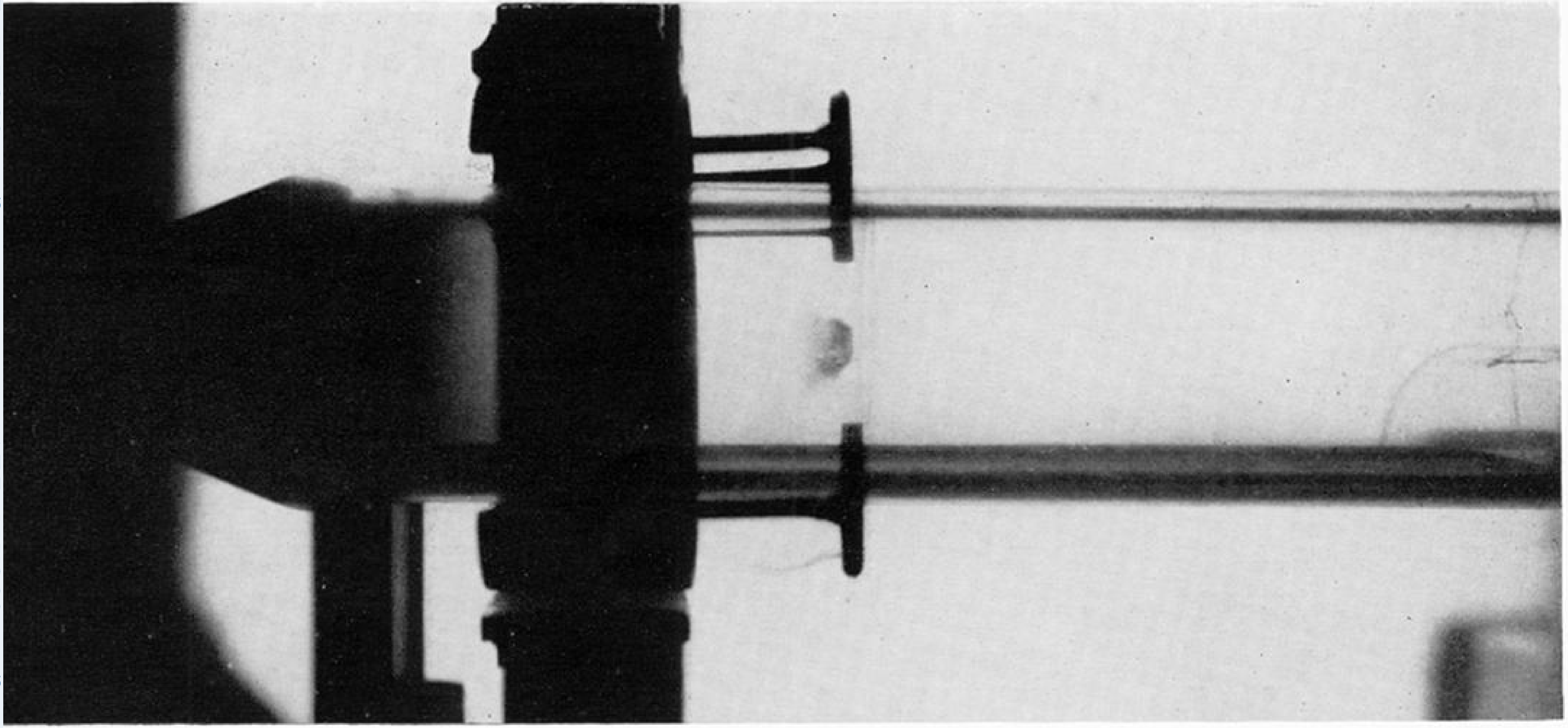

FIGURE 4. Breakup of a 2 mm diameter water drop inside a hollow projectile moving at 560 ft./s.

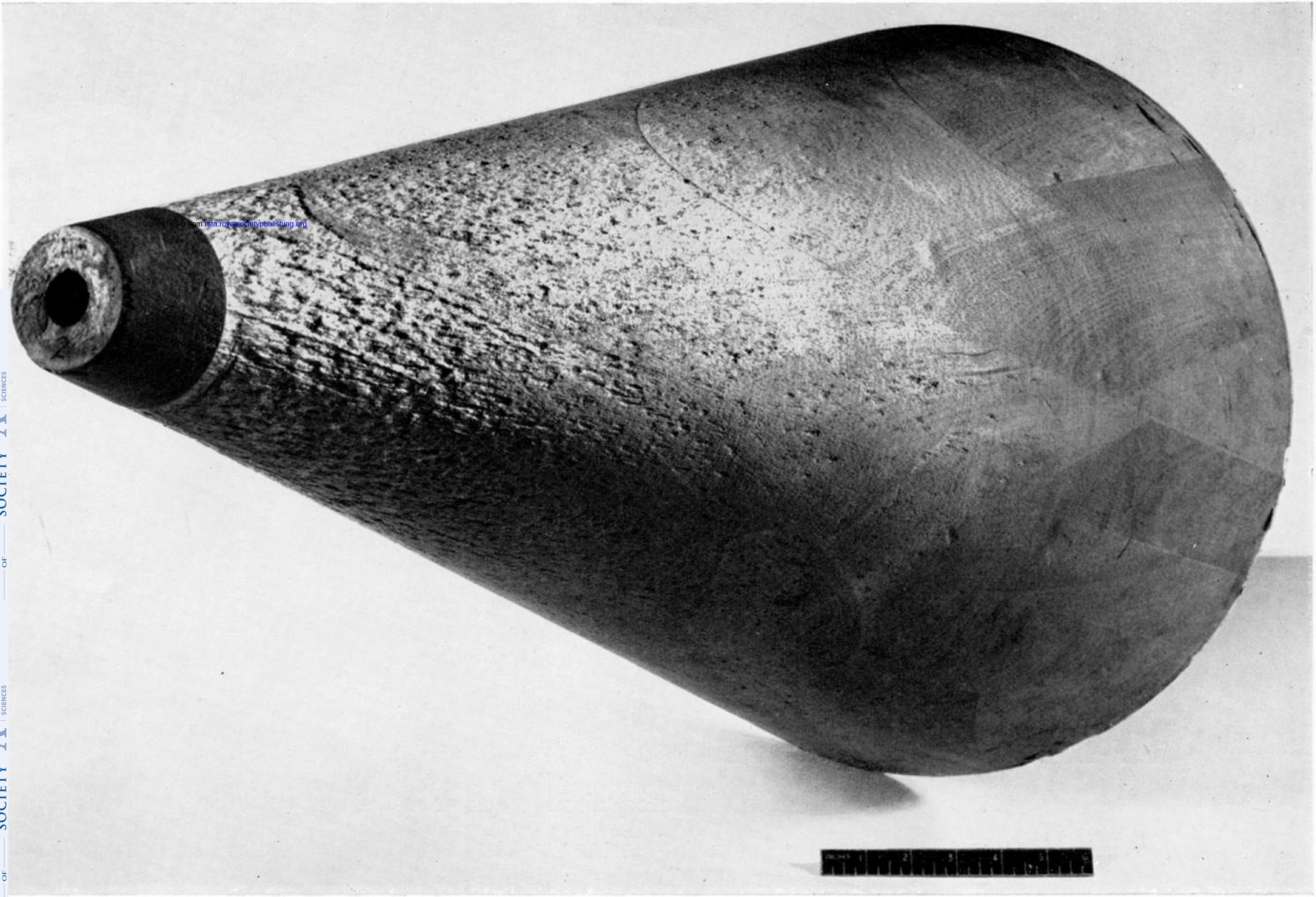

FIGURE 7. Balsa wood cone (semi-angle 30°) after traversing a 500 ft. belt of artificial rain of intensity 6·0 in./h at an average speed of $M = 1{\cdot}03$.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES