THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

# PRELIMINARY WATER-JET IMPACT STUDIES USING A GAS GUN MOMENTUM EXCHANGE FACILITY

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March, 1967

IP-770

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ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance of Michigan Memorial Phoenix Project Number 322, in the development of much of the equipment used and to thank the Mechanical Engineering Department for the use of their Dynafax Camera.

This report is based largely upon the term paper[1] submitted by one of the authors, Paul Drucker, in partial fulfillment of the requirements for the Master's Degree in Nuclear Engineering at the University of Michigan.

Much of the experimental equipment used was designed by H. G. Olson of the Nuclear Engineering Department for use in connection with his Ph. D. dissertation[2] which contains much related material concerning damage caused by the jet impact mechanism associated with cavitation bubble collapse.

Paul Herman of the Michigan Memorial Phoenix Project designed and built the time-of-flight measuring apparatus.

## ABSTRACT

A gas gun and a momentum exchange device are used to produce a high velocity jet to simulate rain erosion damage to materials. The operation and calibration of the test equipment is described. With the use of a high speed camera, the formation and impingement of the high velocity jet are studied and the results compared with those of other investigators. In order to obtain a better estimate of the shape and velocity of the water-jet which produces the erosion damage, many pictures were taken of the jet with the target specimen removed. The results indicate that the jet velocities obtained are comparable to the relative velocity between a supersonic aircraft and a falling raindrop. Further work is required to more completely determine the factors influencing the shape of the water-jet; to "tailor" the jet into a configuration most closely resembling a rain-drop; and to compare the damage resulting from a high velocity liquid jet impacting a stationary target to that of a supersonic aircraft impacting a falling raindrop.

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

PRELIMINARY WATER-JET IMPACT STUDIES

USING A GAS GUN-MOMENTUM EXCHANGE FACILITY

## I. INTRODUCTION

The problem of liquid drops impinging on the surface of aircraft flying at high speeds has become increasingly serious as the speed of these aircraft has been increased. This problem is not, however, unique to high speed aircraft; similar damage has occured on turbine blades from droplet impingement and on missle re-entry cones.

Although various models have been proposed to describe the manner in which the damage occurs, no clear-cut explanation of the mechanism exists today that is applicable to all substances. The resistance to fluid impact damage is certainly a function of the mechanical properties of the material. It is also dependent upon drop size and shape, and the number of impacts, and will occur in significant amounts only above a minimum velocity for a given drop size, fluid and test material. This threshold velocity is also dependent upon the manner in which the specimen is supported.

This report is concerned with the design and operation of one type of facility to study the mechanism of rain erosion damage by observing the impingement of a liquid jet or droplet on selected target materials. In this facility the liquid is propelled by momentum exchange with a pellet from a gas gun, in a manner similar to that used by Bowden and Brunton(3).

## II. DESCRIPTION OF EXPERIMENT AND EQUIPMENT

A high velocity water jet is obtained by placing a water droplet in a small cavity which is then submitted to a sudden pressure pulse from the impact of a pellet from a gas gun. Under the influence of the resulting sharp pressure rise, the water is forced through a nozzle and accelerated to a high velocity. The resulting water jet or slug is directed against a target specimen to simulate the impingement of rain on the surface of high velocity aircraft.

The high pressure pulse necessary to accelerate the water jet is obtained by firing a lead pellet into a sealing disc which forms one side of the water cavity as shown in the sketch of Figure 1. The disc is free to move axially into the cavity against the water, resulting in a relatively efficient exchange of momentum between the pellet and the water.

The water cavity initially used was formed by a 5.5 mm diameter hole, 3.16 mm long, in a stainless steel block. This hole converges to form a nozzle with a throat diameter of 0.5 mm at the exit. In later tests, the cavity hole diameter was increased to 6.1 mm. The nozzle dimensions were specified to obtain a nozzle of the same design as that used by Bowden and Brunton(3). For each test the cavity is loaded with a given volume of water (usually about 0.02 to 0.07 cc) and sealed by the impact disc. In the initial tests, a neoprene disc 0.125 inches thick was used. Later tests were conducted using discs of teflon and also of a thinner neoprene material. A photograph of the nozzle and cavity with the impact disc removed is shown in Figure 2.

The lead pellet is fired into the impact disc by a 0.22 caliber gas gun. The rifle, originally designed to use $CO_2$ cartridges as

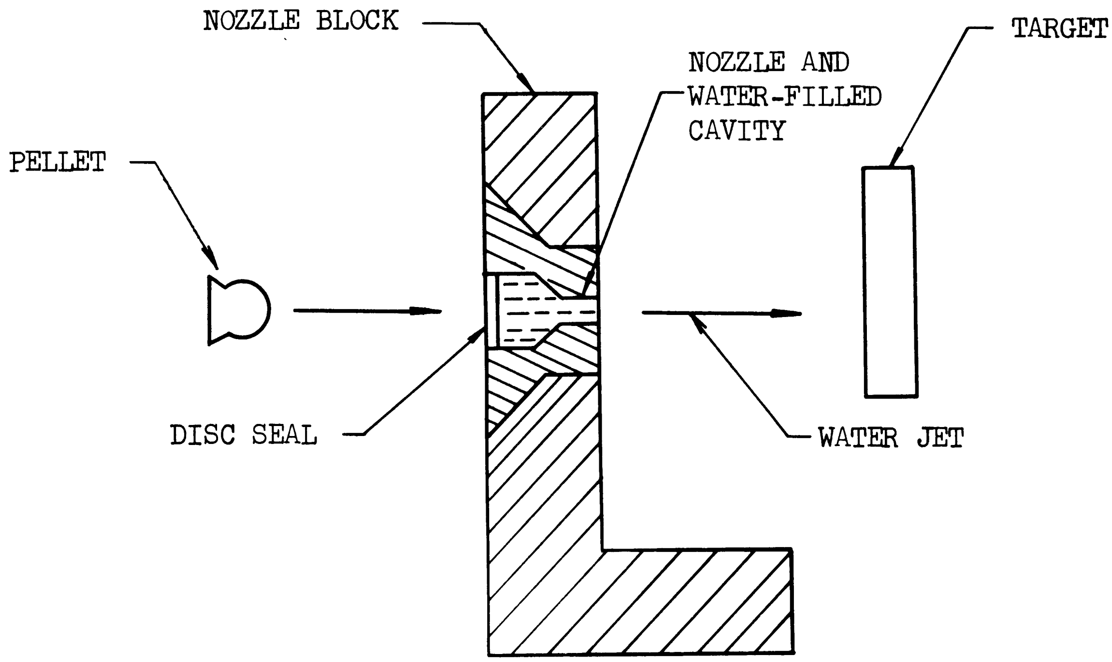


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Figure 1. Sketch of Momentum Exchange Device.

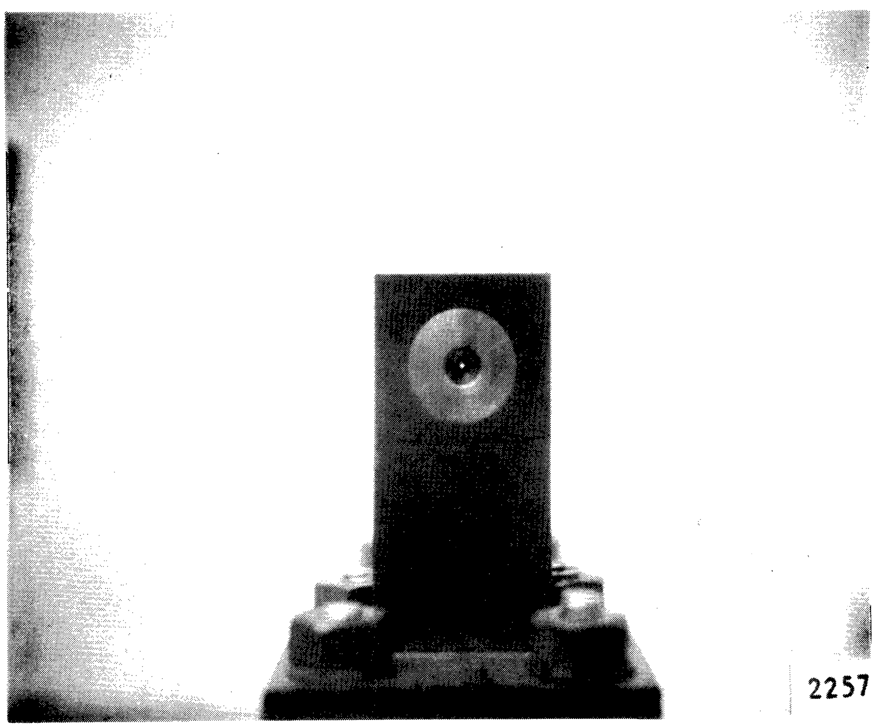

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Figure 2. Nozzle and Water Cavity with Impact Disc Removed.

a propellant, was modified to use nitrogen from high pressure tanks. Although the exact pressure limits for the rifle are not precisely known, pressures up to 325 psig were used in these tests, and presumably somewhat higher pressures are possible.

The velocity of the lead pellet is determined by use of a time-of-flight apparatus which consists of an electronic timing circuit and two photoelectric cells. These photo-cells, initially located 15 cm apart along the flight path of the pellet, produce a pulse whenever the pellet interrupts a light beam, which is directed across the flight path to the photo-cell. The pulse from the first cell triggers the on-gate of the timing circuit and the second pulse (from the second photo-cell) triggers the off-gate. The time required for the pellet to traverse the distance between the light beams is displayed on a four-decade register. This circuit provides time measurements accurate to within 2 microseconds.

The pulse from the first photo-cell also activates an adjustable time-delay circuit which controls a light source. With the desired delay time set into the circuit (approximately 1.5 milliseconds in these tests), a pulse from the time delay circuit triggers the light source which provides a flash of approximately 2. milliseconds duration. This apparatus is used in conjunction with a high-speed camera to obtain photographs of the water jet and its subsequent impingement upon a specimen.

The photo-cells are positioned with the outer edge of the first cylinder in line with the end of the rifle barrel to minimize the flightpath of the pellet so that the pellet will experience the least possible vertical drop before reaching the target.

The flash unit (a 1.5 joule bulb) is placed 15 inches from the target and aligned so that the center of the bulb is in direct line with the camera lens of which the field of view includes the target specimen and the nozzle arrangement (Figure 3). The face of the unit is covered with ordinary tracing paper in order to evenly distribute the light for photographic purposes. A photograph of the test facility is shown in Figure 4.

A Dynafax camera with a maximum framing rate of 26,000 has been used. In all tests to date, the pictures were taken at either 20,000 or 25,000 frames per second, i.e. frame separation is 40 or 50 microseconds. However, this framing rate proved much too slow for a detailed study of the jet in flight. It is evident that a framing rate of $10^6$ frames per second will be necessary to analyze the jet in detail as it approaches and impinges upon the surface of the target. This laboratory expects to obtain such a camera in the reasonably near future through an N.S.F. grant, which has now been approved. On the basis of past experience with the Dynafax camera, Kodak Plus X Pan film (35 mm) was selected as most suitable for this work.

The shutter of the Dynafax camera is operated manually; it is held open for about 2 seconds during which time the entire sequence of pictures is obtained. This shutter is necessary only to close the camera when not in use and prevent lengthy exposures of the film; the duration of the light pulse controls the total exposure time during the sequence, and prevents multiple exposure.

In these tests the target-to-nozzle distance was varied between 0.026 and 0.50 inches. These distances were chosen in accordance with the Bowden and Brunton study[3] in which it was found that for a

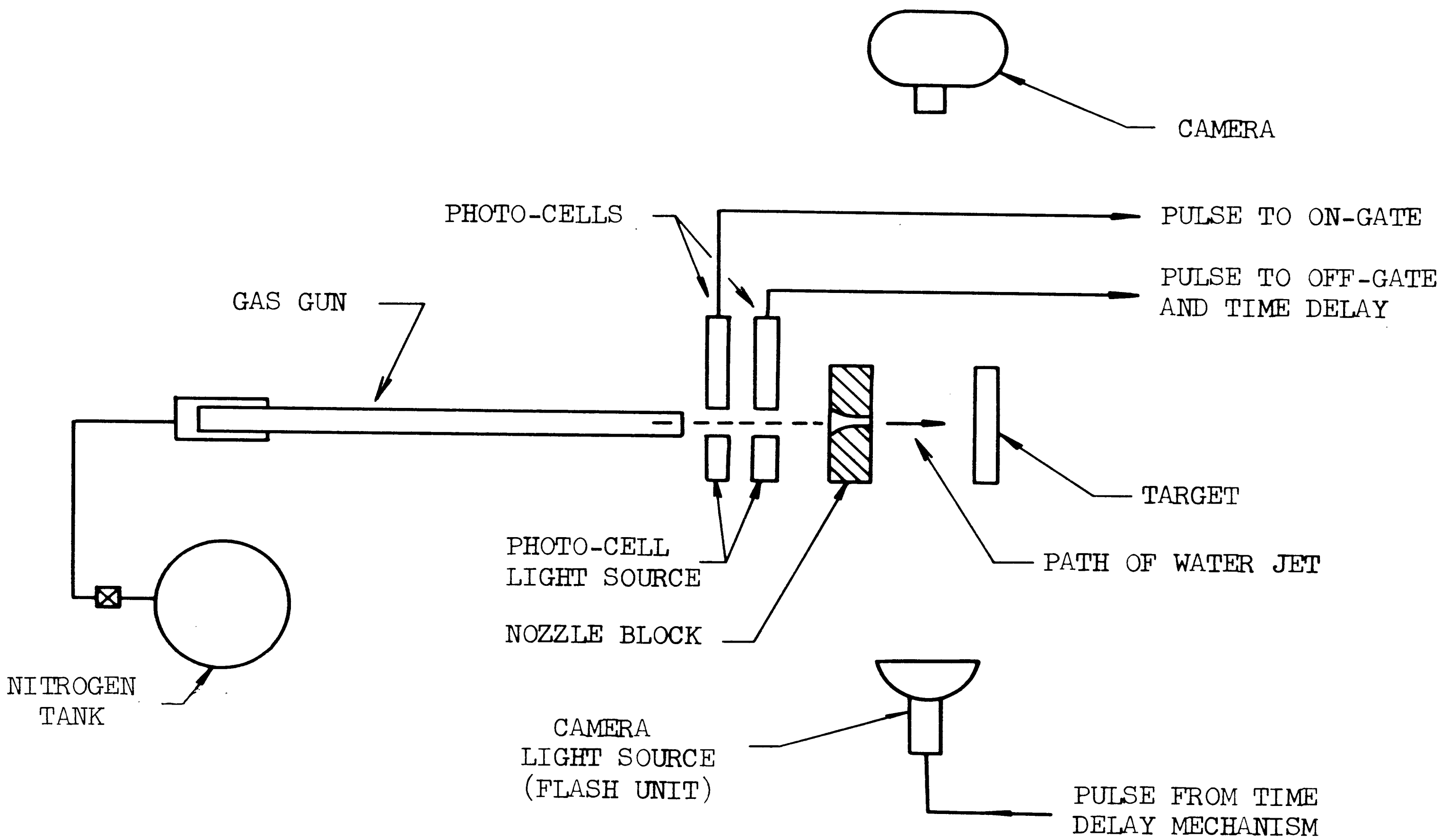


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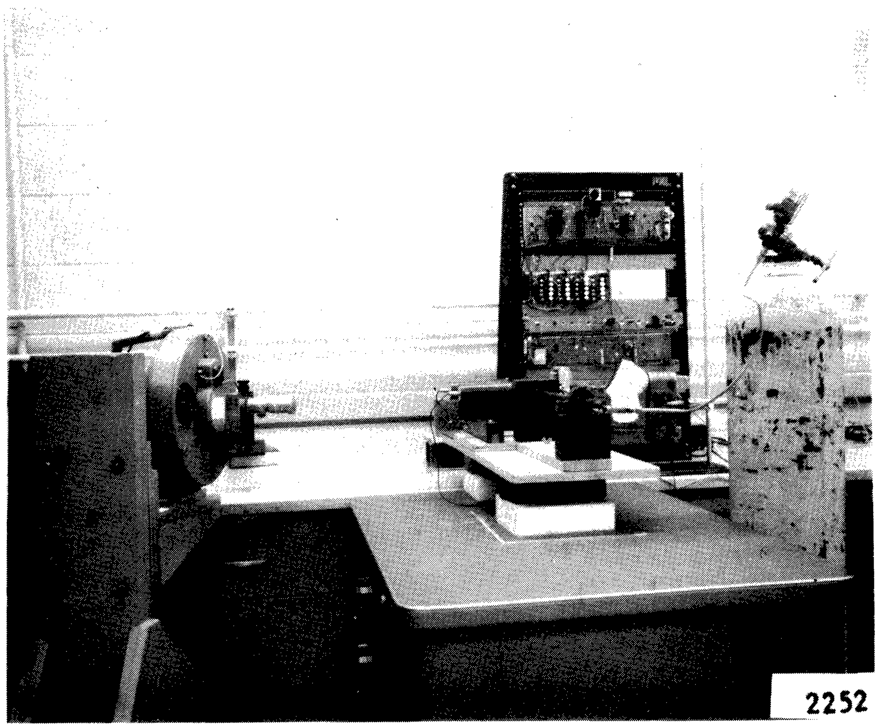
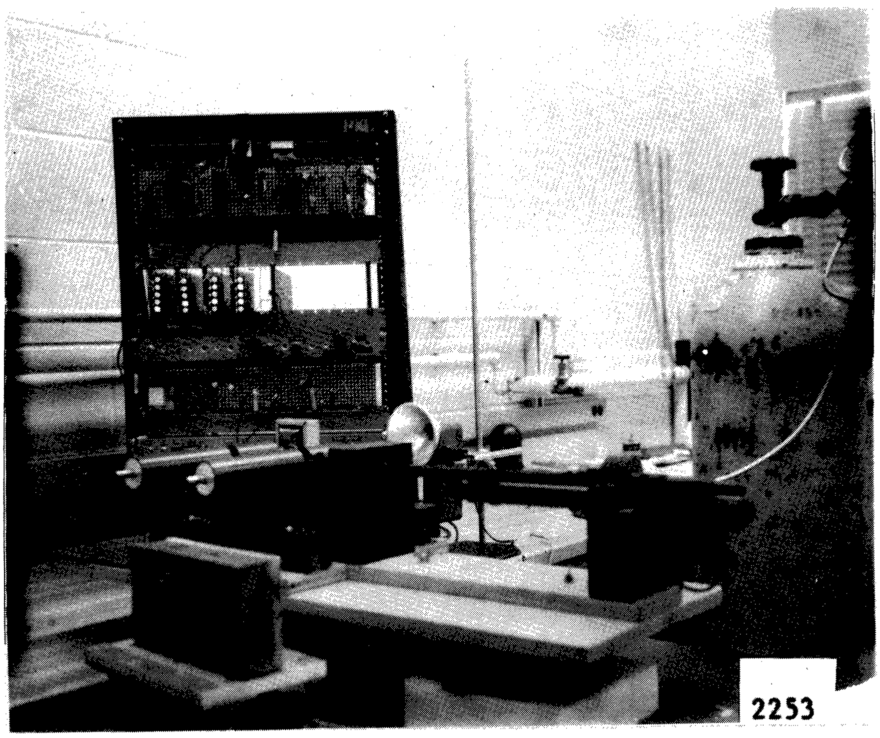
Figure 3. Sketch of Experimental Apparatus for Liquid-Jet Impingement Tests.




(a)




(b)

Figure 4. Photographs of the Liquid-Jet Impingement Test Apparatus.

distance greater than 12 mm (0.473 inch) the jet begins to turn back on itself to form an envelope. With the jet thus distorted from its original shape the interpretation of the damage mechanism, in terms of rain erosion droplets, becomes more difficult. However, photographic studies of the jet with the target removed indicated jet distortion at much less than 0.473 inches with the present equipment.

The four support posts for the test specimen holder are so arranged that a test specimen and its support piece is a 1.250 inch plexiglas square, 0.125 inch thick, with a central 1.18 inch diameter hole so that the back face of the test specimen is a free surface.

## III. CALIBRATION OF EQUIPMENT

The variation of the pellet velocity with the chamber pressure of the rifle was obtained using two pressure regulators. (Airco Regulator for the lower chamber pressures and a Victor Regulator for the higher pressures) A minimum rifle chamber pressure of about 80 psig was required to prevent the pellets from sticking in the rifle barrel.

At each pressure, 25 velocity points were recorded; the data assumed a normal (Gaussian) distribution. The resulting calibration curves are shown in Figure 5 and Figure 6. The relationship between pellet velocity and pressure was linear indicating that frictional resistence in the barrel is controlling. Note that the standard percent deviation in velocity obtained for a given pressure setting is about 7% for the lower pressure range and about 3% for the higher.

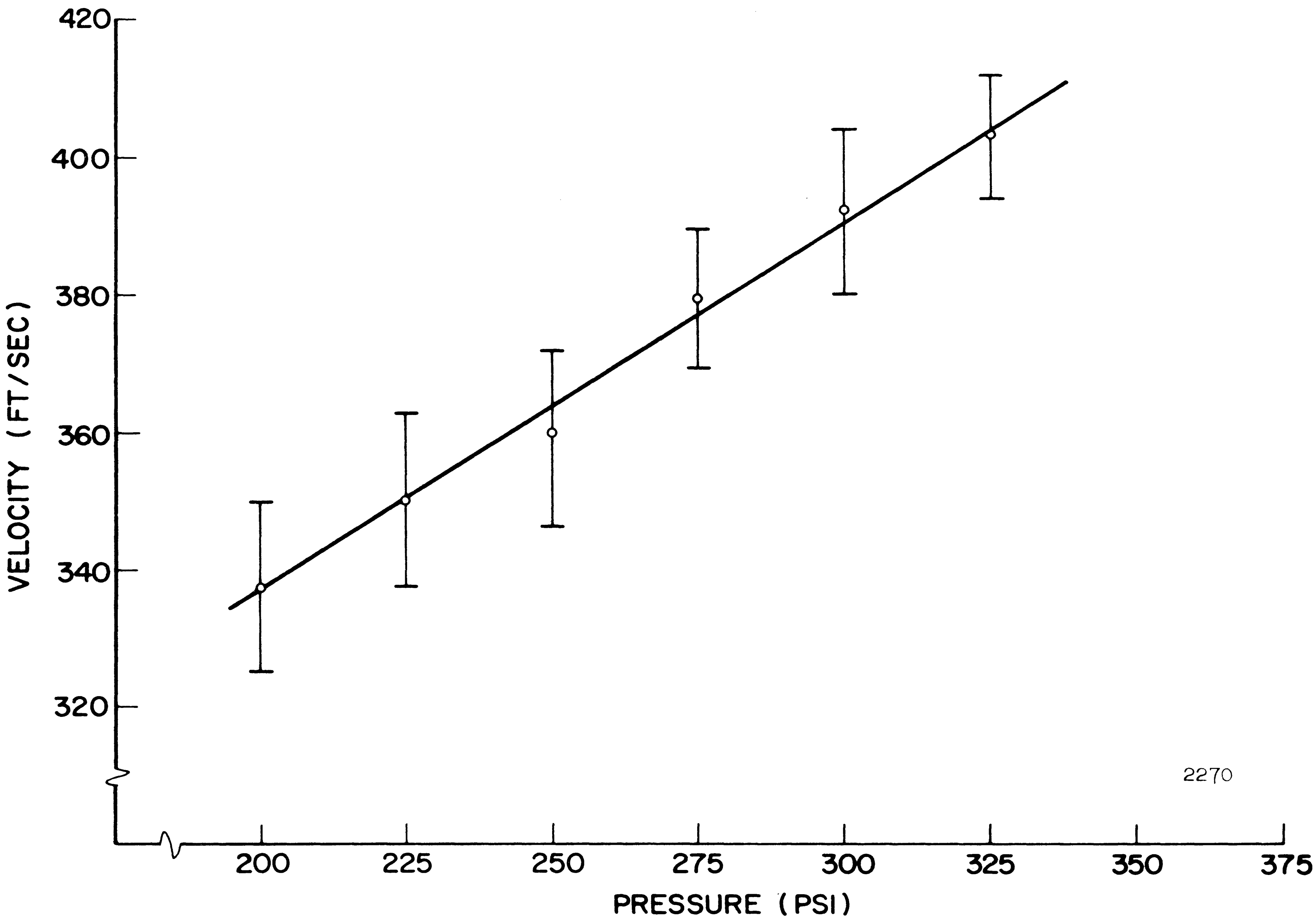



Figure 5. Rifle Pressure vs. Pellet Velocity for Victor Company Regulator.

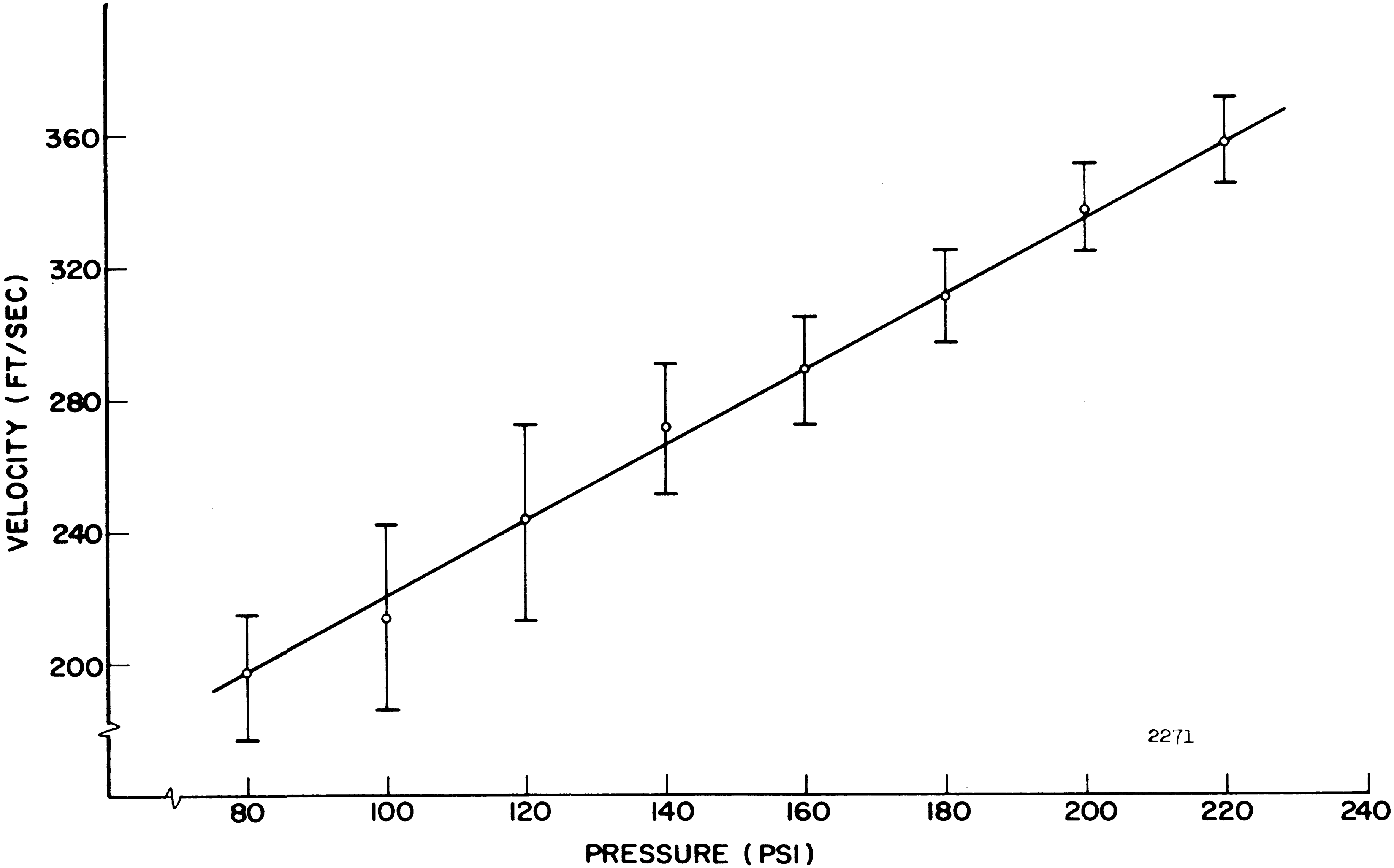



Figure 6. Rifle Pressure vs. Pellet Velocity for Airco Company Regulator.

## IV. PHOTOGRAPHIC RESULTS

### A. Target-Impact Studies:

Twelve filmed series of pictures of the liquid jet impacting the target were obtained in these preliminary experiments: ten with poly-methyl methacrylate (plexiglass) and two with 1100-0 aluminum targets. The chamber pressure for these runs ranged from 200 to 300 psig. The nozzle to target distance was varied from 3 to 12 mm. The camera speed was either 20,000 or 25,000 frames per second in these tests, much too slow to obtain more than one picture of the jet in flight (Figures 7, 8, 9, 10 and 11), since time between frames is 40 microseconds and the jet flight time about 20 microseconds at 25,000 frames per second with the 12 mm target distance.

The velocity of the jet for 250 psig chamber pressure was estimated at 1130 feet per second by considering the approximate distance the head of the jet has travelled in one frame. In this case, the jet has already impinged on the surface and was flowing in the radial direction (Figure 7) at the time the picture was taken. The best estimate of the radial velocity is 710 feet per second, the outer fringe of the flow being used as the reference point. These estimations are substantially low since the elapsed time for the estimates is assumed to be the full framing interval, whereas it is actually an unknown portion of this.

Further, the average radial velocity was estimated, using a modified version of the "water hammer" equation to estimate the maximum pressure in the drop at impact and then computing the radial velocity from Bernoulli's equation. Using this pressure:[4]

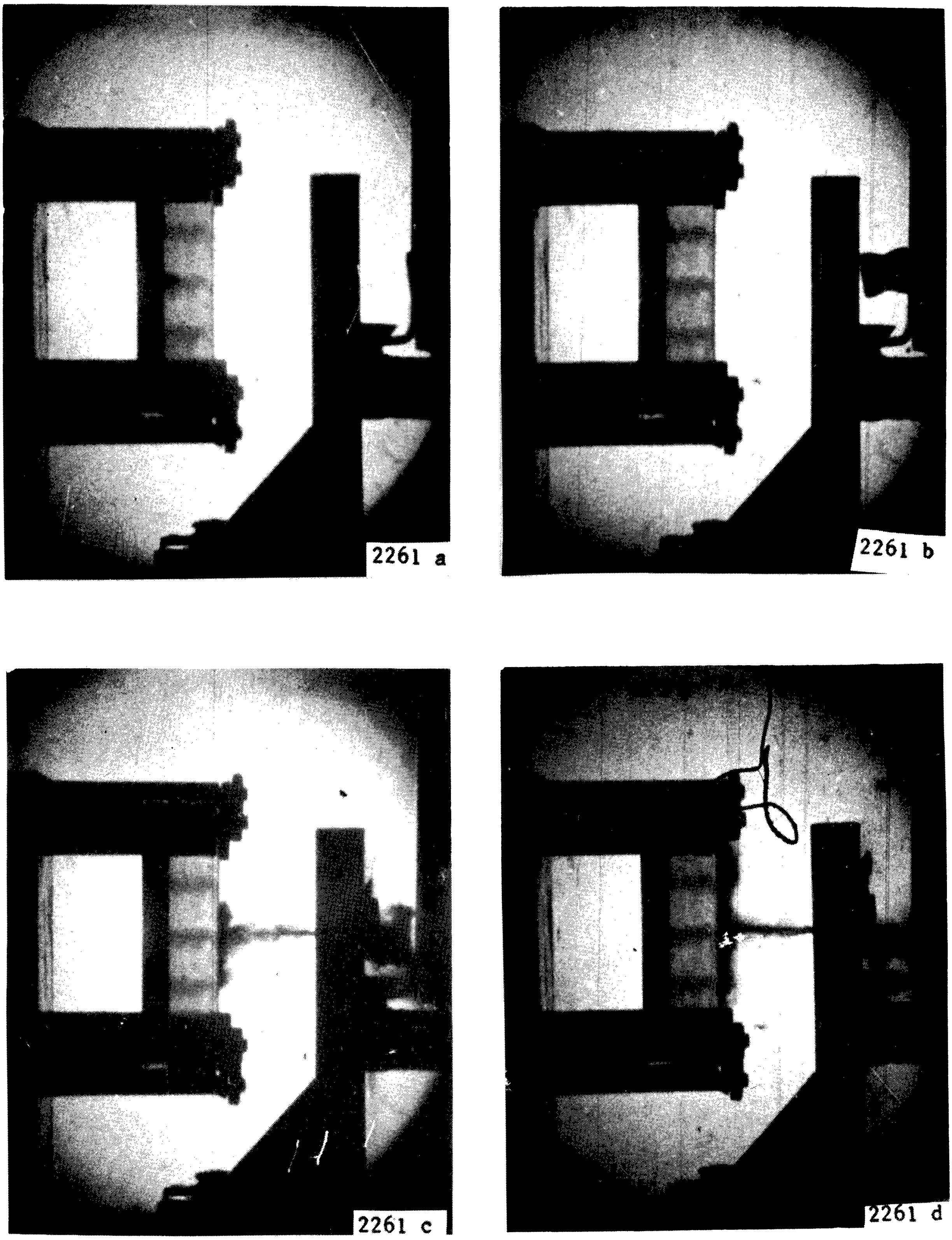



Figure 7. Jet Impinging on Plexiglas Target. Run #1. Chamber Pressure -- 250 psig. Target Distance -- 12 mm.

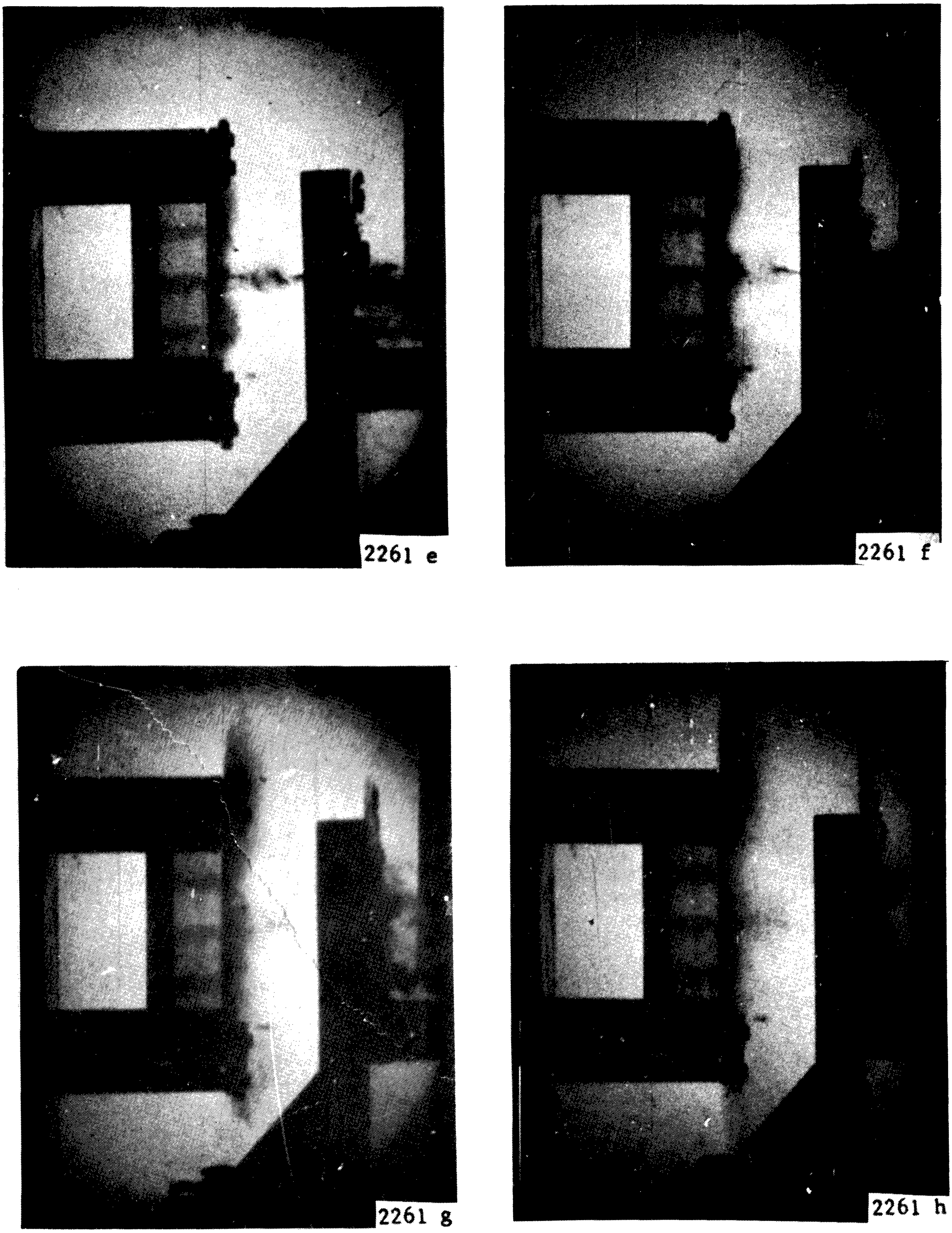



Figure 7. (Cont'd)

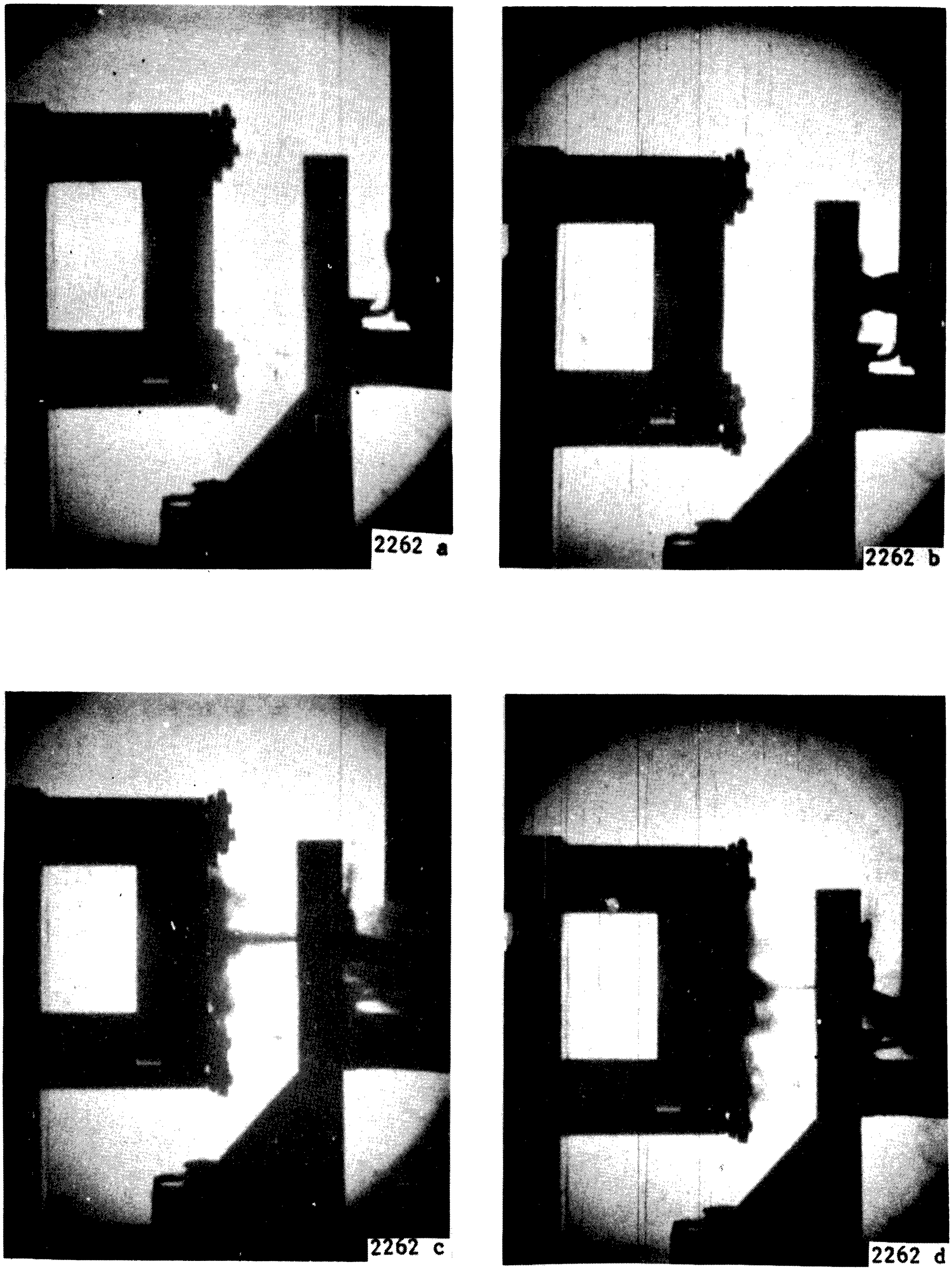



Figure 8. Jet Impinging on 1100-0 Aluminum Target. Run #2. Chamber Pressure -- 300 psig. Target Distance -- 12 mm.

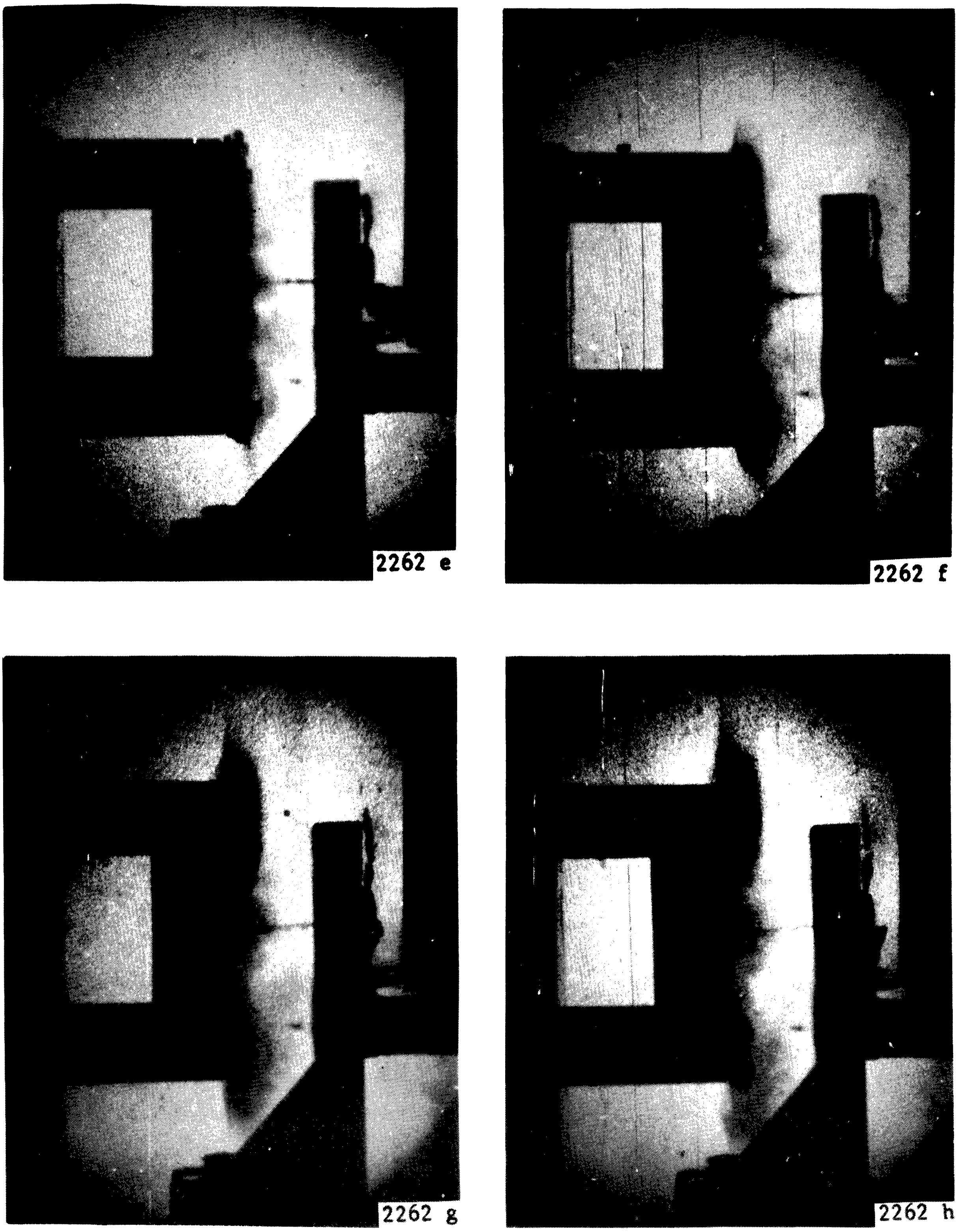



Figure 8. (Cont'd)

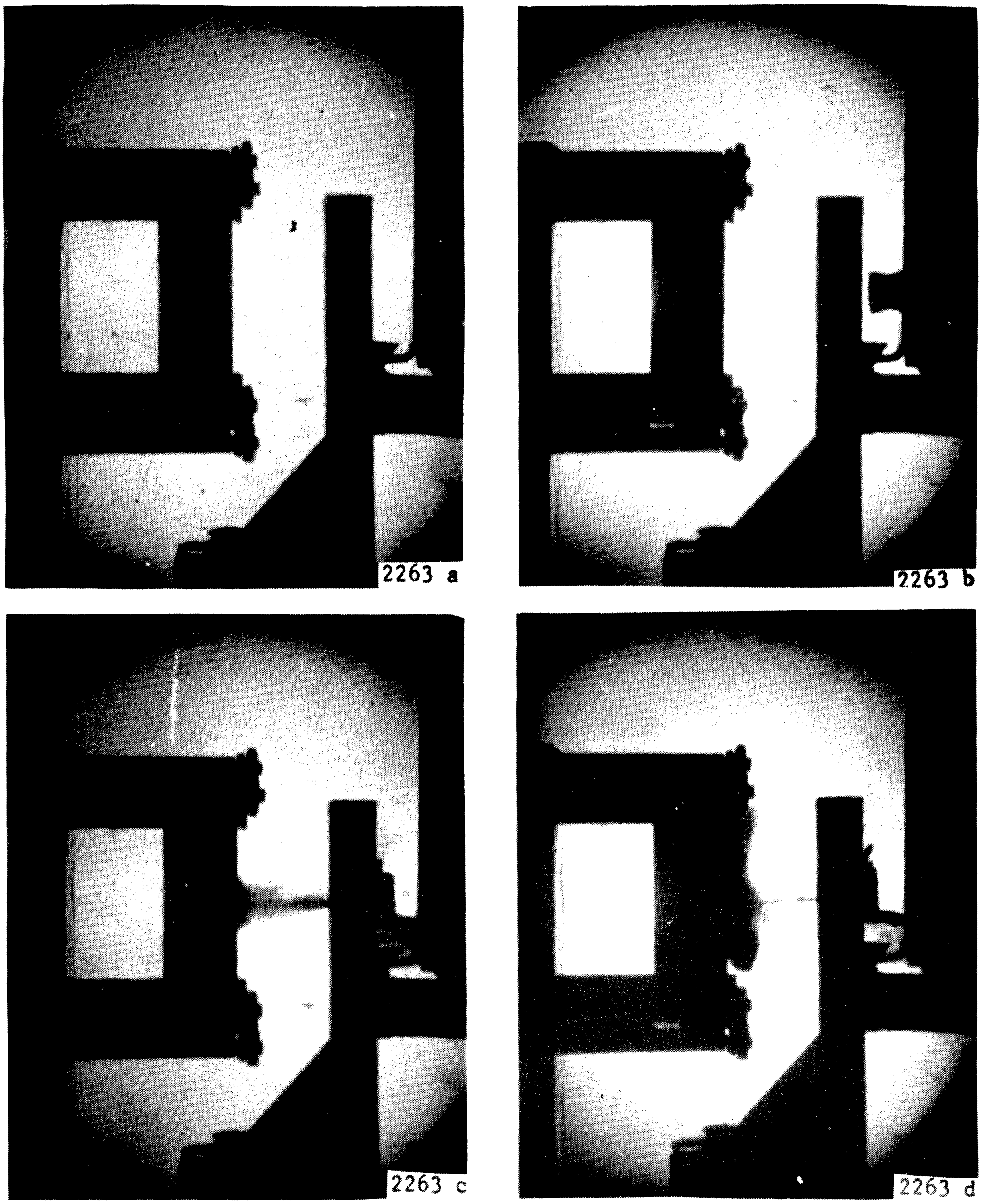



Figure 9. Jet Impinging on 1100-0 Aluminum Target. Run #3. Chamber Pressure -- 300 psig. Target Distance -- 12 mm.

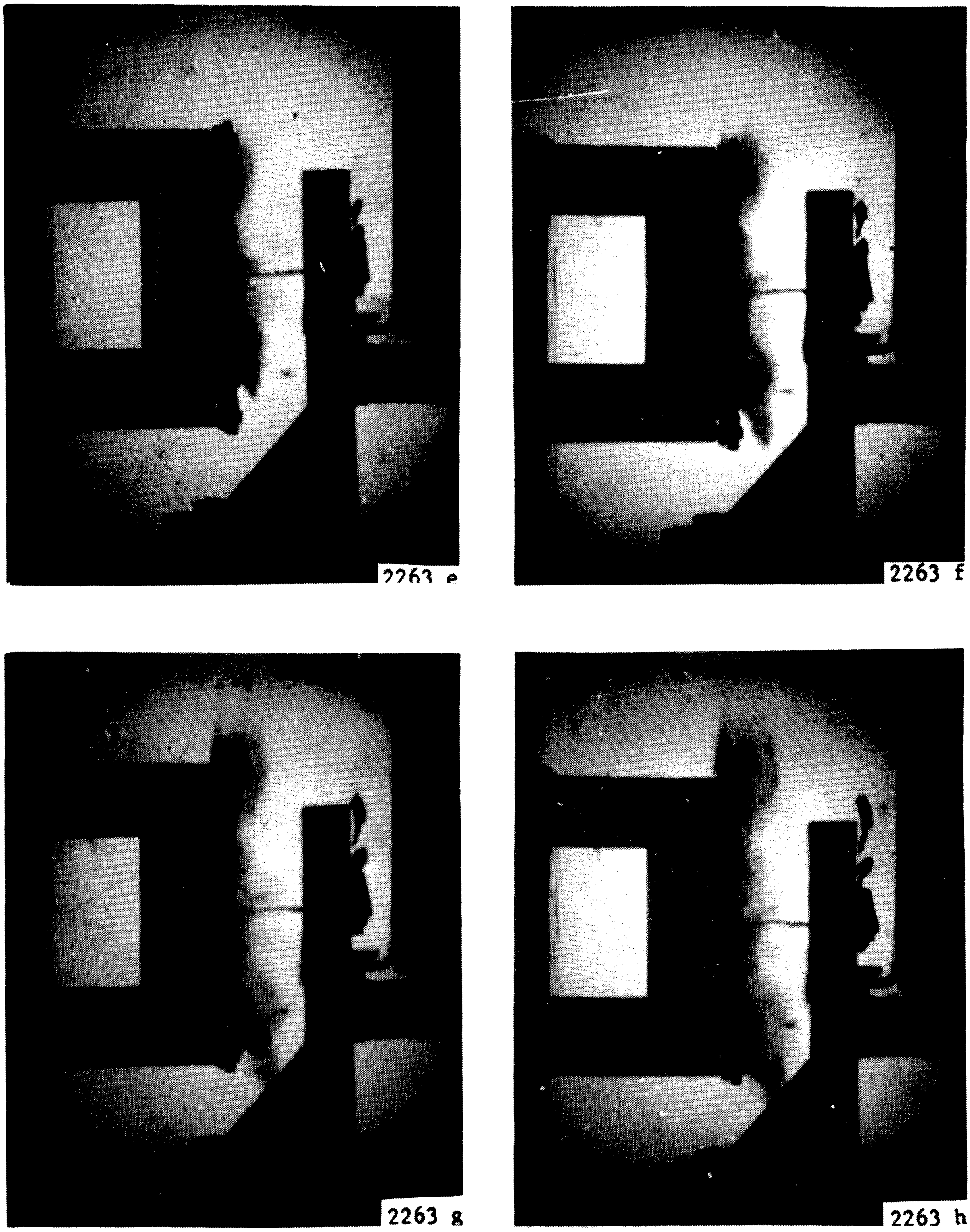



Figure 9. (Cont'd)

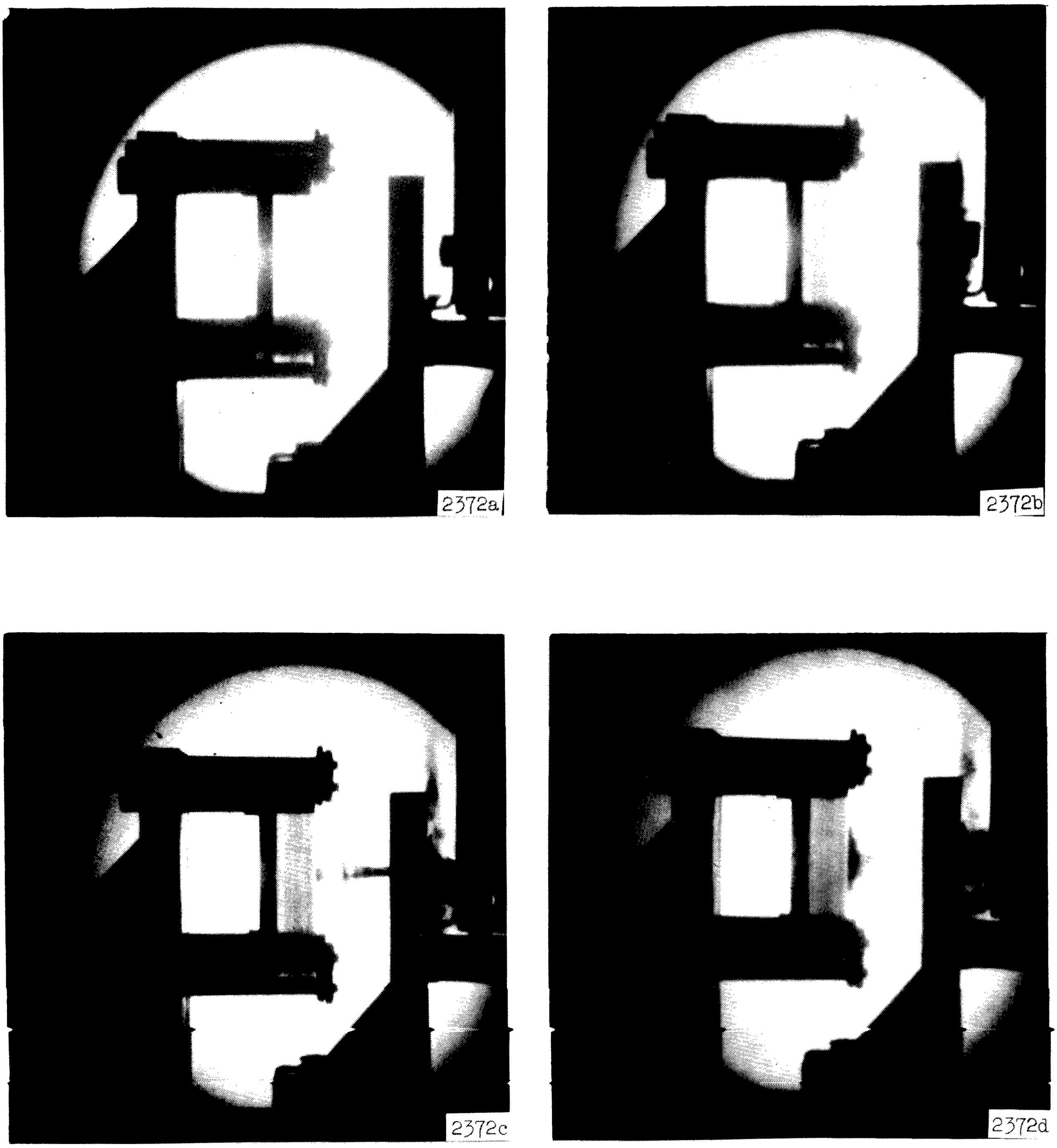



Figure 10. Jet Impinging on Plexiglas Target. Run #4. Chamber Pressure -- 200 psig. Target Distance -- 12 mm.

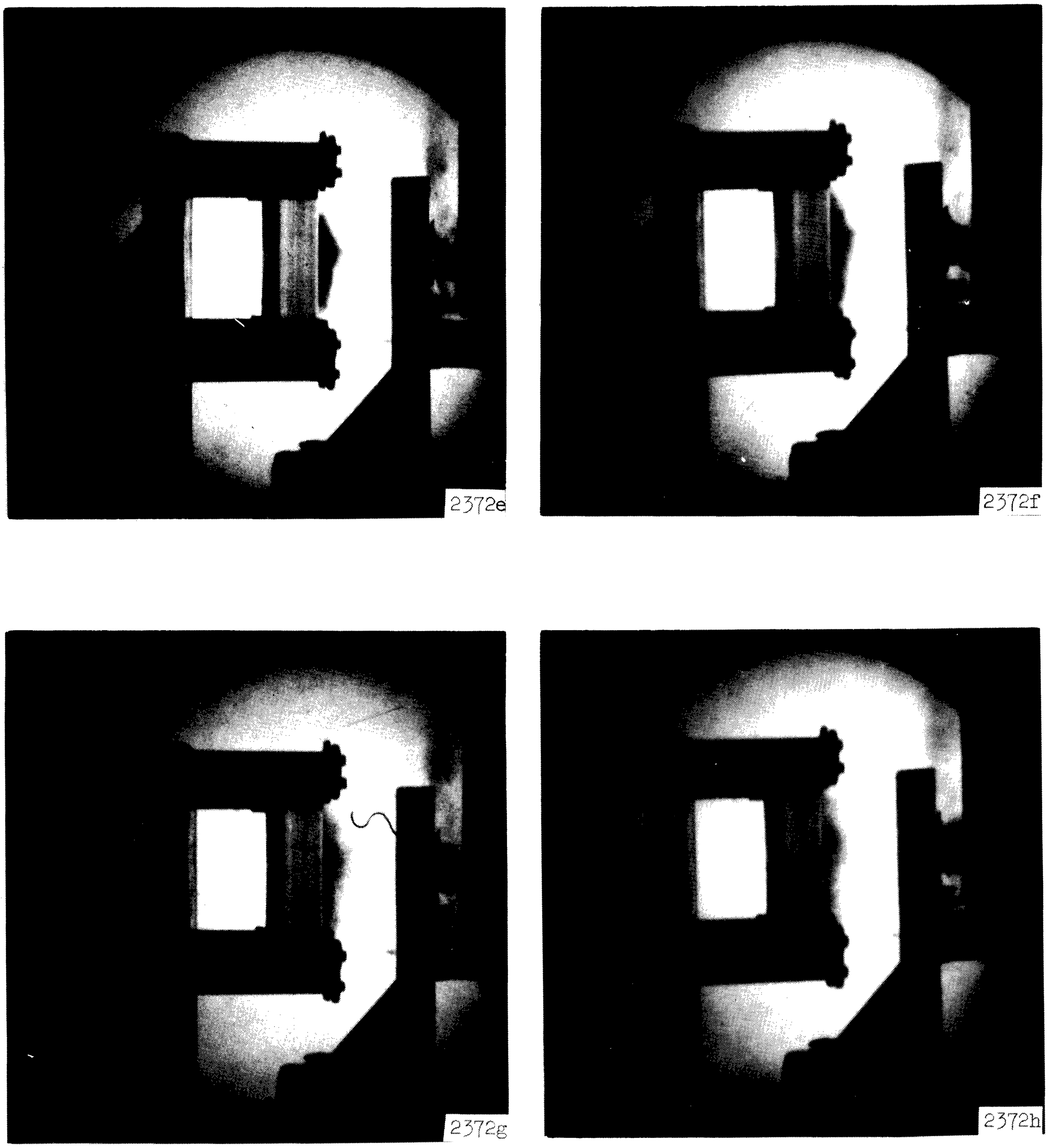



Figure 10. (Cont'd)

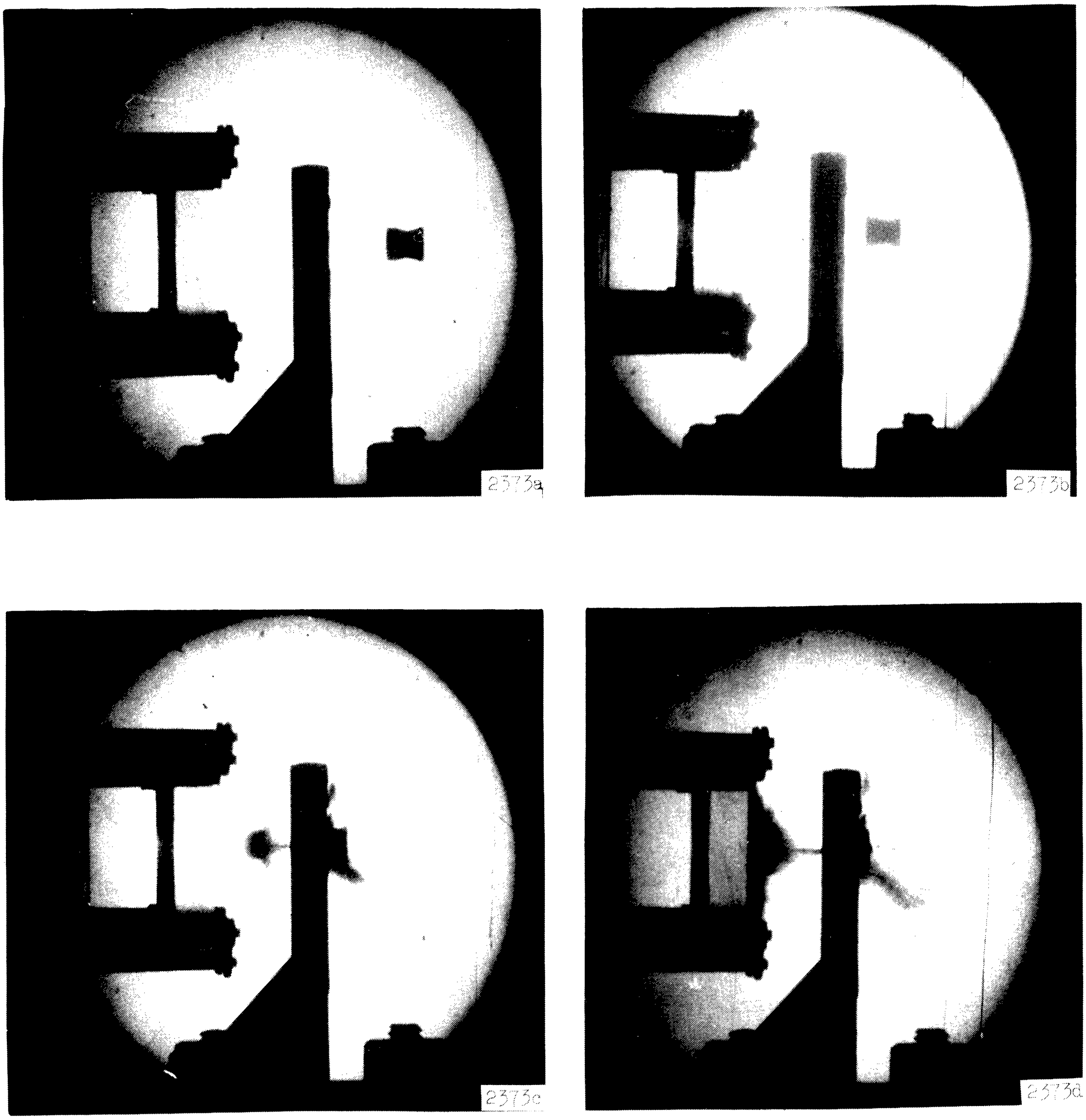



Figure 11. Jet Impinging on Plexiglas Target. Run #12. Chamber Pressure -- 300 psig. Target Distance -- 12 mm.

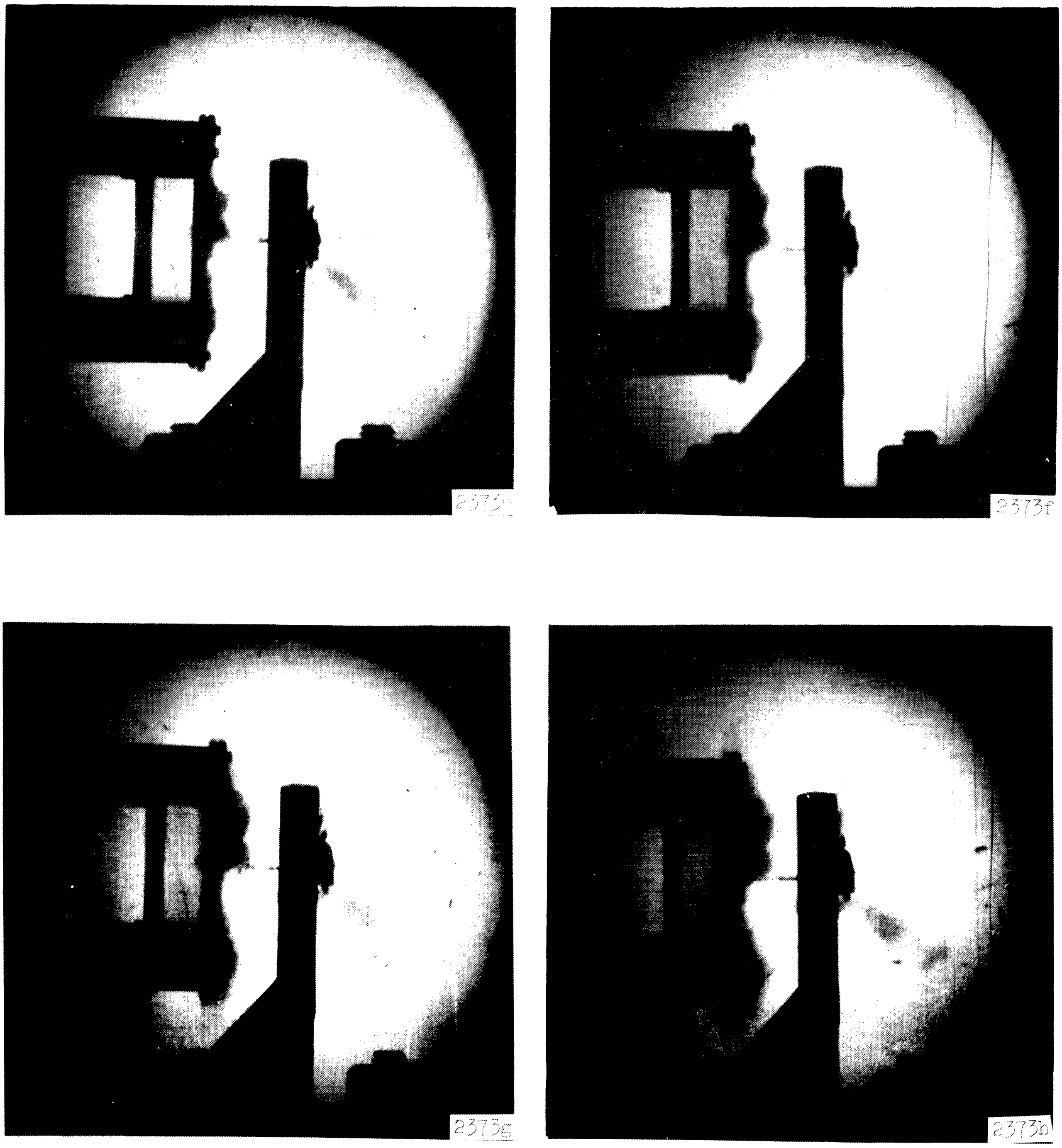



Figure 11. (Cont'd)

$$V_r = \sqrt{\alpha c \ Vo} \qquad (1)$$

where Vo = impact velocity at the surface.
$\alpha$ = coefficient less than unity arising from the flow properties of the liquid.
c = speed of sound in the liquid.

For water at 25°c, $\alpha$ can be taken as = 0.90 and c = 4910 feet per second. Using the estimated impact velocity of 1130 feet per second, the radial velocity then becomes 2240 feet per second, about three times greater than the estimated value of 710 feet per second, which was estimated from the photograph as previously described.

The second and third runs were performed using 1100-0 aluminum as the target material, set 12 mm from the nozzle with a chamber pressure of 300 psig in the rifle and a delay time of 1.300 milliseconds. Notice the duration of the radial flow in the second run (over 6 frames or 300 microseconds, Figure 8) as compared with the plexiglas run (approximately 4 frames or 200 microseconds, Figure 7). Notice also the tremendous difference in the outward flow itself, i.e., the overflow near the ends. The impact velocity for the second run was estimated at 1415 feet per second, a substantial increase over the previous run. Using Equation (1) the radial velocity becomes 2510 feet per second.

The third run produced relatively the same type of jet as did the second. In this sequence the jet impinges in a direction almost exactly perpendicular to the specimen surface. The angle of impingement becomes important when the damage produced by the jet is considered. The impingement velocity approaches 1000 feet per second.

The velocities of the jets of the second and third runs should be approximately the same since the pellet impinges on the neoprene disk at the same mean velocity. The apparent discrepancy is due to the fact that the pellet in the second run is at the target (Figure 8b), while in the third the pellet has yet to reach the disk (Figure 9b). The radial velocity estimated from the photograph is approximately 700 feet per second, far less than the 2100 feet per second predicted by Equation (1), and probably less than the actual value as already explained.

In confirmation of the existence of very high radial velocities, Jenkins and Booker[5] reported that when a solid impinged on a suspended 2 mm waterdrop at 1000 feet per second, the resultant radial velocity was 3400 feet per second, much faster than the 2100 feet per second predicted by Equation (1). Further, their photographic results appear very similar to the pictures from the second and third runs of the present investigation.

The remaining runs used plexiglas as the target specimen. These runs produced photographic results generally simialr to those discussed above. Figures 10 and 11 are rather interesting in that they show the jet in progress before it has struck the target. It is evident in these two figures that the jet begins to "turn back" on itself before reaching the target. In some of the test runs, it was decided to use teflon instead of neoprene as the impact gasket material. These runs appeared to result in greater damage to the target material than runs with neoprene gaskets. In order to determine the effect of gasket material as well as other parameters on the shape and velocity of the jet, and also to obtain more accurate estimates of jet velocity, the target and its support were removed and a photographic investigation of the water jet was undertaken.

B. Liquid-Jet Studies:

A total of 34 runs were made with the target removed in order to investigate the effects of gasket material, water volume, and pellet velocity on the velocity and shape of the impacting liquid jets. In some of these runs, an attempt was also made to determine the effect of a miniscus at the exit orifice. Typical results are shown in Figure 12 through 21. Data sheets containing the test conditions and jet velocities for all these runs are included in Appendix A. Jet velocities greater than 2,500 feet per second were obtained in four of these runs.

Due to the limited availability of a high speed camera, it was necessary to take several series of photographic runs in a limited time and then proceed with an analysis of the results after the camera was returned. Thus these results must be considered very preliminary in nature and will serve primarily as a basis for future studies. Also, problems were encountered in obtaining direct impacts of the pellet on the gasket with the original nozzle design and experimental setup. In fact, in some cases the pellet was observed to be "tilted" just prior to impact (i.e. Figure 7). Therefore, after Run # 34, the water cavity and impact gasket diameters were imcreased from 0.215 to 0.24 inches. Also, the distance between the photocells was reduced from 5.93 to 2.0 inches, and the distance from the first photocell to the target was reduced from 8.5 to 4.0 inches, thus placing the target much closer to the end of the gun barrel. These changes greatly increased the probability of the pellet impacting entirely on the gasket

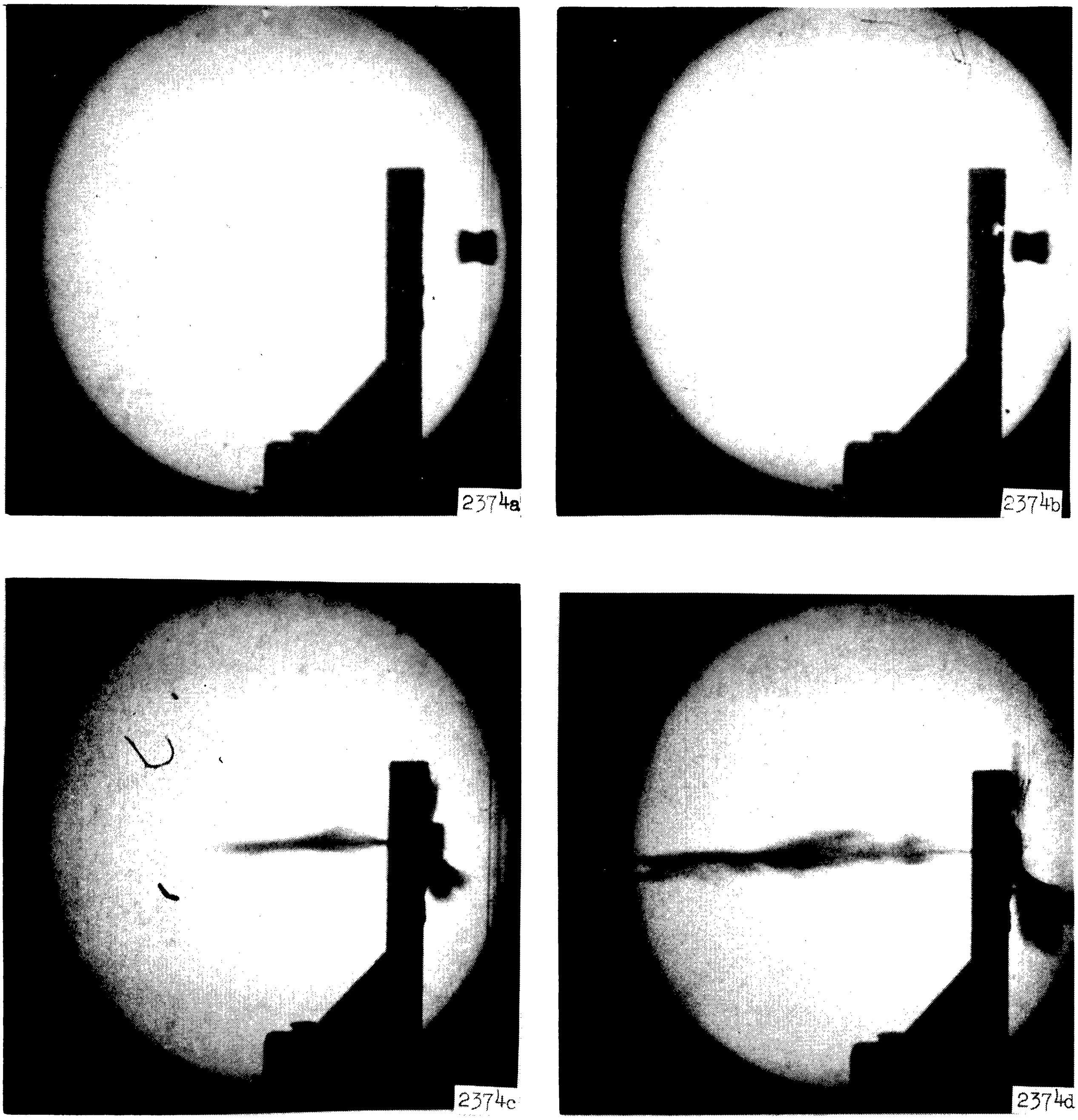



Figure 12. Liquid Jet Progression. Run #32.
Chamber Pressure -- 300 psig.
Initial Jet Velocity over 2,800 feet per second.

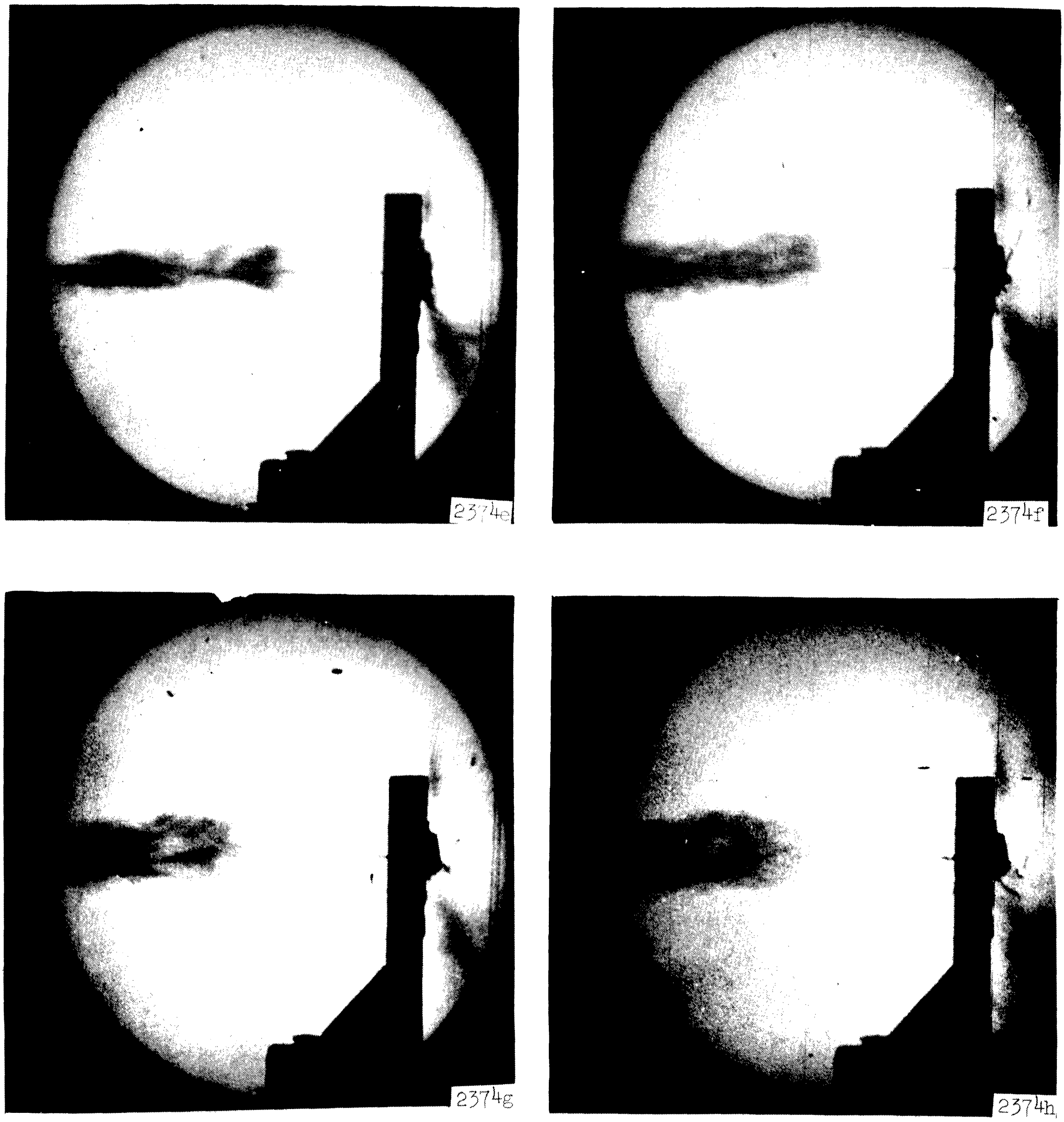



Figure 12. (Cont'd)

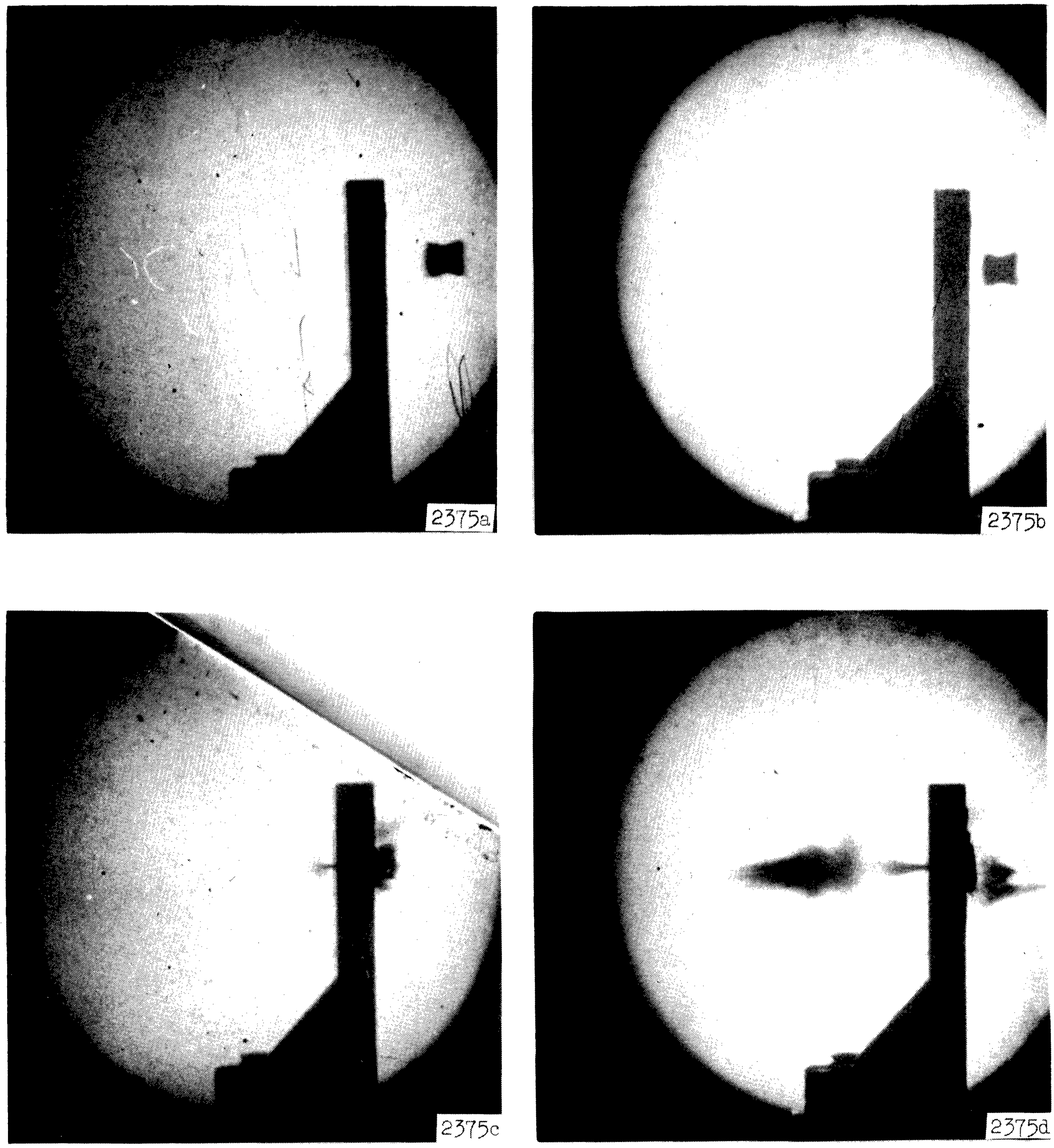



Figure 13. Liquid Jet Progression. Run #35.
Chamber Pressure -- 300 psig.
Jet Velocity Approximately 2,800 feet per second.

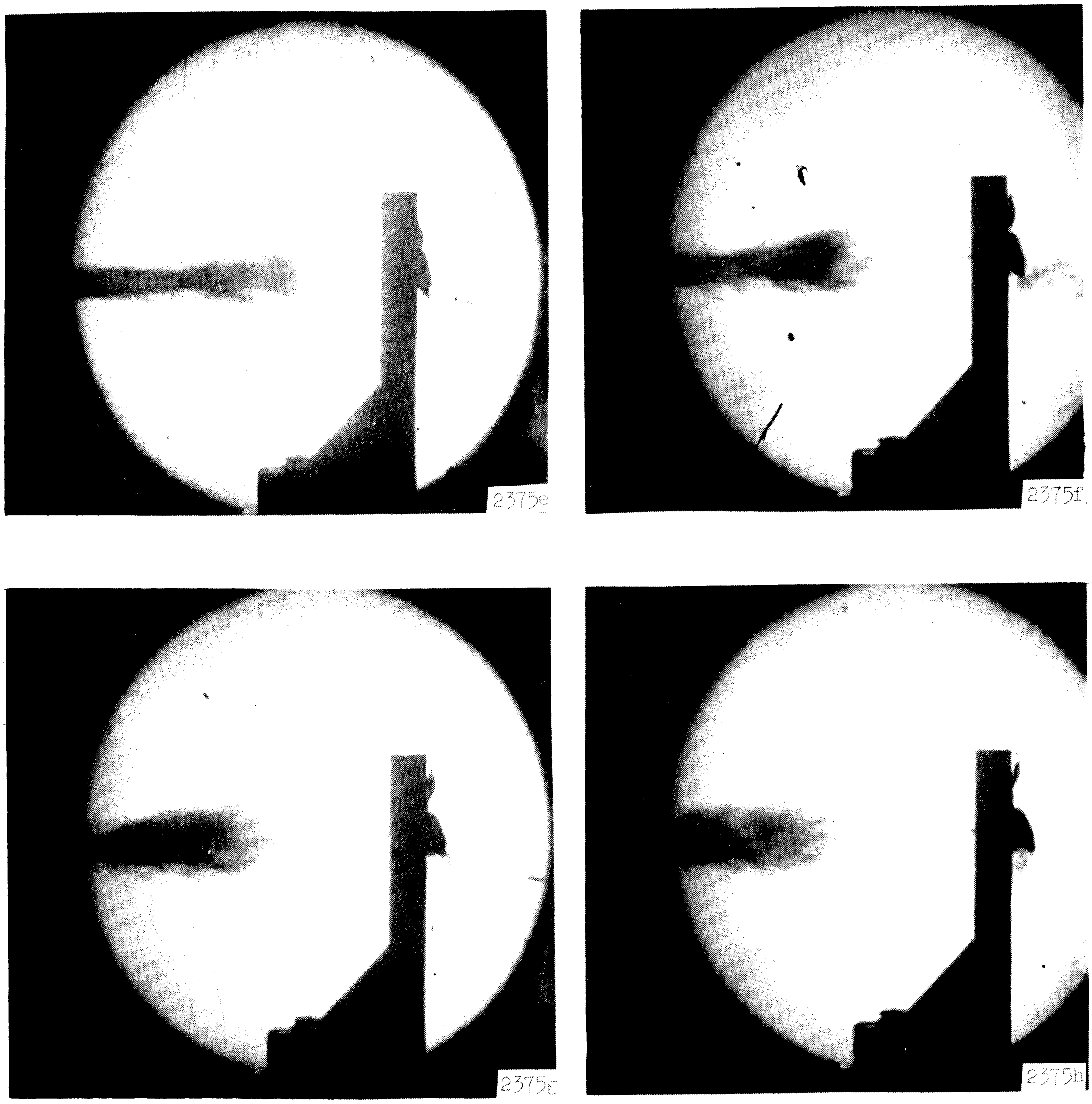



Figure 13. (Cont'd)

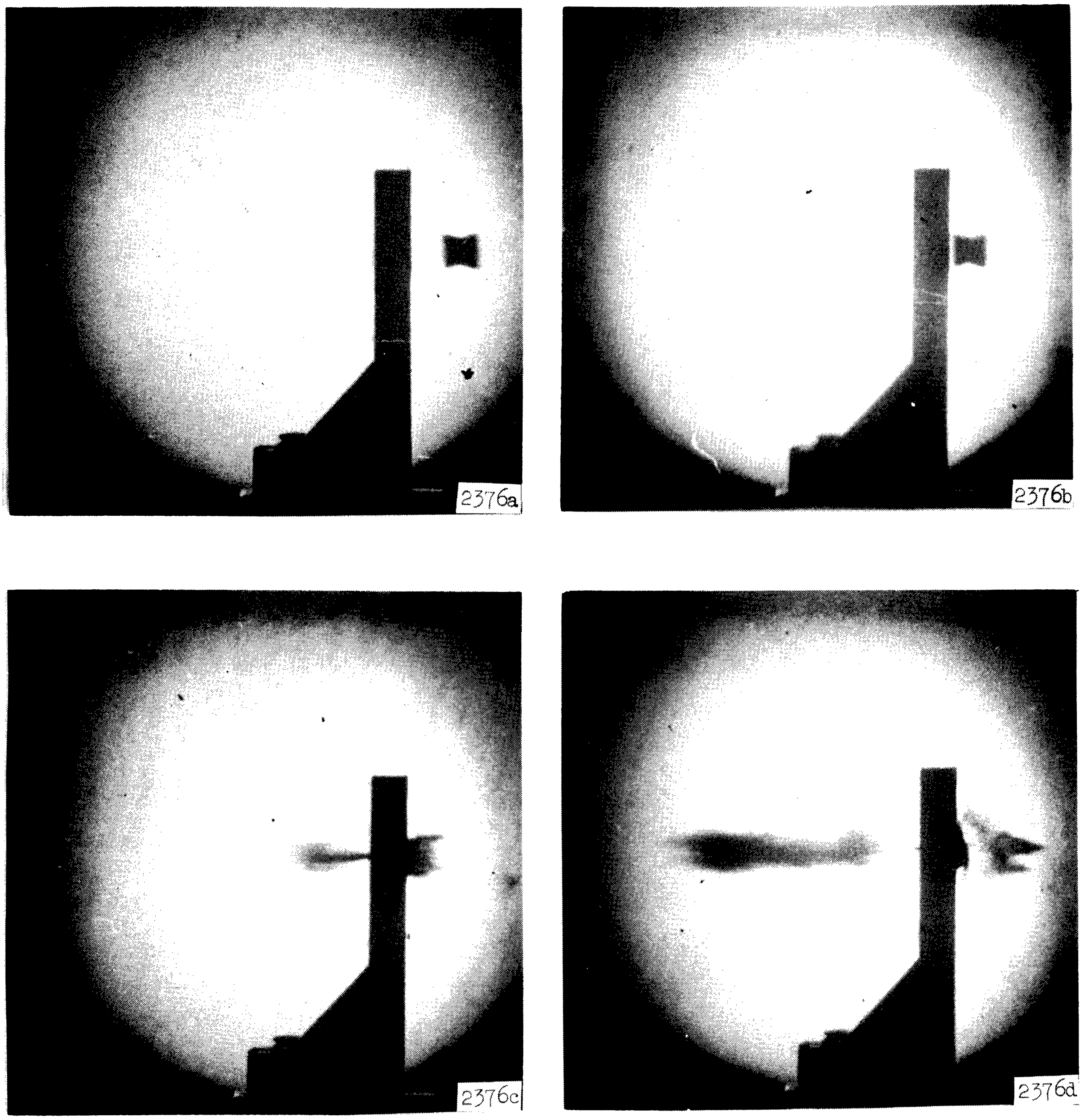



Figure 14. Liquid Jet Progression. Run #40.
Chamber Pressure -- 300 psig.
Jet Velocity Approximately 2,500 feet per second.

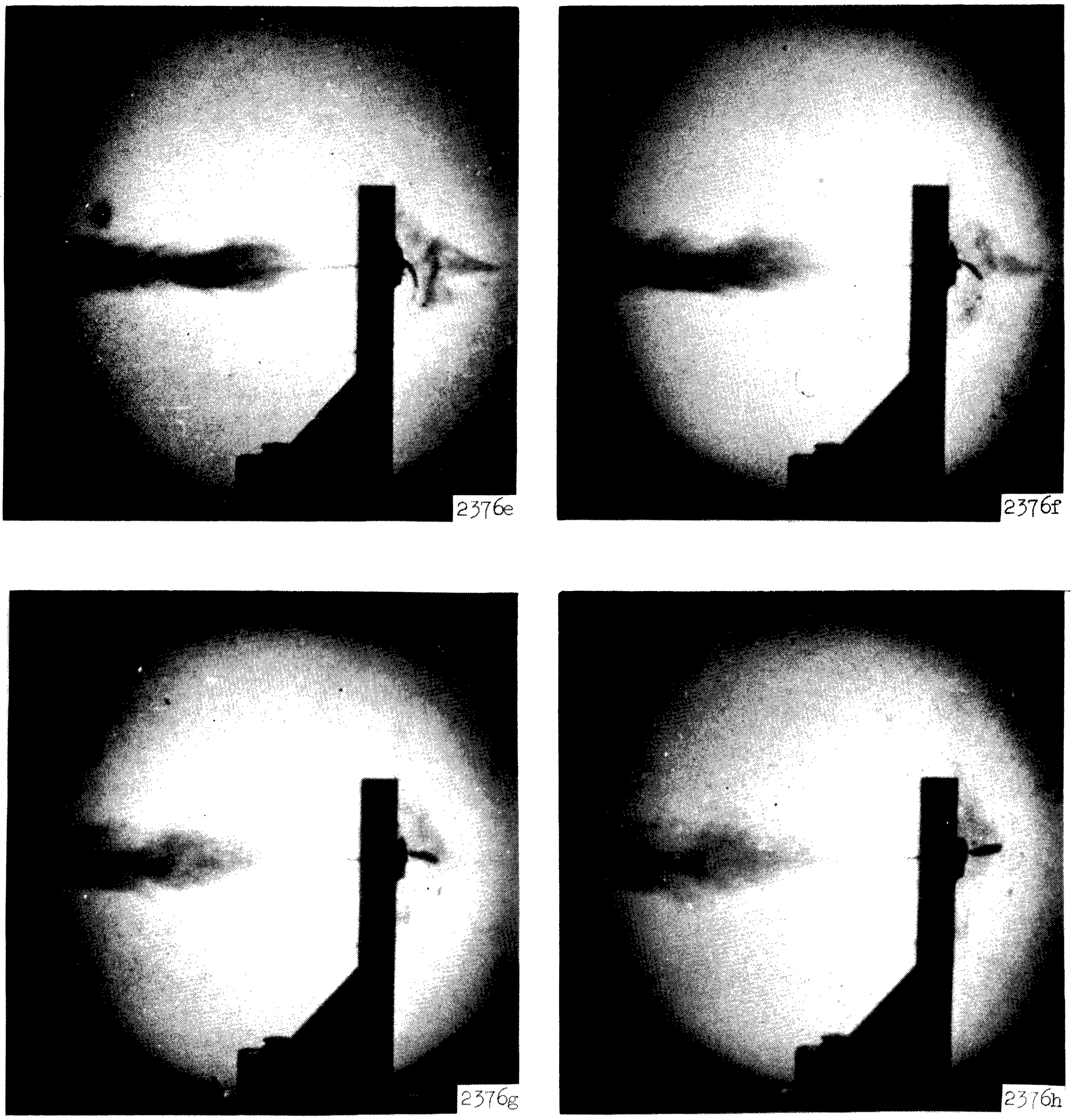



Figure 14. (Cont'd)

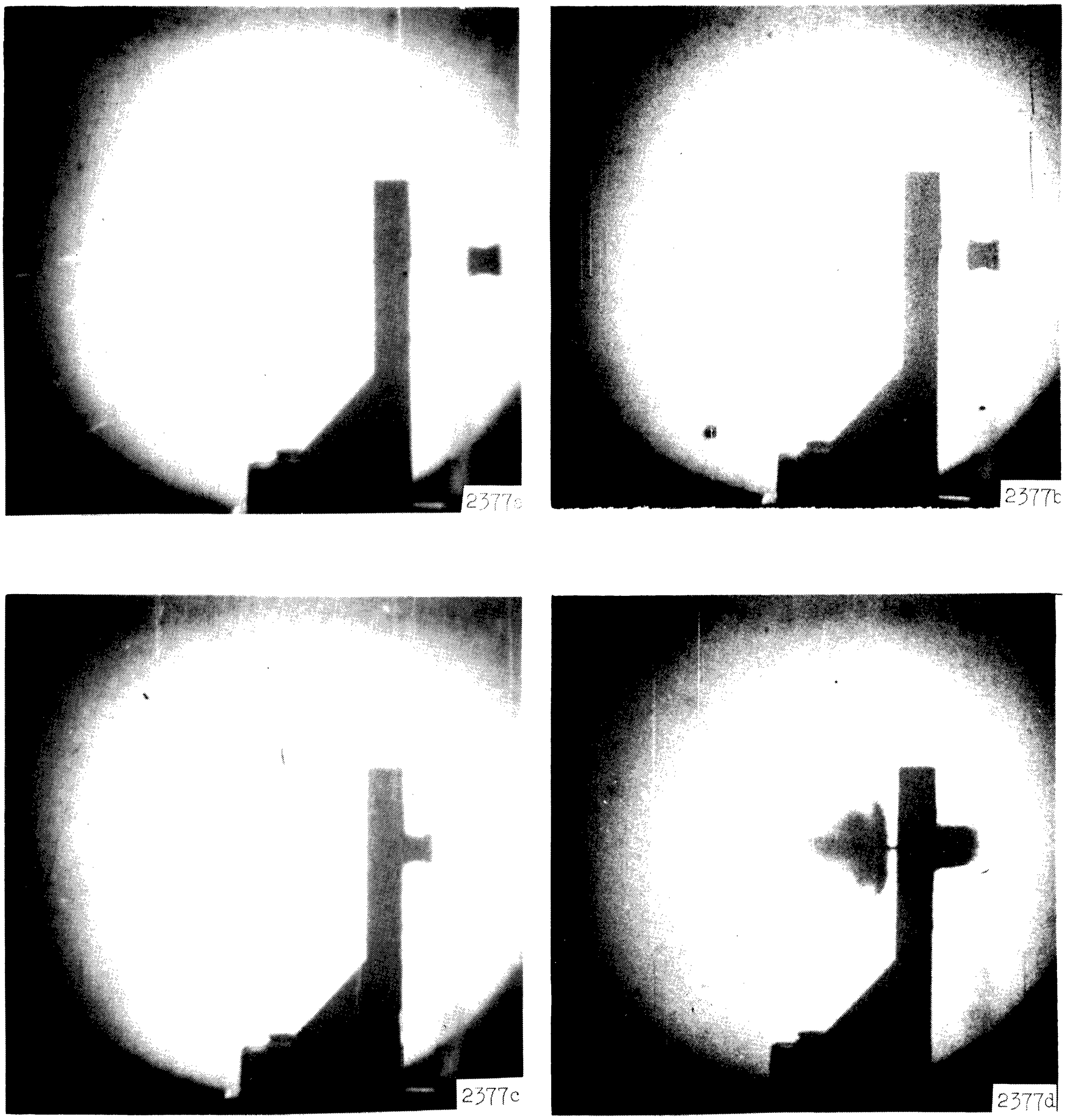



Figure 15. Liquid Jet Progression. Run #41.
Chamber Pressure -- 300 psig.
Jet Velocity Approximately 1,940 feet per second.

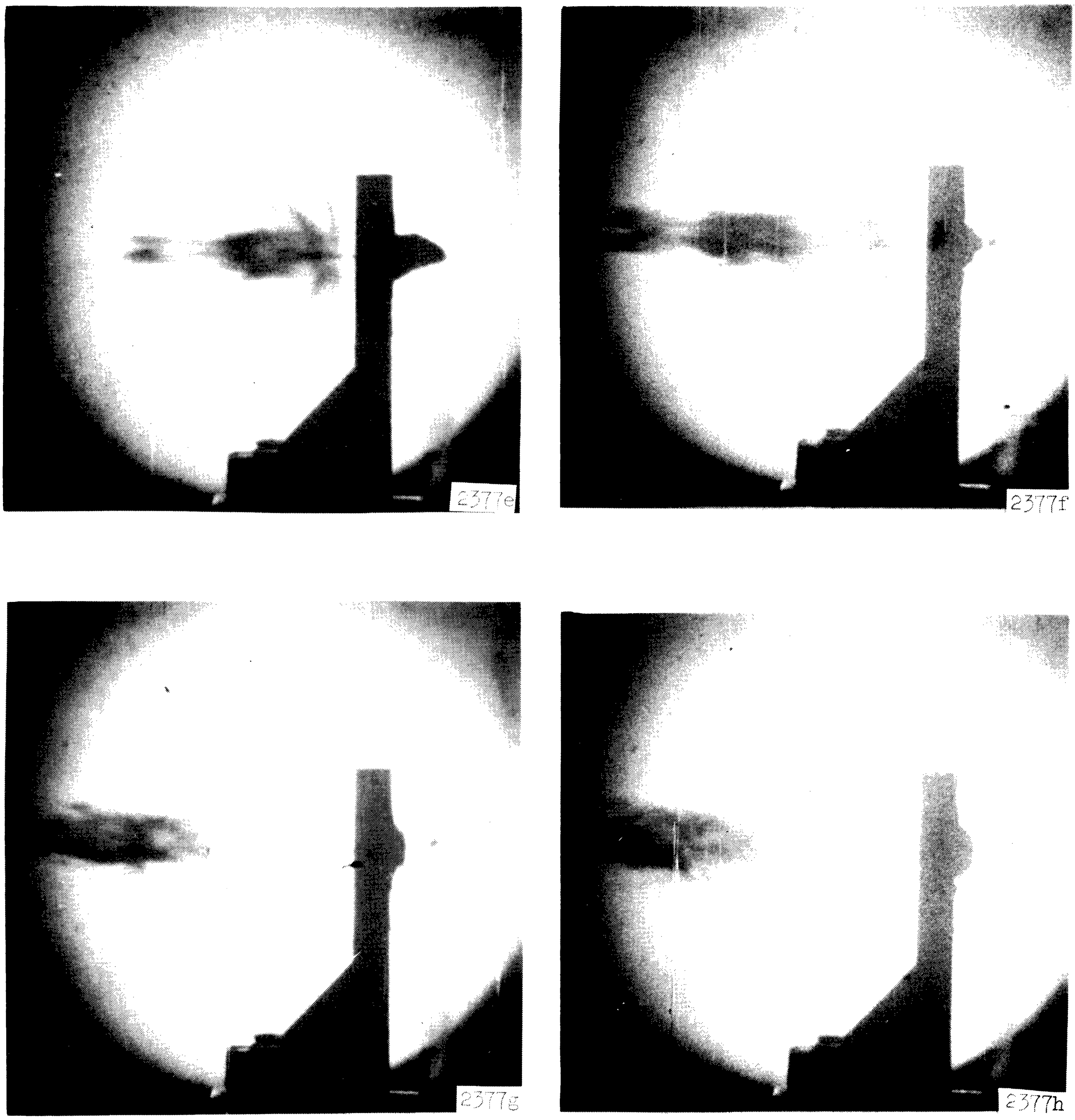



Figure 15. (Cont'd)

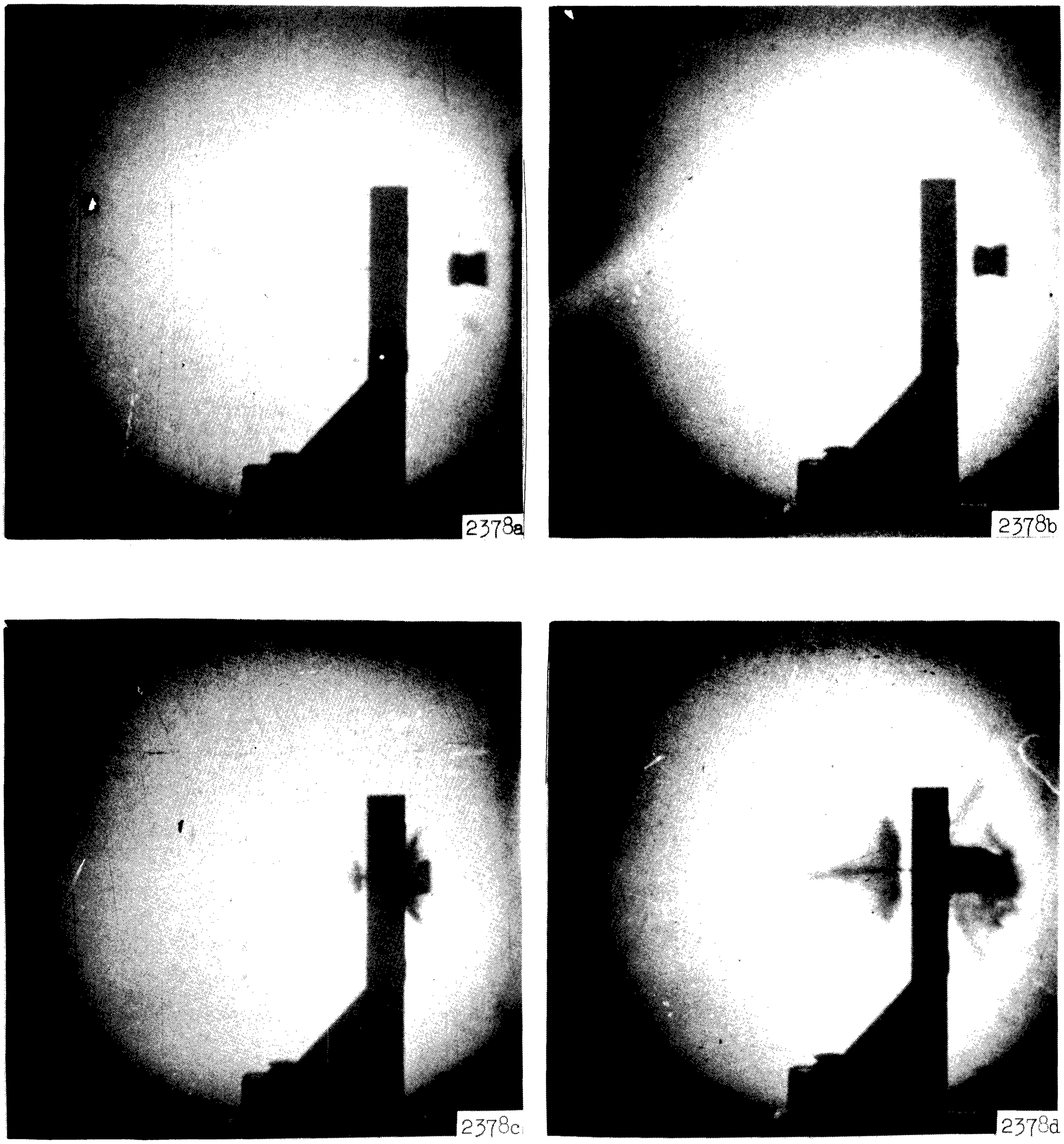



Figure 16. Liquid Jet Progression. Run #43.
Chamber Pressure -- 300 psig.
Jet Velocity Approximately 1,690 feet per second.

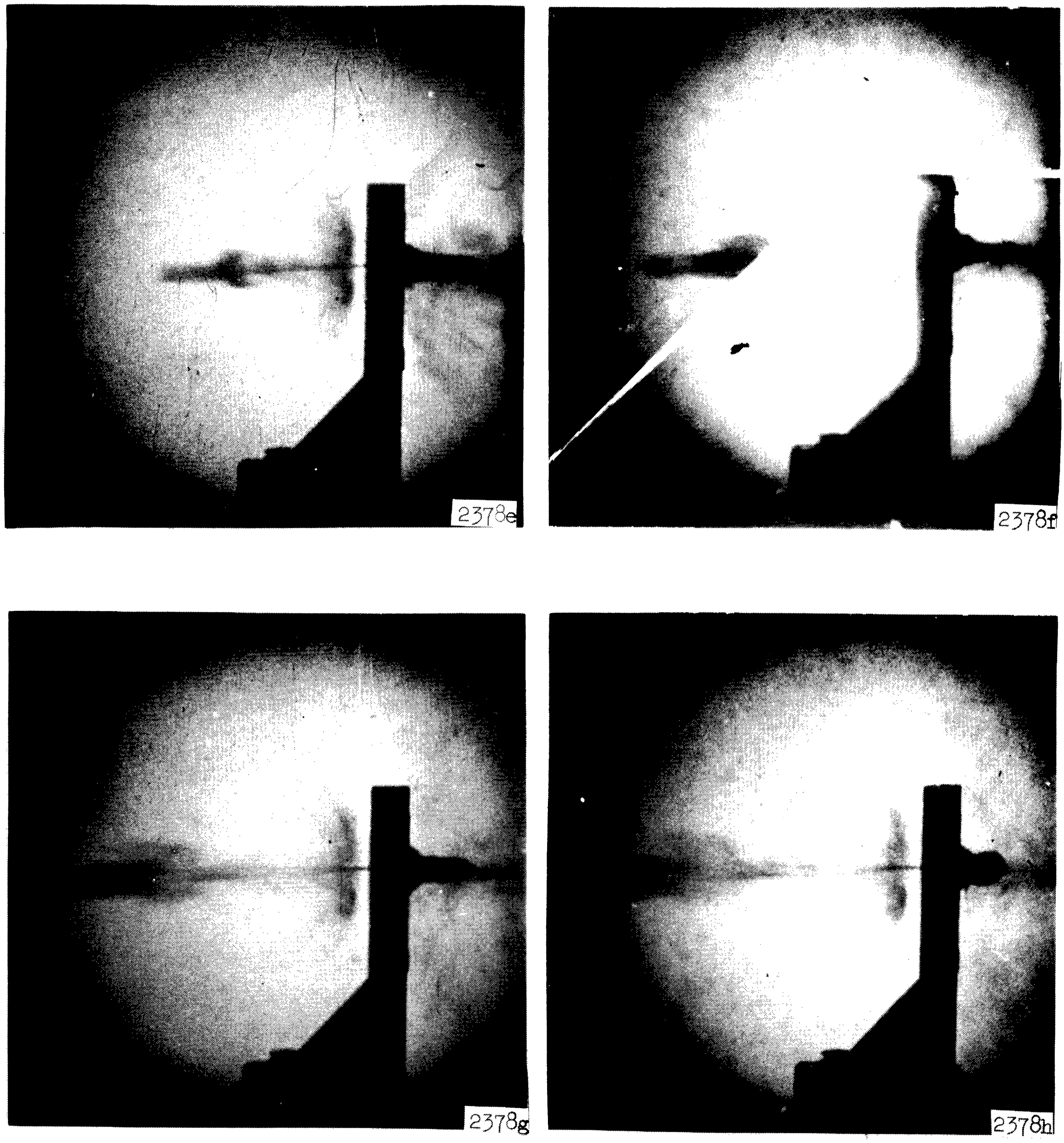



Figure 16. (Cont'd)

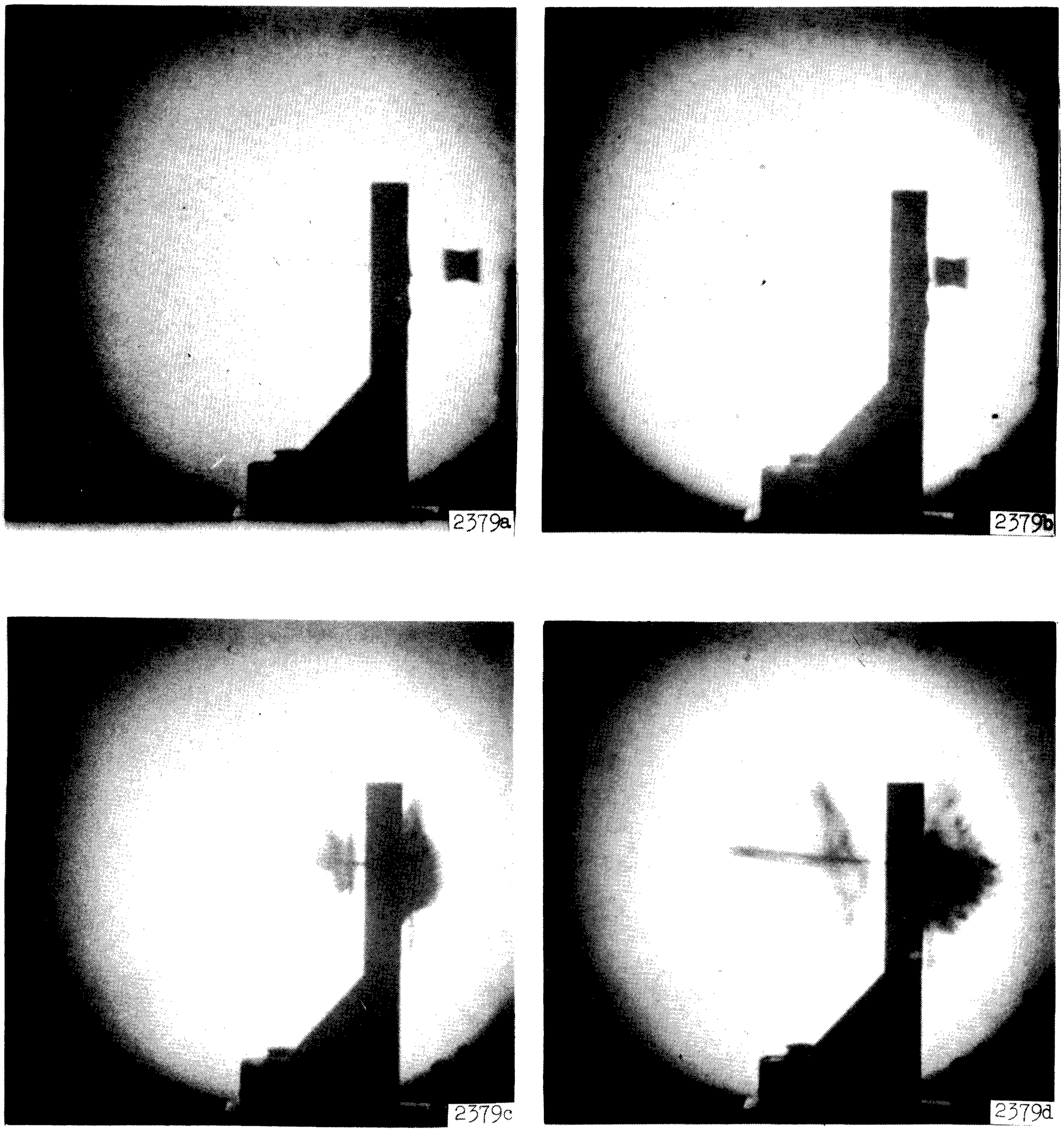



Figure 17. Liquid Jet Progression. Run #44.
Chamber Pressure -- 300 psig.
Jet Velocity Approximately 1,670 feet per second.

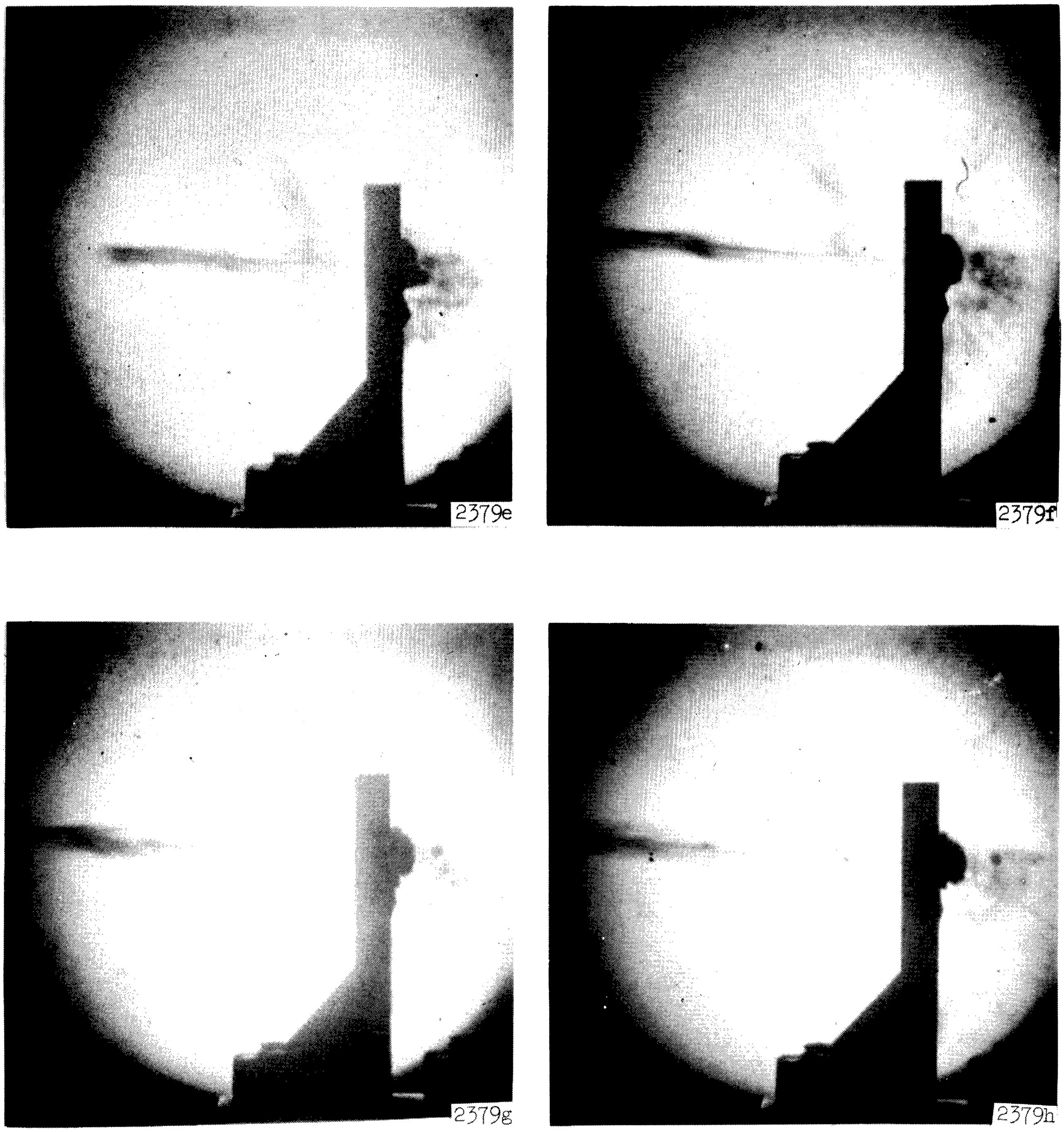



Figure 17. (Cont'd)

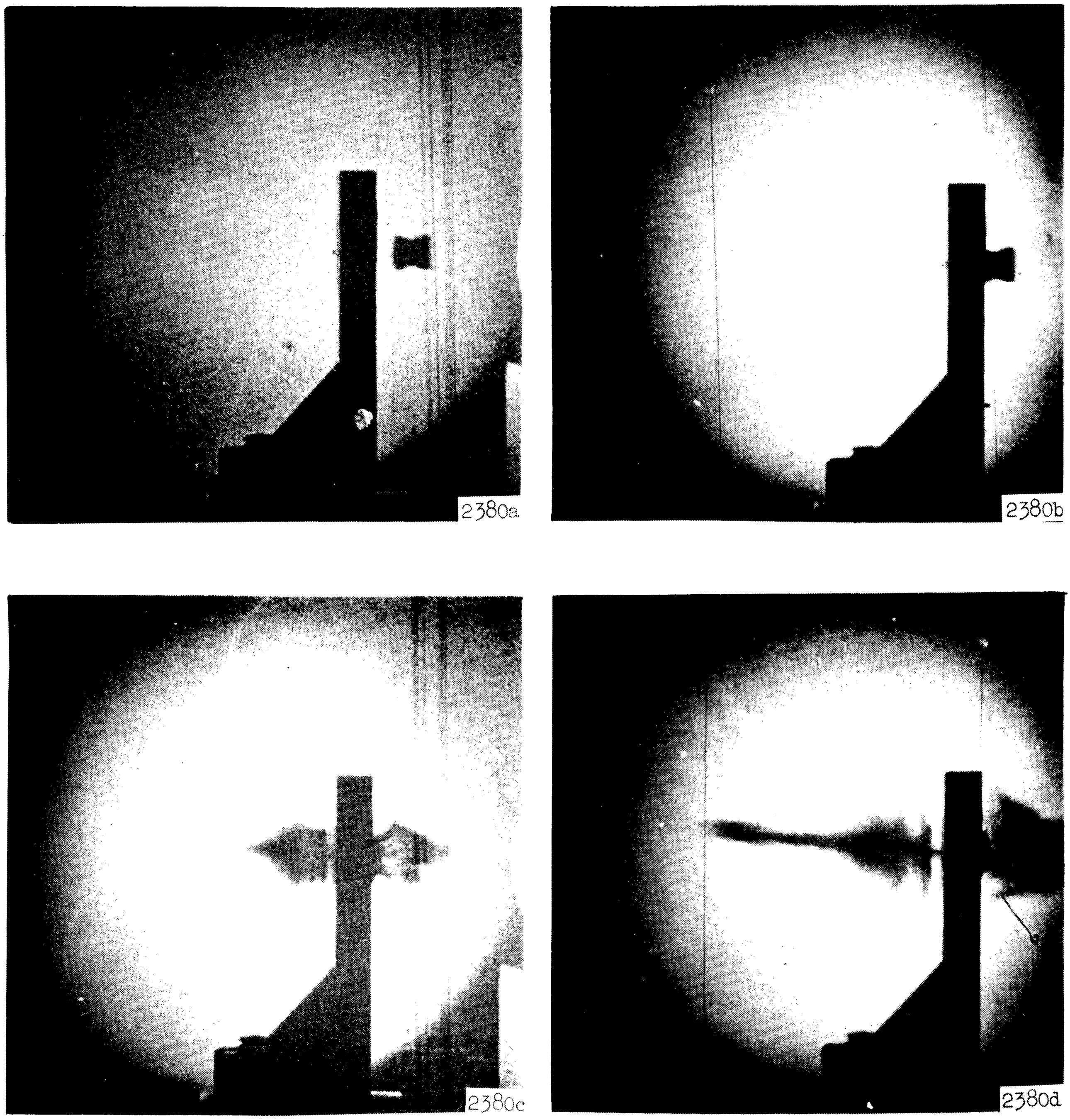



Figure 18. Liquid Jet Progression. Run #52.
Chamber Pressure -- 250 psig.
Jet Velocity Approximately 2,130 feet per second.

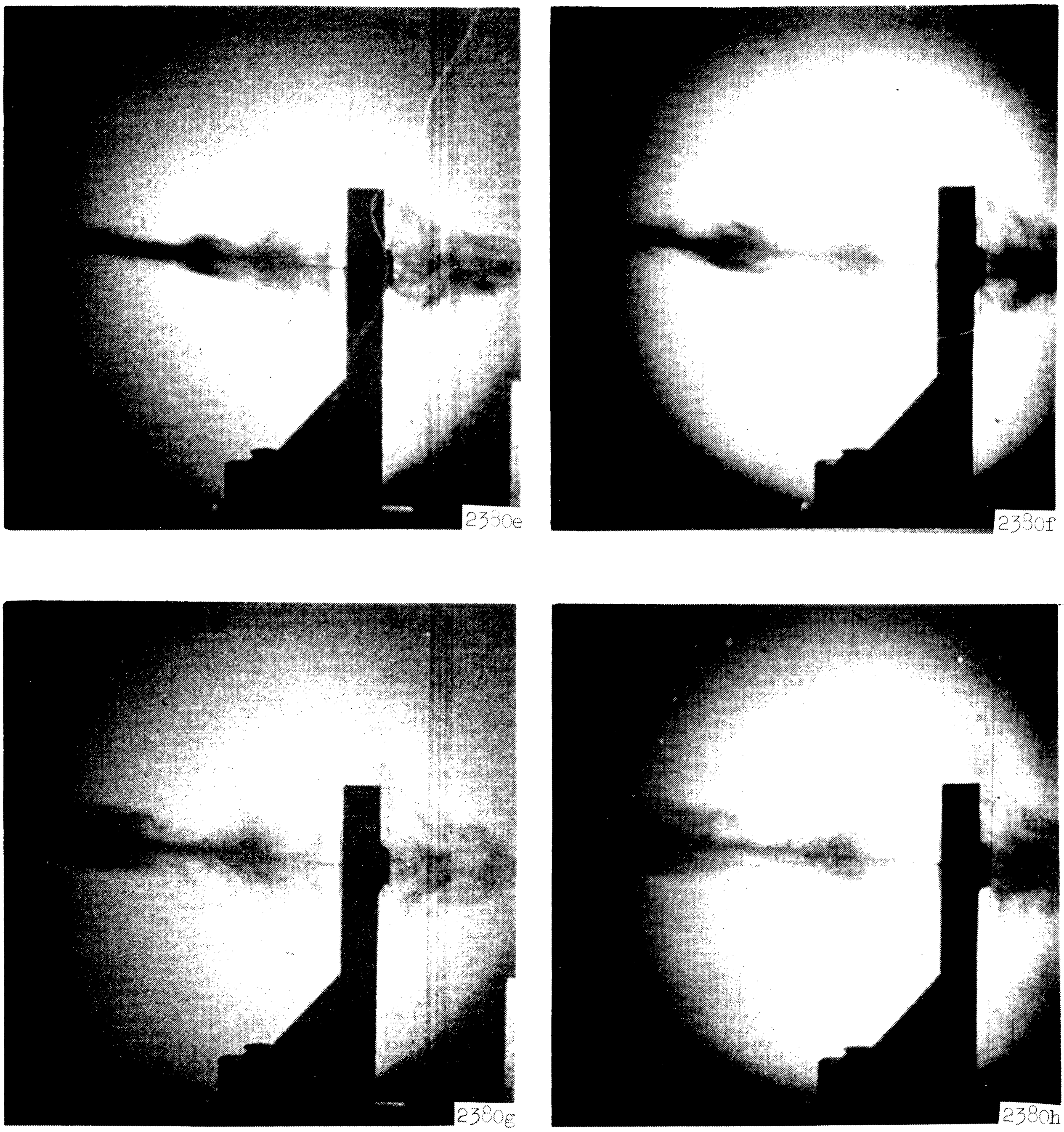



Figure 18. (Cont'd)

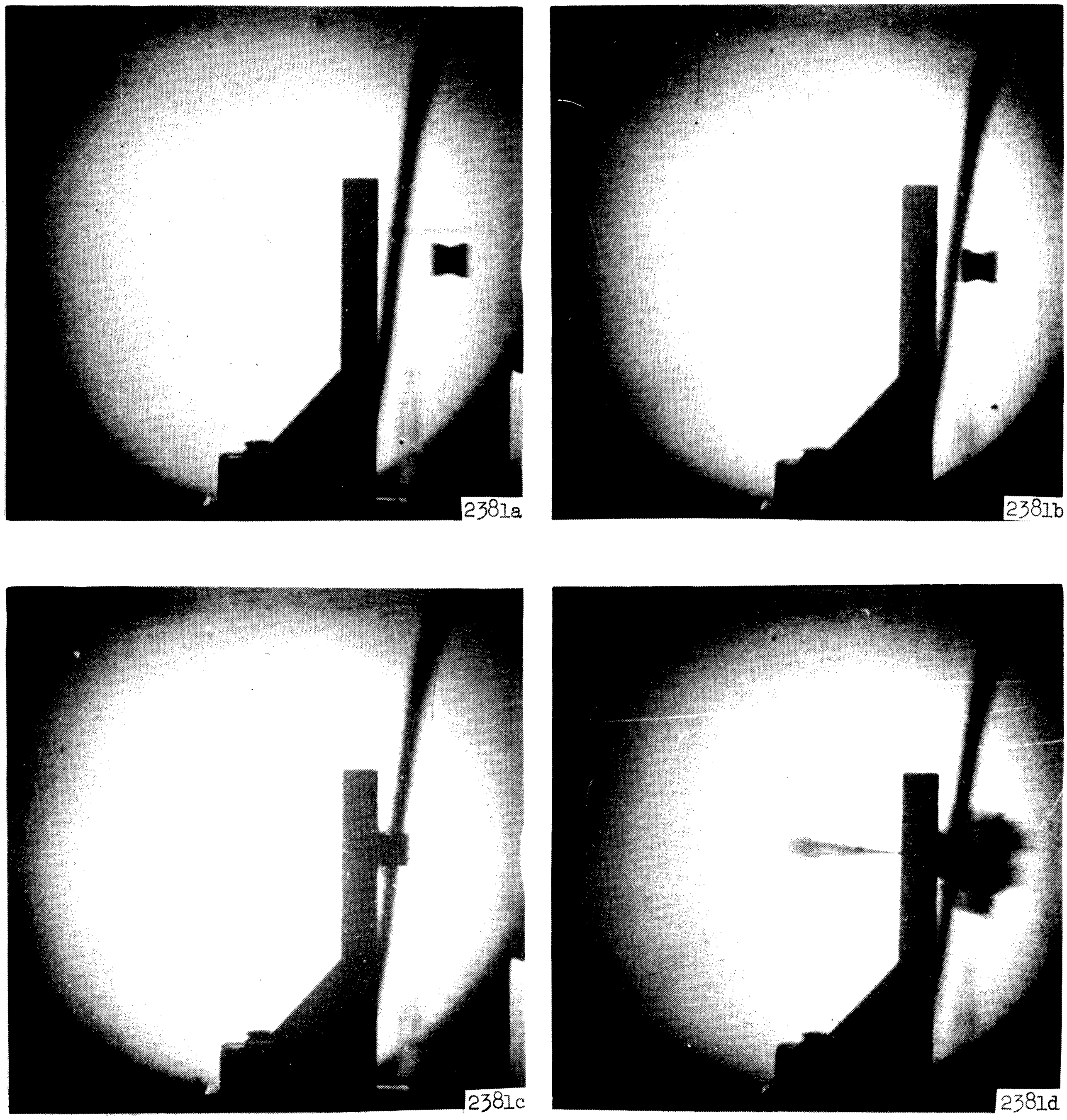



Figure 19. Liquid Jet Progression. Run #42.
Chamber Pressure -- 300 psig.
Jet Velocity Approximately 1,880 feet per second.

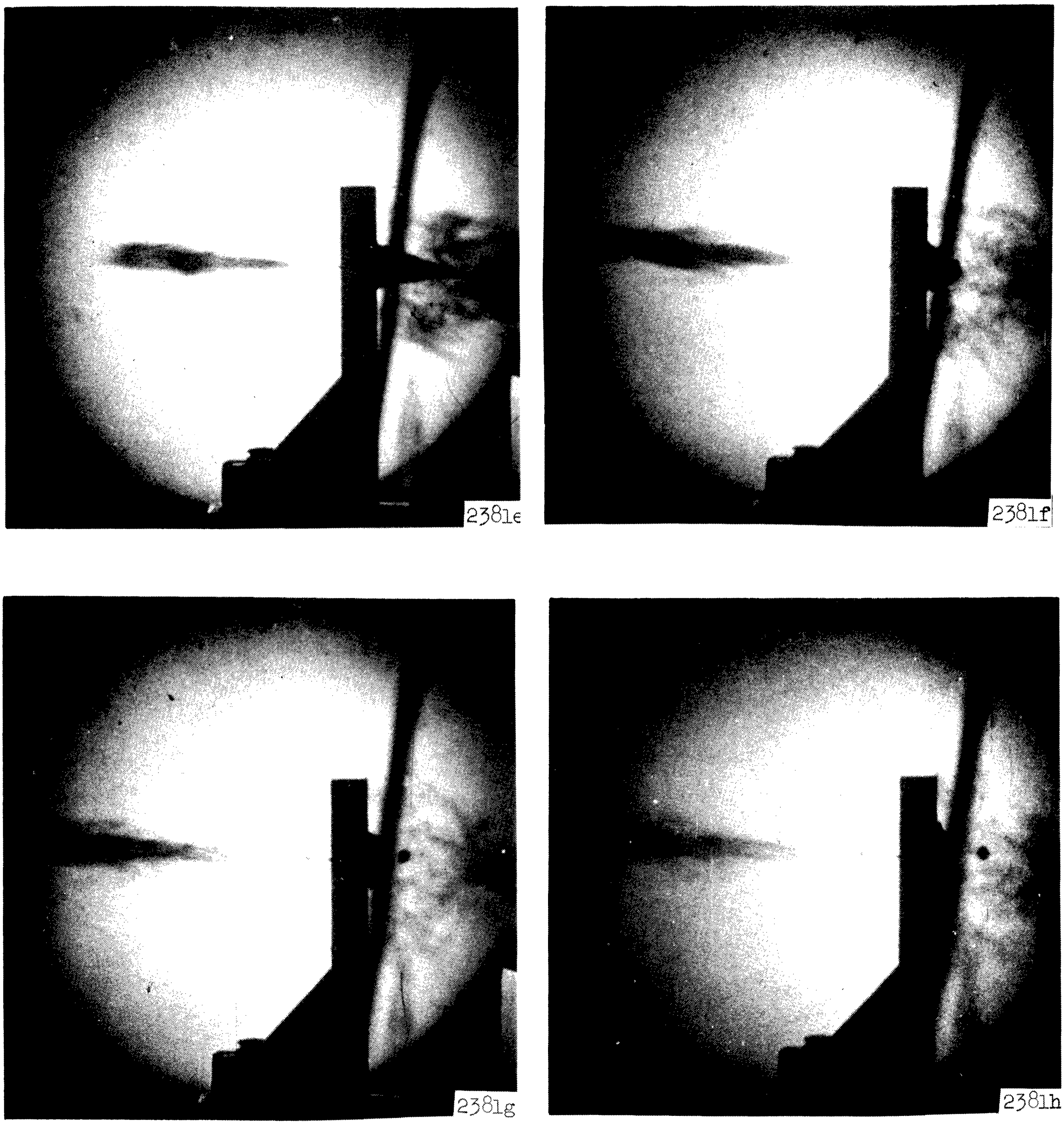



Figure 19. (Cont'd)

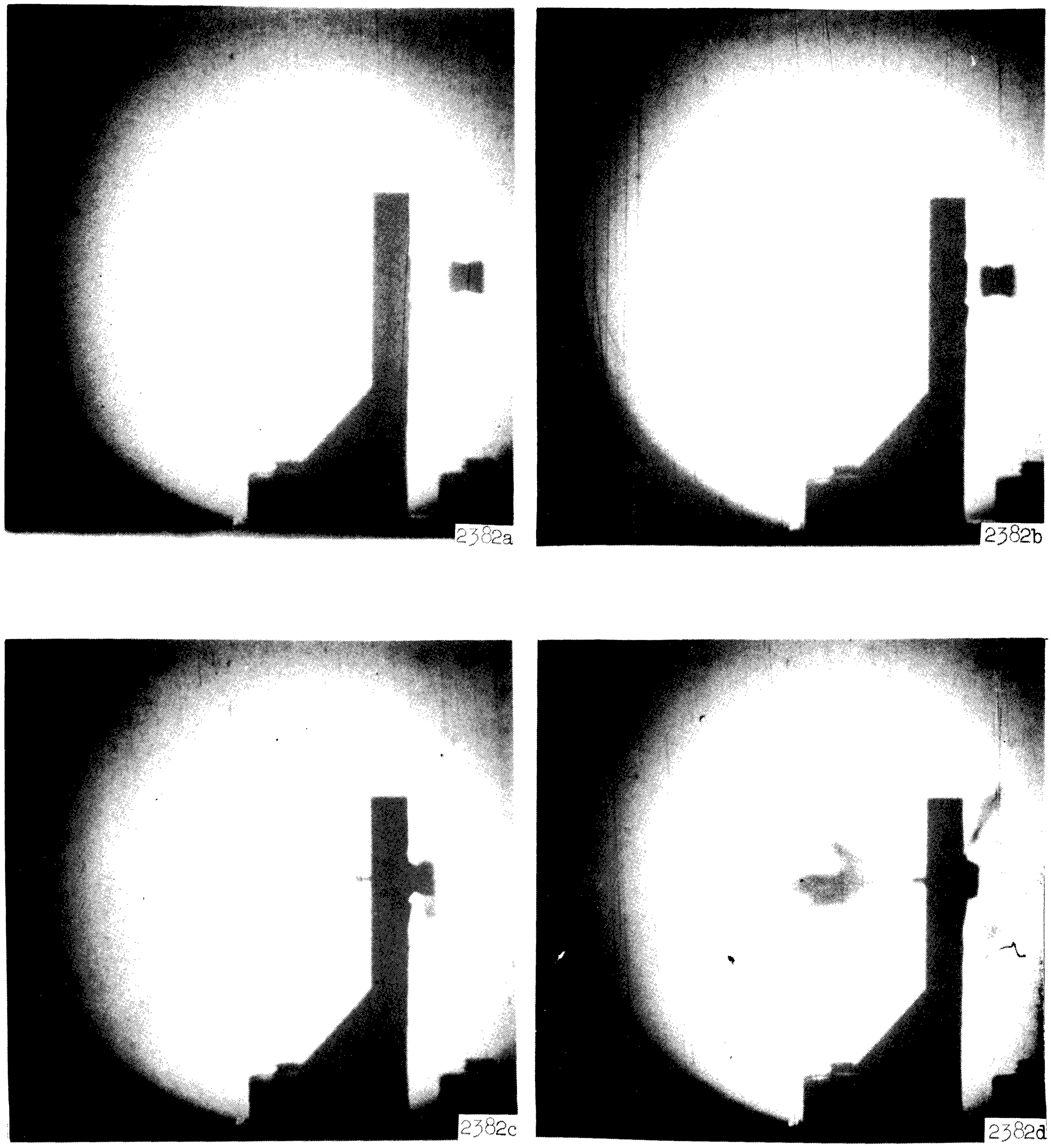



Figure 20. Liquid Jet Progression. Run #37.
Chamber Pressure -- 300 psig.
Jet Velocity Approximately 2,080 feet per second.

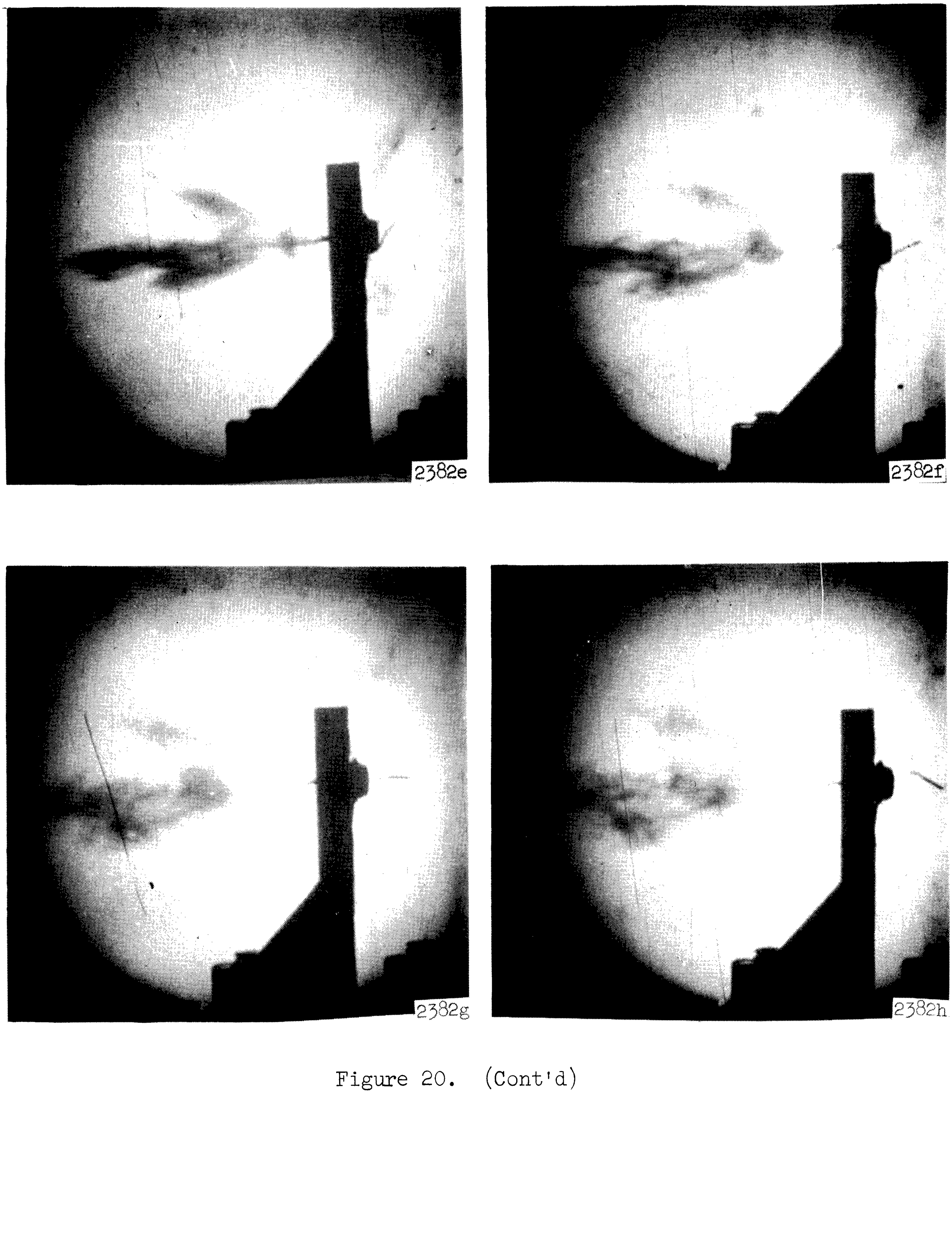



Figure 20. (Cont'd)

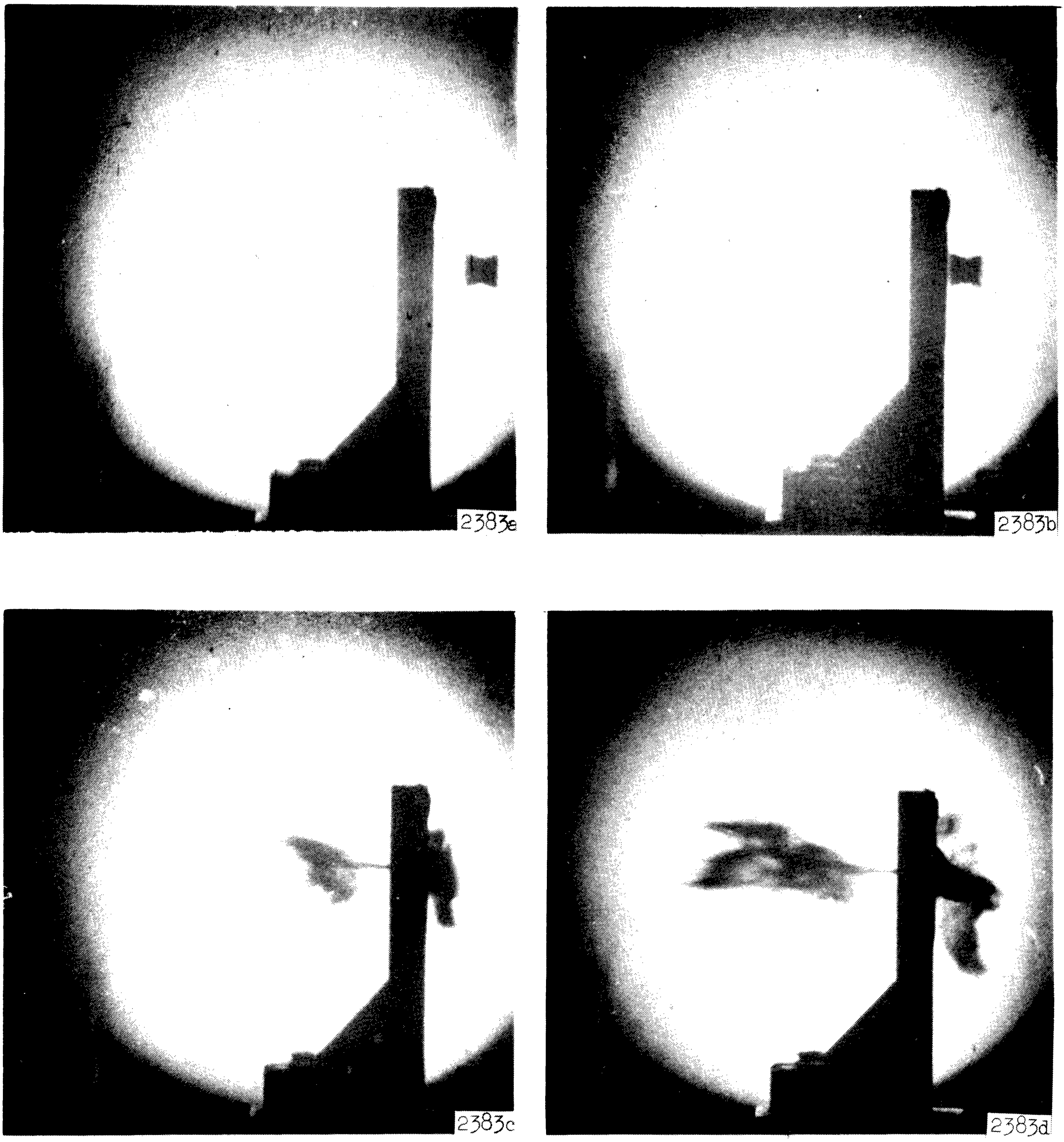



Figure 21. Liquid Jet Progression. Run #45.
Chamber Pressure -- 300 psig.
Initial Jet Velocity Over 1,830 feet per second.

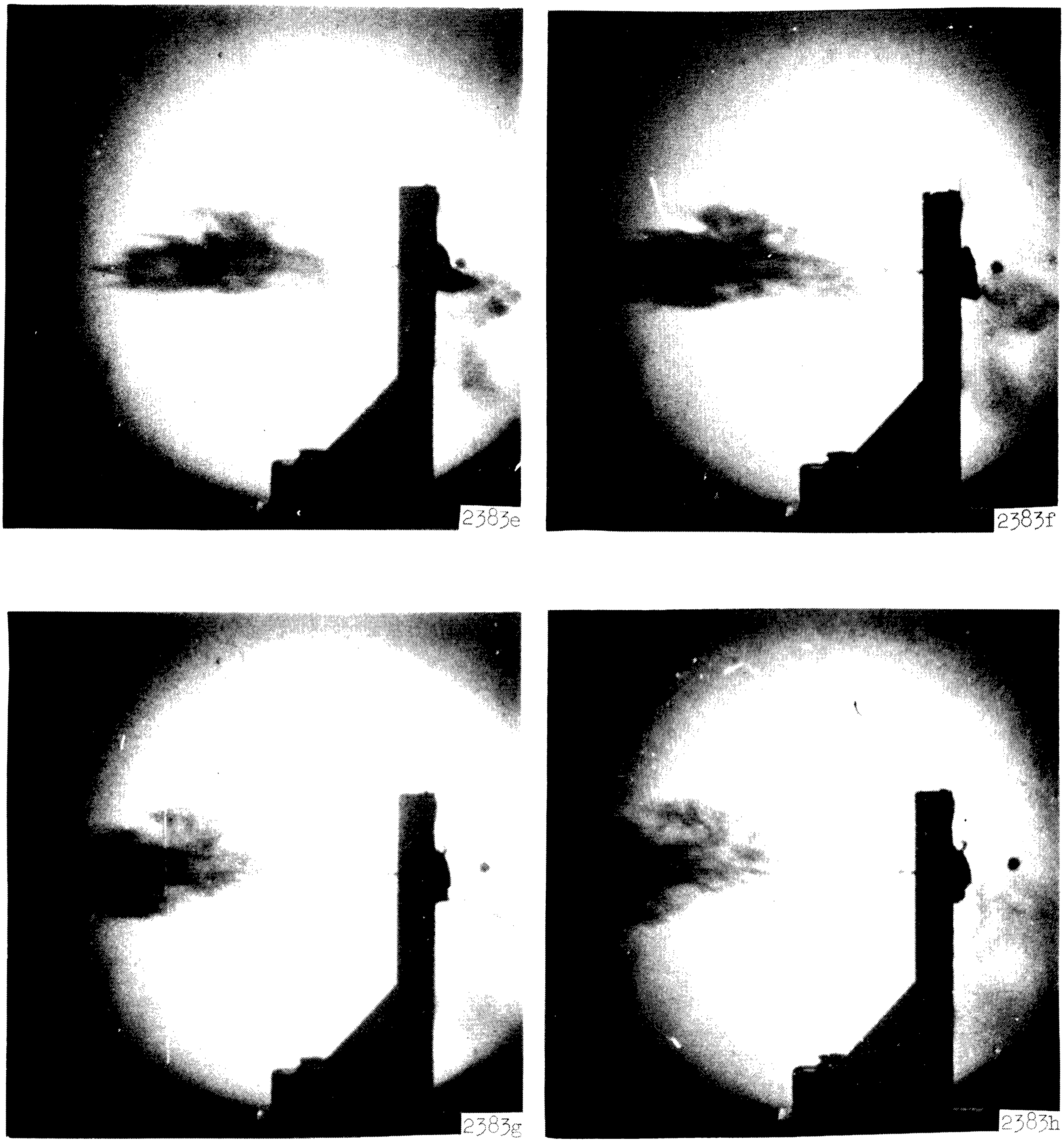



Figure 21. (Cont'd)

and transferring the bulk of its momentum to the liquid in the cavity, rather than partially hitting the edge of the nozzle resulting in a substantial loss of momentum. The changes also reduced the possibility of the pellet tilting in flight by reducing its time of flight to the target.

The results of these preliminary tests concerning the effect of gasket material and water volume on jet velocity are somewhat inconclusive. Decreasing the water volume from 0.07 cc to 0.04 cc resulted in an overall average velocity increase from about 1,770 feet per second to about 2,200 feet per second. No substantial further changes were noted with a further decrease in water volume to 0.02 cc. Generally, a substantial amount of water was left in the nozzle chamber after impact, the exact volume of which was difficult to determine. This factor, along with a substantial spray of water in the backward direction due to gasket leakage (i.e., away from the target) tended to confuse the results and subsequent analysis.

The effects of gasket material are also somewhat difficult to ascertain. The original neoprene gaskets gave higher average jet velocities with the original chamber design, whereas the teflon gaskets gave higher average jet velocities with the increased diameter water chamber. A thinner neoprene gasket (1/16 inch thick) gave higher average jet velocities than either the original neoprene (1/8 inch thick) or the teflon (5/64 inch thick) gaskets.

Test runs at higher chamber pressures (and thus higher pellet velocities) generally resulted in higher jet velocities than runs at lower chamber pressures, as would be expected. However, the number of test runs at the various fixed chamber pressures was too small to give statistically valid results for the effect of this parameter.

An examination of a few typical results may prove to be interesting and informative. Figures 12, 13 and 14 are all examples of extremely fast fluid jets ($V \geq 2,500$ feet per second for all). They tend to be rather narrow with a strong central jet. Figures 15, 16, 17 and 18 all exhibit strong "wave" type effects. These all had a visible "miniscus" at the nozzle exit prior to the impact event, which can be seen in most of the figures. These jets tended to be relatively slow, except for the one in Figure 18 ($V \approx 2,100$ feet per second). Figure 19 is another example of a narrow jet. Its velocity appeared rather low, considering the shape. However, the pellet impact point was slightly off center, which may have resulted in considerable loss of momentum transferred to the water, thus explaining the low velocity. Figures 20 and 21 are two more examples of relatively "slow" jets which do not exhibit pronounced wave effects. Here the low velocities are apparently due to the rapid disintegration of the jets.

One would intuitively expect that the "fast" narrow jets would cause the greatest damage. However, it is not presently obvious which combination of parameters will result in this type of jet. Since strong "wave" effects and rapid disintegration were evident in many of the lower velocity jets with the larger diameter chamber, and since a large miniscus at the nozzle exit appeared related to this condition, it would seem desirable to avoid such a miniscus. However, a faster camera to allow more pictures of the jet before it impacts the target is needed to establish definitely which type of jet (and the controlling parameters) will result in the greatest material damage. Although many questions remain as yet unanswered, it has been established that jet velocities of the order of 2,500 feet per second can be obtained with the present test facility, and that visible damage can be inflicted upon target speciments with a single water-jet impact. Further work is now needed to achieve a jet more closely approaching the shape of a raindrop and also to determine the conditions resulting in maximum test specimen damage. One obvious step in this direction is to vary nozzle geometry, in particular, to increase the nozzle exit diameter. Jet velocities can be easily increased by increasing the pellet velocity with the existing facility.

## V. MATERIAL REACTION

As mentioned in the introduction, the mechanism for rain erosion depends mainly upon the mechanical properties of the solid, the size and shape of the jet, the velocity of impact, and certain fluid properties such as density, bulk modulus, viscosity, and perhaps others. The general types of deformation and damage can be classified as:

(1) Circumferential surface fractures.
(2) Subsurface flow and fracture.
(3) Large scale plastic deformation leading to a permanent depression of the surface.
(4) Shear deformation around the periphery of the impact zone.
(5) Failure due to the reflection and interference of stress waves.

Surface fracture is usually observed in relatively brittle materials such as plexiglas. In these materials a compressive stress will be induced in the area under the head of the jet. The distribution of the pressure over the impacted portion of the surface is likely to be uniform initially and to decrease rapidly in the outer regions as the radial flow begins. However, the precise distribution is unknown. The stress distribution induced by the sudden application of such pressure on a region of the surface will be such that an intense radial tension will exist around the periphery of the area under fluid pressure and continue for some considerable distance over the surface from the impact zone. At any position along the surface where the radial tension exceeds the tensile strength, circumferential fractures will occur.

Subsurface failure is essentially a plastic flow along the lines of maximum shear. This flow is initiated at the point of maximum shear stress which will lie in the vertical axis through the center of impact. In addition to plastic deformation, fractures sometimes appear along flow lines as a result of short, very intense stress pulses that the solid is unable to relieve rapidly enough. As the expanding compression wave travels through the solid, a tensile stress aligns itself tangentially to the face of the compression wave. It is this tangential stress that tends to open up planes of fracture lying perpendicular to the surface.

Large-scale plastic deformation is observed in the form of a saucer-shaped depression of the surface, similar to that produced by pressing a steel sphere against a flat metal surface, as is done with a hardness tester. The material flow starts just below the surface and continues until the whole stressed region yields. For most materials the mean pressure required for full plastic flow is between 2.5 and 3.0 times the yield strength. For 1100-0 aluminum, the yield strength is 5000 psi, while for plexiglas it is 8000 psi.

When a liquid drop impinges on a planar surface, the impact pressure that results reaches a high value in a very short time. This high pressure drives the liquid that is close to the solid surface radially outward from a central stagnation point. This radial flow then exerts a shear stress on the surface over which it passes, providing an important failure mechanism. The shear stress,

$$\tau = \mu\frac{dv}{dz} \qquad (2)$$

where v = the radial velocity of the liquid.
z = the direction normal to the surface.

exists because the normal velocity gradient is not zero at the surface even though the velocity is. Engel[8], citing the work of Faust[6] and Hyde[7], notes that the viscosity of liquids not only increases with pressure, but increases at an increasing rate as the pressure rises, so that this stress may be greater than would be anticipated from calculations based on conventional conditions.

The radial-flowing liquid exerts forces against surface irregularities such as protrusions, cracks, and defects and tends to push them outward along the planar surface of the solid. Also, the force exerted by the liquid results in a turning moment being applied to the irregularity. If this force is great enough, a failure may occur. In a hard brittle material, shearing is thus expected along surface fractures produced by the normal impact. In metals, surface flaws provide the shear centers.

The reflection of the initial compression pulse from the free opposite boundary of the specimen can cause large tensile fractures to appear at points well removed from the impact zone. For the most part, these effects are significant only at very high velocities, e.g., 3000 feet per second or more in plexiglas. At lower velocities, e.g., 2000 feet per second, only small minute individual fractures are noticed in this material. Such effects were not observed at any time during the present experiment.

Most of the test specimens that were used during the present investigation were plexiglas due to the ease with which the surface of the material could be prepared. Furthermore, being transparent, it is very suitable for photographic purposes. 1100-0 aluminum was also used on some occasions.

Engel[4] suggests the use of a water hammer equation modified because the drop is spherical rather than cylindrical for calculating the impact pressure that results when a spherical drop strikes a flat, solid surface that has an infinite modulus of elasticity:*

$$P = (\alpha/2)\ c\rho V_o \qquad (3)$$

where $P$ = the impact pressure.
$\alpha$ = a coefficient which is less than unity that arises from the flow properties of the liquid.
$c$ = the speed of sound in the liquid.
$\rho$ = the density of the liquid.
$V_o$ = the impact velocity.

While this formula is at best an approximation, the use of it will give the reader an idea of the tremendous pressure that may be applied to the specimen surface.

High magnification photographs of the damage caused by those high speed jets, which were themselves photographed, have been obtained. The damage to a plexiglas sample is clearly visible in Figure 22, which is a segment of a circular damaged area. Due to the high magnification, the center of impact is off of the picture at the top right corner of the page. This type of damage is very similar to

*The original derivation of the equation is attributed by Engel to Boult and Savic[9].

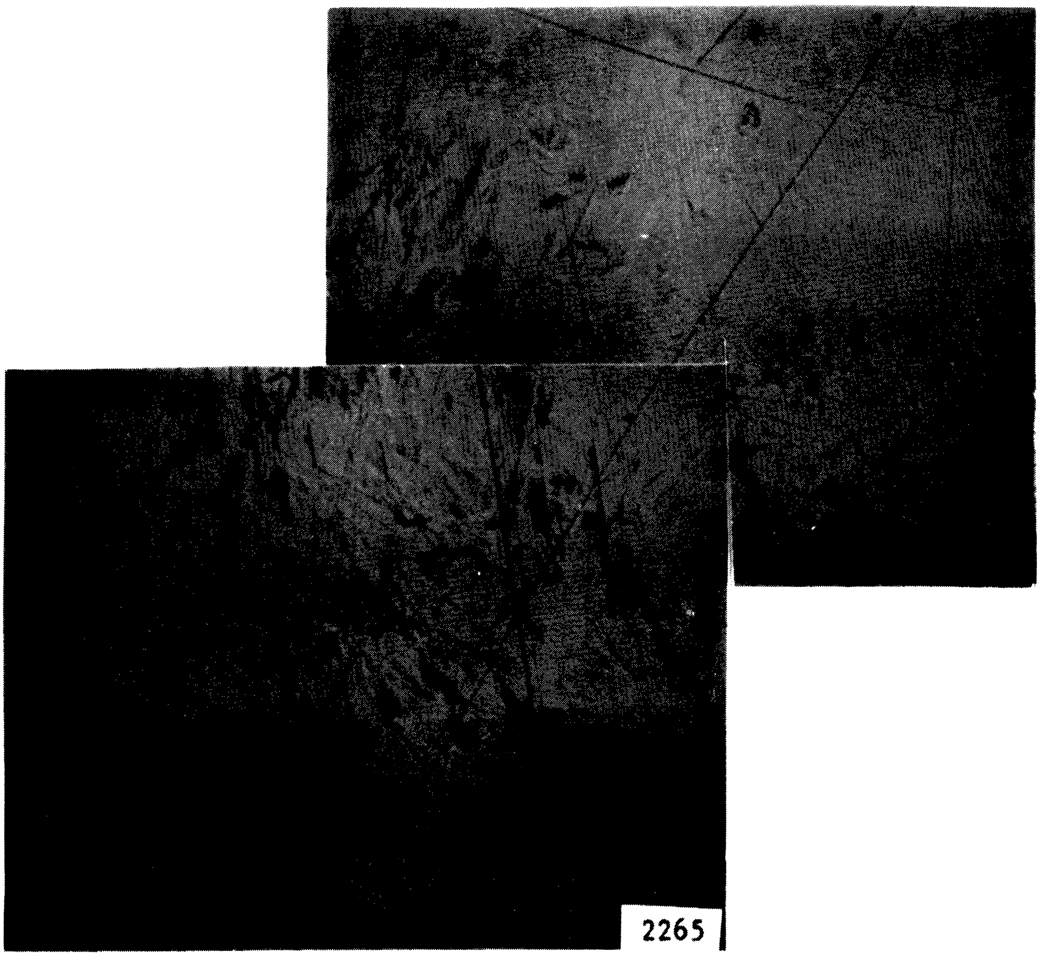



Figure 22. Single Impact Droplet Impingement Damage to Plexiglas. Chamber Pressure -- 300 psig. Target Distance -- 6 mm (100X). (Segment of circular damaged region. Center of impact at top right hand corner of page).

that reported by Engel[8]. Plexiglas specimens were tested on a rotating arm at a velocity of 735 feet per second through a 1-inch per hour artificial rain (mean drop size of 1.9 mm diameter) for a duration of 25 seconds. The damage was much more severe than in the present case, which is a single droplet experiment with an equivalent drop size (based on a liquid volume of 0.08 ml) of approximately 5.38 mm.

Next a multi-impact sequence was taken using the same plexiglas as the target material for all impacts (Figure 23). The large scale plastic deformation is surrounded by a ridge of displaced material in addition to the usual stress lines. The cause of the non-symmetry of the damage is that the jet impinged upon the surface at an angle slightly different from 90°. In Figure 23, more damage appears in the form of two long, narrow depressions surrounded by a ridge which is left open at one end. Note that jet does not apparently hit the target in precisely the same spot in each shot, with damage centers separated by perhaps 0.005 inches. Also note the fracture polygon which develops presumably from the crystalline structure of the plexiglas used. Again the jet hit the surface at an angle and possibly flowed along previous stress lines. (The particular angle varies from shot-to-shot, but is estimated at 5-10° from perpendicular by measuring the angle in photographs of the jet).

The main reason for the jet hitting the surface in non-perpendicular direction is that the pellet has impinged on the neoprene disk at an angle slightly downwards and below dead center (Figure 7b). The maximum vertical drop possible due to gravity effect on the pellet during the flight is 0.00038 inches. The actual drop is in the vicinity of 0.10 inches (about 1/2 the diameter of the neoprene

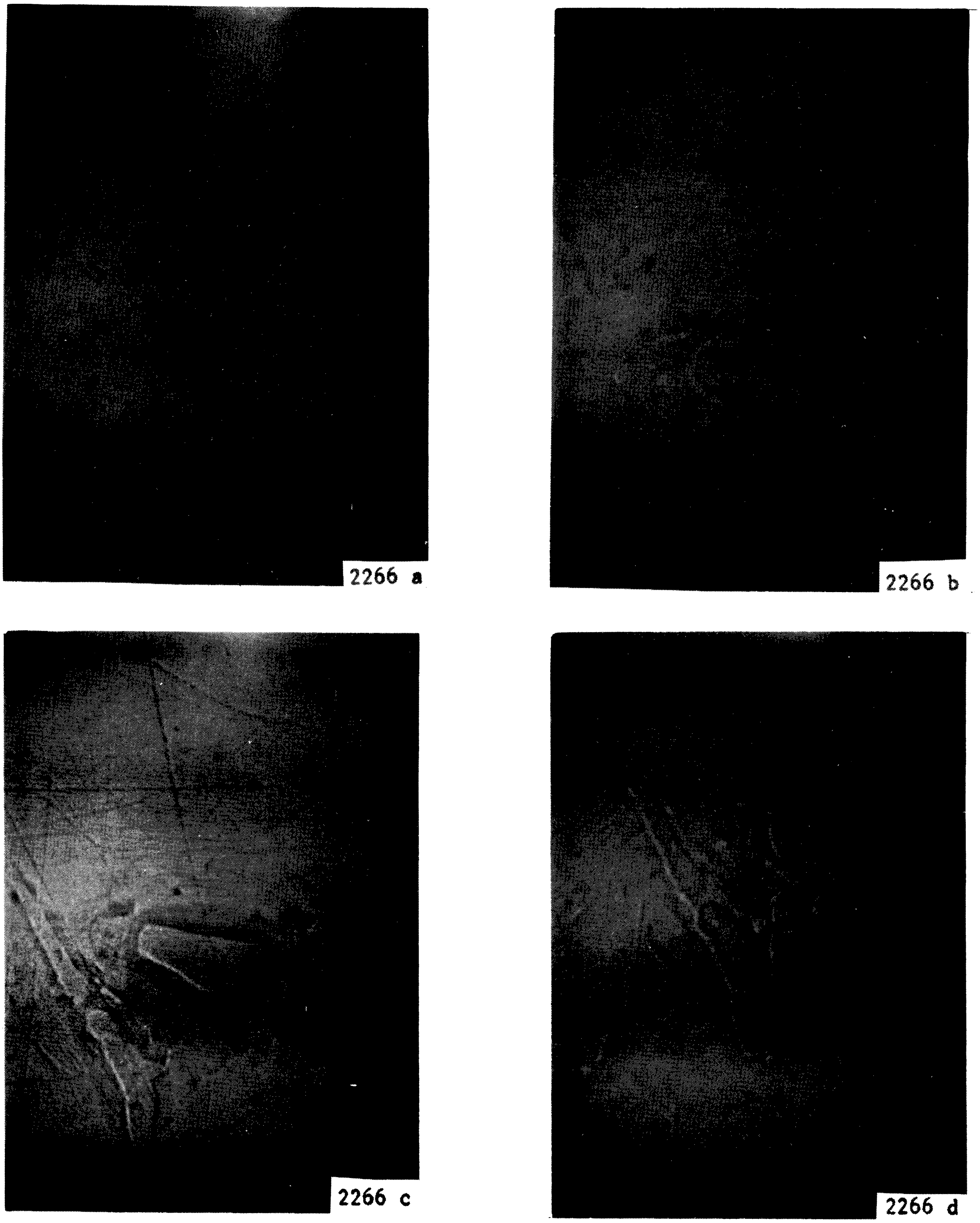



Figure 23. Multi-Impact Damage to Plexiglas Specimen.
Pressure -- 250 psig. Target Distance -- 12 mm (100X).
(a) Before impact.
(b) After two impacts.
(c) After four impacts.
(d) After six impacts.

disk). Hence the barrel of the rifle is in some way affecting the performance of the pellet in some of the shots.

In many of the pictures from the present investigation, it appears that when the jet hits the surface at an angle other than 90°, relatively little sub-surface damage is done to the target, but rather a tremendous amount of gouging occurs.

The relative amounts of damage caused by jets produced with different chamber pressures (250 psi versus 300 psi) appeared nearly the same on the basis of these limited tests. However, when the target-to-nozzle distance was decreased, the damage was significantly increased.

## VI. RECOMMENDATIONS FOR FUTURE STUDY

Future effort on this aspect of our overall rain erosion studies will be primarily directed to two principal areas:

(1) Further study of the factors affecting the velocity and shape (and hence, the damaging potential and its similarity to that of spherical drops) of the liquid jet.
(2) Comparison of damage and factors influencing damage due to impingement of a high velocity jet to that resulting from rain erosion.

In regard to the first area, future tests will be primarily directed to investigating the effects of nozzle design and gun chamber pressure on jet velocity and shape. Orifice diameter will be increased from the present 0.5 mm diameter in steps to possibly as large as 2 or 3 mm diameter. This change should result in a shorter and wider jet, thus more closely approaching the geometry of a raindrop. Tests will also be conducted at higher gun chamber pressures, hopefully as high as 500 psig, thereby increasing the pellet velocity and also the liquid jet velocity. Perhaps at some point a standard "22-rifle" will be substituted for the present gas gun.

Attempts will also be made to compare the damage and factors influencing damage due to a high velocity jet impacting a stationary target to other types of fluid impact damage, including both rain erosion damage and damage resulting from cavitation tests.

Liquid jet impingement tests may also be conducted with fluids other than water, or with certain additives, such as diesel oil and "Polyox," to determine the effect of fluid properties on fluid impact damage and jet shape in hopes that a spherical droplet may be more closely approximated. "Polyox," or polyethylene oxide, has been found to be useful in holding the jet together (i.e., decreasing turbulent breakup) and thus enhancing the jet cutting ability in experiments conducted by the Wood Technology Department of this University.

## VII. CONCLUSIONS

When a liquid collides with a solid surface, a short, but intense compression wave travels through the solid, thus perhaps producing some deformation. Additional deformation may then be caused by a shearing of the surface due to the very rapid radial velocity across the surface. When typical induced-stress values are computed, it becomes apparent that very few solids or plastics are capable of withstanding high-speed liquid impact without some severe deformation.

These tests have shown that it is possible to simulate rain erosion damage by using a high-velocity liquid jet. It has also been demonstrated that as the velocity of the jet is increased or the target distance is decreased, the damage is greatly increased. Certain questions reqarding jet velocity and shape, and parameters influencing them, remain unanswered and will be investigated in more detail in future tests. It has not been demonstrated, but it is to be expected, that the smoothness of the surface will also influence greatly the extent of the deformation, since the forces on a rough surface from droplet impact are much greater than on a smooth surface. Thus, the observation of a single water jet impinging on a target surface with known mechanical properties should provide some of the answers to the problem of rain erosion.

# APPENDIX A

## SUMMARY OF RESULTS

| Run Number | Gun Pressure (Psi) | Camera Speed (Frames/Second) | Approximate Water Volume (cc) | Type Gasket | Approximate Jet Velocity (Feet/Second) | Comments |
|---|---|---|---|---|---|---|
| 4 | 200 | 20,000 | ~.07 | Neoprene | over 700 | See Figure 10. Pellet impact ~20% off center. Backspray. |
| 7 | 300 | 20,000 | " | " | —— | Timing too late. Backjet from pellet or water. |
| 8 | 250 | 25,000 | " | " | over 1,000 | Very much backspray-straight back. |
| 9 | 300 | 25,000 | " | " | over 1,000 | Lots of scattered backspray. Pellet tilted. Pellet impact off center. |
| 11 | 300 | 20,000 | " | Teflon | —— | No backspray. Target damaged. "Diverging" jet. |
| 12 | 300 | 20,000 | " | " | —— | See Figure 11. Target damaged after single impact. |
| 19 | 300 | 20,000 | " | " | 1,170 | Narrow jet. "Wave" effects. Backspray. Pellet velocity may be low. |
| 21 | 300 | 20,000 | " | " | 1,690 | "Wave" effects. Backspray. Pellet tilted. Fairly narrow jet. |
| 22 | 300 | 20,000 | " | " | 1,670 | "Diverging" jet with narrower center jet emerging. Very slight backspray. |
| 23 | 300 | 20,000 | " | " | 2,120 | Initially "diverging" jet - then relatively constant diameter. Little backspray. |
| 24 | 300 | 25,000 | .04 | 2 Teflon | 1,770 | "Wave" effects. Negligible backspray. Impact off center. |
| 25 | 300 | " | .02 | 2 Teflon | 1,600 | "Wave" effects. No backspray. |
| 26 | 300 | " | .07 | Teflon | 1,690 | "Wave" effects. Slight backspray. Gasket snug. |
| 27 | 300 | " | " | " | 1,740 | Fairly narrow jet. Slight wave effects. Gasket loose. Backspray. |

APPENDIX A

SUMMARY OF RESULTS (Cont'd)

| Run Number | Gun Pressure | Camera Speed | Approximate Water Volume | Type Gasket | Approximate Jet Velocity | Comments |
|---|---|---|---|---|---|---|
| | (Psi) | (Frames/Second) | (cc) | | (Feet/Second) | |
| 28 | 300 | 25,000 | .07 | Neoprene | 1,960 | Narrow jet. Negligible backspray. |
| 30 | " | " | .07 | " | 1,620 | "Diverging" jet. "Wave" effect. Slight backspray. |
| 31 | " | " | .04 | " | 1,670 | Narrow jet. "Wave" effect. Lots of backspray. |
| 32 | " | " | .04 | " | over 2,800 estimate at 3,500 | See Figure 12. Very narrow leading jet. Backspray. |
| 33 | " | " | .02 | " | 1,920 | "Diverging" jet. "Wave" effects. Backspray. |
| 34 | " | " | .02 | Teflon | over 2,400 initially | "Diverging" jet. Slight backspray. "Wave" effects. |
| Changes: | Enlarged opening in back side of momentum exchange device. Moved entire setup closer to end of gun barrel. | | | | | |
| 35 | 300 | 25,000 | .04 | Teflon | 2,820 | See Figure 13. Jet diverges initially - then narrows down. Slight backspray. |
| 36 | " | " | .02 | " | —— | Light flashed too late. |
| 37 | " | " | .07 | " | 2,080 | See Figure 20. Jet sort of disintegrates into 3 parts. Backspray. |
| 38 | " | " | .02 | " | 2,400 | Jet diverges initially. Narrower leading part later. Backspray. |
| 40 | " | " | .02 | " | 2,500 | See Figure 14. Rather narrow jet. Backspray. |

APPENDIX A

SUMMARY OF RESULTS (Cont'd)

| Run Number | Gun Pressure (Psi) | Camera Speed (Frames/Second) | Approximate Water Volume (cc) | Type Gasket | Approximately Jet Velocity (Feet/Second) | Comments |
|---|---|---|---|---|---|---|
| 41 | 300 | 25,000 | .02 | Neoprene | 1,940 | See Figure 15. "Bubble" initially on orifice, "Christmas Tree" wave effect. |
| 42 | " | " | .04 | " | 1,880 | See Figure 19. Slight divergence but narrow jet. Lots of backspray. Poor pellet impact. |
| 43 | " | " | .07 | " | 940 initially. 1,690 later | See Figure 16. Slight miniscus initially on oriface. "Christmas Tree" wave effect. Munro jet? |
| 44 | " | " | .07 | " | 1,670 | See Figure 17. Bubble initially on oriface. "Christmas Tree" wave effect. |
| 45 | " | " | .07 | " | over 1,830 at start | See Figure 21. Jet rapidly disintegrates. Lots of backspray. |
| 46 | " | " | .02 | " | 2,200 | Tilted nozzle to leave parallel part empty during filling. Jet disintegrates. Backspray. |
| 47 | " | " | .07 | Thin neoprene | 2,460 | Big miniscus initially on orifice. "Wave" effect. Narrow jet. Jet seems at angle up. |
| 48 | " | " | .02 | Thin neoprene | 2,560 | Jet broadens - then narrows down. Backspray. Narrow centerjet. |
| 49 | " | " | .02 | Thin neoprene | 2,300 | Jet broadens - then narrows down. Looks narrow centerjet. Backspray. |
| 50 | " | " | .02 | Thin neoprene | 2,810 | Looks very ragged, but narrow centerjet. Backspray. |
| 52 | 250 | " | .02 | Teflon | 2,130 | See Figure 18. Bubble initially or orifice. "Wave" effect - narrow leading part. |

APPENDIX A

SUMMARY OF RESULTS (Cont'd)

| Run Number | Gun Pressure (Psi) | Camera Speed (Frames/Second) | Approximate Water Volume (cc) | Type Gasket | Approximate Jet Velocity (Feet/Second) | Comments |
|---|---|---|---|---|---|---|
| 53 | 200 | 25,000 | .02 | Thin Neoprene | 2,340 | Very ragged appearance .. but strong narrow centerjet. Backspray. |
| 54 | 200 | " | .04 | Neoprene | 1,450 | Ragged appearance. Unsymetrical. Most backspray towards top. |
| 55 | 200 | " | .07 | Thin Neoprene | 2,080 | Jet broadens, then narrows down. Strong central backspray. |
| 56 | 325 | " | .04 | Thin Neoprene | 2,440 | Some divergence of jet and wave effect. Central backspray. |

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