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TECHNICAL NOTE 2349

FLUCTUATIONS IN A SPRAY FORMED BY TWO IMPINGING JETS

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SUMMARY

The spray resulting from the impingement of two jets of water was investigated to determine the characteristics of the instability associated with this method of spray formation. It was found that upon impingement of two jets a ruffled sheet of liquid was formed perpendicular to the plane of the two jets. The liquid sheet disintegrated intermittently, forming groups of drops, which appeared as waves propagating from the point of impingement. The intermittent disintegration of the liquid sheet occurred with irregular spacing between waves and with variable wave intensity; however, the frequency of wave formation was a constant over a finite time interval under constant operating conditions. There was an abundance of small waves , with the number of waves of a given intensity decreasing as the wave intensity increased. From the photographic and frequency data obtained, the ruffling of the liquid sheet appears to be caused by both irregularities in the jets and interaction with the air. The ruffling of the liquid sheet persists to the point of disintegration of the sheet and establishes the frequency of the wave formation.

Frequency measurements obtained by a photoelectric technique showed that wave frequency varied between 1000 and 4000 cycles per second for test conditions of jet velocities from 20 to 80 feet per second, impingement angles up to 100°, and jet diameters of 0.025, 0.040, and 0.057 inch. Frequency was found to increase with jet velocity with approximate direct proportionality. An increase in impingement angle resulted in a decrease in wave frequency for impingement angles of from 50° to 100° with the decrease being approximated by the decrease in the cosine of one-half the impingement angle. Both the diameter of the jets and the length of the jets before impingement had negligible effects on wave frequency compared to the effect of jet velocity and impingement angle.

INTRODUCTION

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The combustion process in rocket engines has, under certain operating conditions, exhibited conditions of instability. This instability is characterized by sustained oscillations in combustion-chamber pressure at frequencies that vary from approximately 20 up to several thousand cycles per second. An explanation of such oscillation at low frequencies may be resonance in a circuit where the propellant feed system and the rocket chamber are dynamically coupled. The instability at higher frequencies, however, is not readily explained on the same basis. Combustion instability of this rapidly reoccurring type appears to originate in the injection and mixing process. In view of this relation of the injection process to instability, the flow characteristics and the patterns of sprays formed by the impingement of two liquid jets, a typical method of injection, have been investigated at the NACA Lewis laboratory with the intent that such an evaluation may be useful in the study of combustion instability.

Previously reported characteristics on the formation of sprays do not describe the process in sufficient detail for the objective of this investigation. The process of disintegration of a liquid jet is explained and photographically shown in references 1 to 3. The disintegration process is described as one in which ligaments are initially formed and the ligaments disintegrate to form drops. The disintegration of a liquid with the associated waving or flapping characteristics is described in reference 4. These references as well as photographs presented by other investigators show that the instantaneous flow rate of liquid after disintegration of a sheet or jet is not continuous but varies considerably and that the flow is actually interrupted. A numerical evaluation of the characteristics of disintegration or the effect of injection parameters on these characteristics, however, has not been reported.

In this investigation, the formation of a spray resulting from the impingement of two jets of water was studied by visual, photographic, and photoelectric techniques. High-speed motion pictures and microflash photographs were taken of the spray pattern. Frequency measurements of the disintegration process were obtained by allowing the spray to interrupt the path of light entering a photoelectric cell and analyzing the resulting signal. The effects of jet velocity, impingement angle, jet length before impingement, and jet diameter on the spray pattern and frequency characteristic were evaluated. This investigation was conducted between October and December 1950.

APPARATUS AND INSTRUMENTATION

The experiments were performed with an impinging-jet apparatus schematically shown in figure 1. The apparatus provided for control of liquid supply pressure and allowed variations in impingement angle and length of jet before impingement. The liquid jets were formed with approximately 2-inch lengths of precision-bore glass tubing that were interchangeable. Water was used as the liquid for all the investigations; weight flow was determined from rotameter readings. Equal water flows were obtained from each jet.

Photographs were taken of the spray formation to record the phenomena as well as for quantitative measurements. High-speed motion pictures at approximately 3000 frames per second and single-exposure microflash photographs of approximately 4-microsecond exposure were taken. The exposure time with both methods of photography was sufficiently rapid to effectively stop the spray. Fluctuations within the spray were detected with the use of a photoelectric cell, recording oscilloscope, frequency meter, and associated instrumentation. The arrangement is also shown in figure 1. With this method of measurement, fluctuation within the spray interrupted a slit of light entering a photoelectric cell. The resulting signal was delivered to a frequency meter for frequency measurements. The signal could also be observed visually on the screen of an oscilloscope, or the oscilloscope trace could be photographically recorded. A slit of light 1/8 by 1/4 inch was used with the photoelectric cell. The light was oriented with the spray in such a manner that the resulting signal on the oscilloscope represented the maximum amplitude of the most symmetrical wave for the test condition. Analysis of the oscilloscope trace showed that frequency did not vary with orientation. The value of frequency obtained from the frequency meter did vary with orientation of the light, although this variation was small for the orientations used in the investigation.

A comparison of the frequency obtained from an analysis of the oscilloscope trace with the value obtained from the frequency meter indicated agreement within 5 to 10 percent. Lower values of frequency were obtained with the frequency meter. The variation presumably resulted from a combination of the inability of the meter to record signals below a given amplitude and to identify indistinct pulses.

The reading of the frequency meter was used as a measure of the frequency because of the time required to obtain the value from the oscilloscope trace and because relative rather than absolute values were satisfactory. Frequency values obtained from high-speed motion pictures confirmed the frequency obtained with the photoelectric-cell techniques. The inability to distinguish readily the fluctuations in the spray and the time involved to determine the frequency, however, made this an inconvenient method of frequency measurement.

Jet velocities were determined from calculations using flow measurements and jet diameters. The jet diameters were assumed to be equal to the bore of the glass tubing used to form the jets. An attempt was made to measure jet velocities from high-speed motion pictures. Although this method of measurement correlated with the calculated velocity, the method was undesirable because of the tedious procedure of velocity evaluation and the limited accuracy of the technique.

SINGLE-JET CHARACTERISTICS

The spray formation resulting from the impingement of two equally sized jets 0.025, 0.040, and 0.057 inch in diameter was investigated. These jet diameters are the apparent diameters as determined from the bore of the glass tubing. Microflash photographs of the 0.025-inch diameter jets at velocities of 20, 40, 60, and 80 feet per second are shown in figure 2. It will be noted that a solid but ruffled solid stream exists for a distance of from 1 to 4 inches from the exit of the glass tubing after which the stream disintegrates or separates.

The photographs indicate that a longer unbroken stream is obtained at high jet velocities than at low velocities. If the ruffling of the jet were the result of air friction on the surface of the jet, it would appear that the opposite effect would be obtained. For the range of velocities used in this investigation, it is probable that turbulence in the jet and surface tension force are more instrumental in the disintegration than air friction. Under these conditions, the liquid in a higher-velocity jet would travel a greater distance before surface tension forces cause it to disintegrate. This theory is in agreement with that presented in reference 5.

The ruffling in the jet immediately after it leaves the glass tubing is probably the result of averaging or balancing of velocities in the jet. The velocity profile in the tubing represents a condition where a higher velocity exists in the center of the stream than at the surface. The same profile will not exist after it leaves the tubing and the transition will result in turbulence in the jet. The Reynolds numbers of the streams in figure 2 are above critical, 3500 to 15,000, and it is probable that the cross-sectional velocity gradient in the tube is sufficient to cause eddies in the jet.

The jets obtained in this study are not unique in their turbulent or disintegration characteristic. Reference 5 presents microflash photographs of water jets under similar conditions and describes the disintegration phenomena. This agrees with the characteristics shown in figure 2. Microflash photographs of jets with liquids having higher viscosity and lower surface tension than water are shown in reference 3. Both of these properties would tend to produce more stable jets for a jet velocity range of 20 to 80 feet per second where disintegration is primarily a function of surface tension forces; this tendency is confirmed by the photographs. The roughened surface of the jets at the exit of the glass tubing was found to be similar in all the jets investigated and therefore does not appear to be a function of irregularities in the glass tubing. Comparatively large length-diameter ratios were used to produce the water jets in this investigation. Reference 5, however, used orifices with length-diameter ratios of about 10, which are comparable to those used in rocket engines, and the resulting jets are similar to those obtained in this investigation.

IMPINGING-JET-SPRAY CHARACTERISTICS

Spray Fluctuations

The instability associated with impinging jets was initially observed by viewing the spray formed by two impinging jets with stroboscopic light. The spray formation had the appearance shown in the microflash photograph of figure 3. The photographs shown are views parallel and perpendicular to the plane of two impinging jets. These photographs indicate that the formation of liquid drops is an intermittent phenomenon rather than a continuous process. The photographs illustrate that upon impingement of two jets a ruffled sheet of liquid is formed perpendicular to the plane of the two jets. This sheet of liquid disintegrates intermittently, forming groups of liquid drops and giving the appearance of waves propagating from an origin at the point of impingement.

Various data were taken to clarify the nature of the fluctuations in the spray. In figure 3, it will be noted that the groups of drops propagating from the point of impingement are of various sizes with irregular spacing between groups. This characteristic is more clearly portrayed in figure 4, which shows a sequence of high-speed motion-picture frames. The progression of the groups of drops can be followed in successive frames. Again the irregular size and spacing of the groups of drops, or of waves, will be noted. The waves became less distinct as the distance from the point of impingement increased due to the dispersion of the spray. Data recordings using the photoelectric-cell apparatus and the recording oscilloscope verify the irregular occurrence of the waves. A typical oscilloscope trace is shown in figure 5. Each pulse on the trace represents one wave in the spray.

A quantitative evaluation was made of wave intensity, the quantity of liquid per unit volume, and the frequency from an oscilloscope trace obtained for a typical spray. This evaluation was made assuming proportionality between oscilloscope deflection and quantity of liquid per unit volume intercepting the light beam. The results of this evaluation are shown in figure 6(a), which shows frequency and intensity on an accumulative basis. For example, the frequency at an intensity of 3 is 450 cycles per second, where 450 is the frequency based on the number of waves of intensity 3 plus all those larger than 3. The intensity scale used is linear, but the magnitude is arbitrary. Figure 6(a) indicates that there is an abundance of low-intensity waves. Approximately one-half the waves have an intensity of 1/12 the maximum intensity. Further analysis of the data represented by figure 6(a) indicated an exponential relation between frequency and intensity. A replot of the data on semilogarithmic coordinates is shown in figure 6(b). This representation suggests that the oscillation characteristic is similar to that obtained in other phenomena such as noise. It also is typical of the relation between drop size and number of drops obtained from a spray nozzle. Although on first impression the fluctuations in the spray appear to be random in nature, on the basis of frequency and intensity the fluctuations do have defined characteristics as illustrated in figure 6. Under constant operating conditions, these characteristics were reproducible and the frequency of wave formation over a finite time interval is constant.

Effect of Injection Parameters on Wave Frequency

Jet velocity and impingement angle. - The effect of jet velocity on wave frequency over a jet velocity range of 20 to 80 feet per second for impingement angles of 40°, 60°, 80°, and 100° was determined for the 0.025-inch-diameter jets. The relation between frequency and velocity at the various impingement angles is shown in figure 7. The frequencies shown in this and succeeding figures are those obtained with the frequency meter, which represents the frequency based on all waves in the spray. Figure 7 shows that frequency increases with velocity with the relation approaching direct proportionality. The frequency gradient is approximately 30 cycles per second per foot per second velocity. Although no data were taken below a velocity of 20 feet per second, the nature of the curves suggested extrapolation to the origin.

A similar frequency-velocity relation for all impingement angles is shown in figure 7; however, the trend of increasing frequency with decreasing impingement angle obtained for impingement angles of 100°, 80°, and 60° was reversed for an angle of 40°. A lower frequency was obtained at an impingement angle of 40° than at 60° for jet velocities below 80 feet per second. This effect is more clearly shown in figure 8. In this case the effect of impingement angle on frequency was determined for the 0.040-inch-diameter jets. The frequency was determined over the maximum impingement cycle range of the apparatus including the frequency measured in the nonimpinging jet at a point where complete disintegration of the jet exists. The curve shown in figure 8 is a theoretical relation that will be discussed later. Good agreement with the theoretical curve was obtained at impingement angles of 50° and above. The frequencies obtained at low impingement angles are reproducible; however, some of the deviation from the theoretical curve may be attributed to the indistinct nature of the waves at low impingement angles. The frequency meter was not completely responsive to those indistinct waves.

The variations in the spray pattern resulting from changes in jet velocity are shown in figure 9. The patterns for velocities of 20, 40, 60, and 80 feet per second at an impingement angle of 60° are shown for the 0.025-inch-diameter jets. Views perpendicular as well as parallel to the plane of the jet are shown. These photographs illustrate that the wave pattern is not substantially altered by jet velocity. Smaller drops, however, are formed at the higher velocities.

The wave patterns for impingement angles of 30°, 60°, and 90° at a jet velocity of 60 feet per second for the 0.025-inch-diameter jets are shown in figure 10. These photographs indicate greater definition of wave pattern as well as a shorter distance for complete disintegration of the liquid sheet as impingement angle increases. The photographic views perpendicular to the plane of the two jets indicates a larger dispersion of the spray as impingement angle increases.

Jet diameter. - Frequency measurements were made over a velocity range of from 20 to 80 feet per second and at an impingement angle of 80° for jet diameter of 0.025, 0.040, and 0.057 inch. These results are shown in figure 11. An increase in frequency with decreasing diameter at constant velocity is indicated; however, the effect of diameter is comparatively small. A diameter range of from 0.025 to

0.057 inch at constant velocity represents a flow range of approximately 5 and resulted in a frequency variation of from 200 to 300 cycles per second. An equal flow range at constant diameter and varying velocity results in a frequency variation of approximately 2500 cycles per second. The effect of jet diameter on the relation between frequency and impingement angle is shown in figure 12 for a jet velocity of 60 feet per second. Figure 12 is similar to figure 11 in that an increase of frequency with decreasing diameter is observed. The effect of jet diameter, however, is shown to be larger at small impingement angles.

Inasmuch as an indicated velocity was used in the comparison in figures 11 and 12, the small variations in frequency are insufficient to predict the effect of diameter beyond that the effect is small in comparison to the effect of impingement angle and velocity.

The effect of diameter on the spray pattern is illustrated in the photographs shown in figure 13. The spray pattern for the 0.025-, 0.040-, and 0.057-inch-diameter jets at a velocity of 50 feet per second and an impingement angle of 70° is shown. Beyond that the size of the resulting spray changes with diameter, only small differences are detectable. Figure 13 gives the appearance of successive enlargements of the same picture.

Jet length. - The length of the jets before impingement was varied under several conditions to determine the effect of this parameter on wave frequency. The effect on the 0.025-inch-diameter jets at an impingement angle of 80° and jet velocity of 60 feet per second, and on the 0.040-inch-diameter jets at a velocity of 40 feet per second and impingement angles of 40° and 90° is shown in figure 14. The stream length was varied in the range of 6 to 80 diameters. The effect over this range is shown to be negligible; a small increase in frequency, however, occurs below a stream length of 30 diameters. The increase amounts to only 100 to 200 cycles per second.

The effect of stream length is more pronounced in spray pattern than in the frequency. Figure 15 portrays the effect on the 0.025-inch jets at a velocity of 40 feet per second and angle of 60°. Stream lengths of 10, 20, 40, and 60 diameters are shown. It will be noted that dispersion of the spray increases as stream length increases. At a stream length of 60 diameters, the jet has become very unstable and almost complete separation occurred. Beyond this length it is possible for liquid from one jet to pass through the path of the other jet without interference or impingement. The spray patterns perpendicular to those shown in figure 15 are not presented. The spray pattern in this plane was substantially unaffected.

DISCUSSION OF RESULTS

The results obtained expose the phenomena of fluctuations in the formation of a spray from two impinging jets. As previously stated, upon impingement of two jets a ruffled sheet of liquid is formed perpendicular to the plane of the two jets. This sheet disintegrates intermittently, forming groups of drops and giving the appearance of waves propagating from the point of impingement. Further analysis of the waves indicates that the ruffling of the sheet persists to the point of disintegration and determines the frequency of the waves in the resulting spray. This is particularly evident at small impingement angles, as in figure 10. At small angles the disintegration of the sheet occurs over a greater distance and the resulting waves can be traced to the ruffling in the sheet. Of particular interest in these phenomena, therefore, are the factors instrumental in ruffling of the liquid sheet.

The ruffling of the liquid sheet is attributed to the action of air friction and air turbulence in reference 8. The photographs of the spray patterns and the frequency measurements presented indicate that ruffling of the sheet is also affected and promoted by disturbances or irregularities present in the jets before impingement. Such irregularities in the jets result in continuous changes in momentum of the jets at the point of impingement and deflect the liquid sheet toward the path of the jet with the larger momentum, thus originating a ruffling action. The two forces causing the sheet to ruffle - that is, the interaction of the liquid sheet with air and the irregularities in the jets - apparently act simultaneously and the resultant frequency of the waves will depend on the relative magnitude and characteristics of these forces.

If the ruffling of the spray is caused primarily by air friction and turbulence, the ruffling will be largely dependent on the velocity of the sheet. As the velocity increases, the friction and hence the frequency will also increase. Such a relation was obtained for the effect of jet velocity on frequency (fig. 7), if the jet velocity and sheet velocity are assumed to be directly proportional for a constant impingement angle. As the impingement angle is changed, the resultant velocity of the sheet should vary as the cosine of one-half the impingement angle (based on conservation of momentum). This relation applied to the experimental effect of impingement angle on frequency is shown in figure 8. The correlation appears good for impingement angles between 50° and 100° and the frequency of a nonimpinging jet corresponds to the frequency for a 0° impingement angle. Lack of correlation at small impingement angles, however, indicates that the frequency is not a unique function of the sheet velocity.

If the ruffling of the spray is caused primarily by irregularities in the jet, increasing jet velocity at constant impingement angle will again result in an increase in frequency, as shown in figure 7, because irregularities in the jets increase with jet velocity. It would appear that changes in impingement angle would not change the frequency of waves in the liquid sheet; however, the effect of changes in impingement angle on the combination or addition of irregularities in two jets is not readily predictable and cannot be determined from the data obtained. Further evidence to show the influence of irregularities in the jets on the liquid sheet can be seen from the spray pattern for various jet lengths shown in figure 15. As jet length is increased, the irregularities in the jets become more fully developed and are reflected in the spray by a greater deflection or ruffling of the sheet. In this case, the greater degree of ruffling appears to be primarily a function of the irregularities of the jets because the changes in velocities of the sheet and, hence, the effect of air friction are small. Although changes in jet length resulted in relatively small changes in frequency, as shown in figure 14, the changes obtained were apparently a function of the irregularities in the jets.

The separate effects of air friction and irregularities in the jets can be combined for a possible explanation of the effect of impingement angle, as shown in figure 8. Irregularities in the jets establish a given frequency, but this frequency is modified by the changes in the velocity of the sheet and the action of the air. The modified frequency would apparently correlate with the velocity of the sheet, as was obtained for impingement angles between 50° and 100°. At small impingement angles, however, the frequency established by irregularities in the jets is reduced because the component of momentum tending to deflect the sheet is decreased and all irregularities in the jets do not appear in the sheet. Such a decrease in frequency was obtained below an impingement angle of 50°. Whether such an explanation decribes the phenomenon, it is apparent that both irregularities in the jets and action of the air influence the frequency. If liquids of lower viscosity and surface tension are used or if the flow in the jets is caused to oscillate (from combustion instability), the additional disturbances in the jets must therefore be considered in extrapolating the frequency measurements obtained in this investigation.

SUMMARY OF RESULTS

From the investigation of the fluctuations in the formation of spray from two impinging water jets, the following results were obtained:

1. Upon impingement of two jets, a ruffled sheet of liquid was formed perpendicular to the plane of the two jets. The liquid sheet disintegrated intermittently, forming a group of drops that appear as waves propagating from the point of impingement.

2. The intermittent disintegration of the liquid sheet resulted in irregular spacing between waves and in variable wave intensity. There was an abundance of small waves with the number of waves above a given intensity decreasing as the intensity increased.

3. The frequency of wave formation was constant over a finite time interval under constant operating conditions. The frequency varied between 1000 and 4000 cycles per second for the range of test conditions used in this investigation.

4. An increase in jet velocity resulted in an increase in wave frequency. The relation approached a direct proportionality. For the jet diameters and velocities used in this investigation, an increase in jet velocity of 60 feet per second resulted in an increase in frequency of approximately 2500 cycles per second.

5. An increase in impingement angle resulted in a decrease in wave frequency for impingement angles of from 50° to 100°. The decrease in frequency with impingement angle was approximated by the decrease in the cosine of one-half the impingement angle.

6. A diameter change from 0.025 to 0.057 inch had a negligible effect on wave frequency compared to the effect of jet velocity and impingement angle.

7. A change in jet length from 10 to 80 diameters before impingement had a negligible effect on wave frequency.

8. From the photographic and frequency data obtained, it appeared that the ruffling of the liquid sheet persists to the point of disintegration of the sheet and determines the frequency of the wave formation and that irregularities in the jets before impingement may be as instrumental in controlling the ruffling of the liquid sheet as is the friction of the air.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, February 16, 1951.

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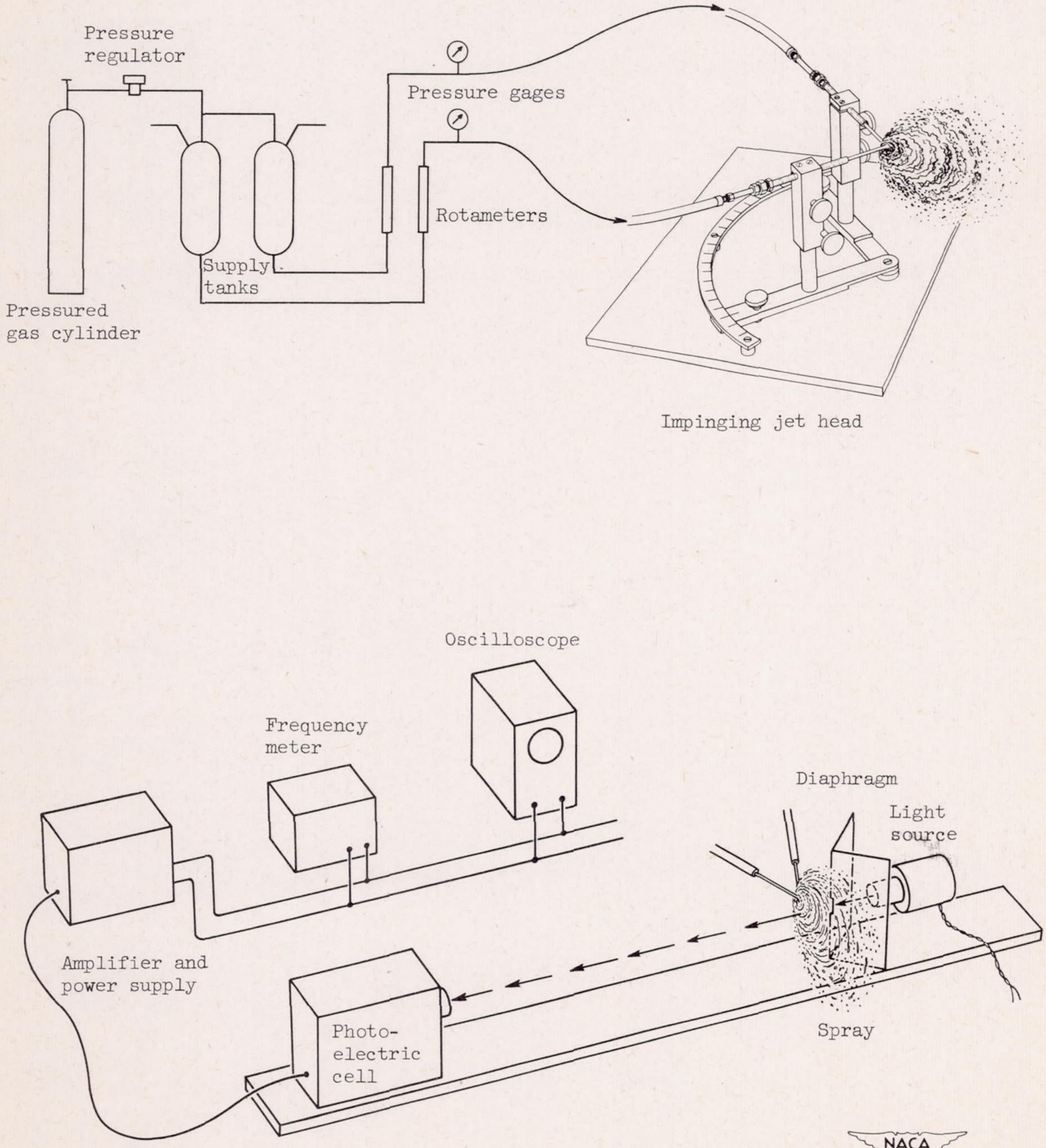
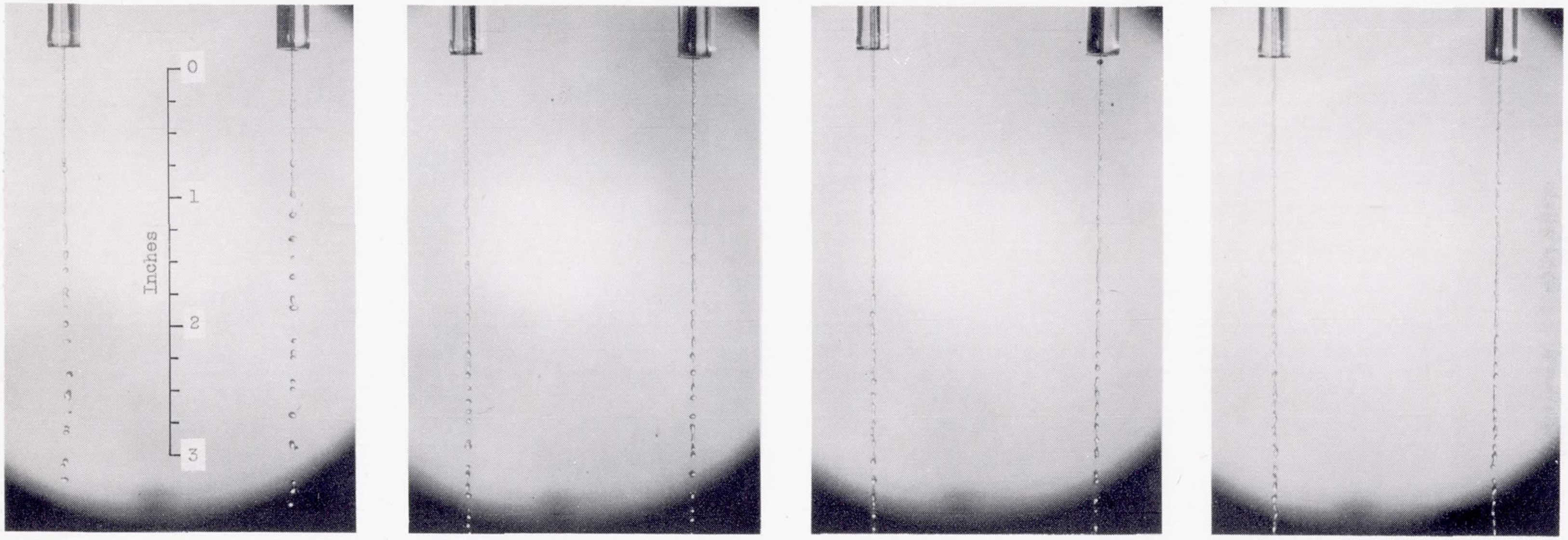


Figure 1. - Schematic diagram of impinging-jet apparatus and instrumentation.



20 40 60 80

Jet velocity, ft/sec

Figure 2. - Effect of jet velocity on pattern of 0.025-inch-diameter jets.

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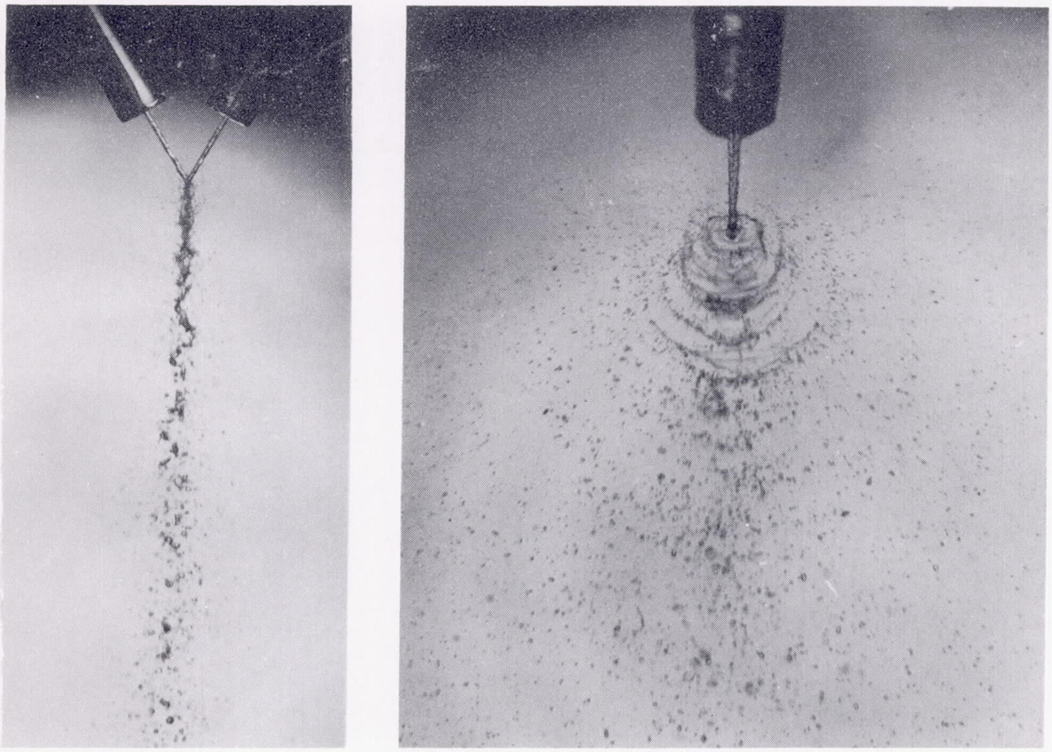

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Figure 3. - Microflash photographs of formation of spray by two impinging jets of water. Views perpendicular and parallel to plane of jets are shown.

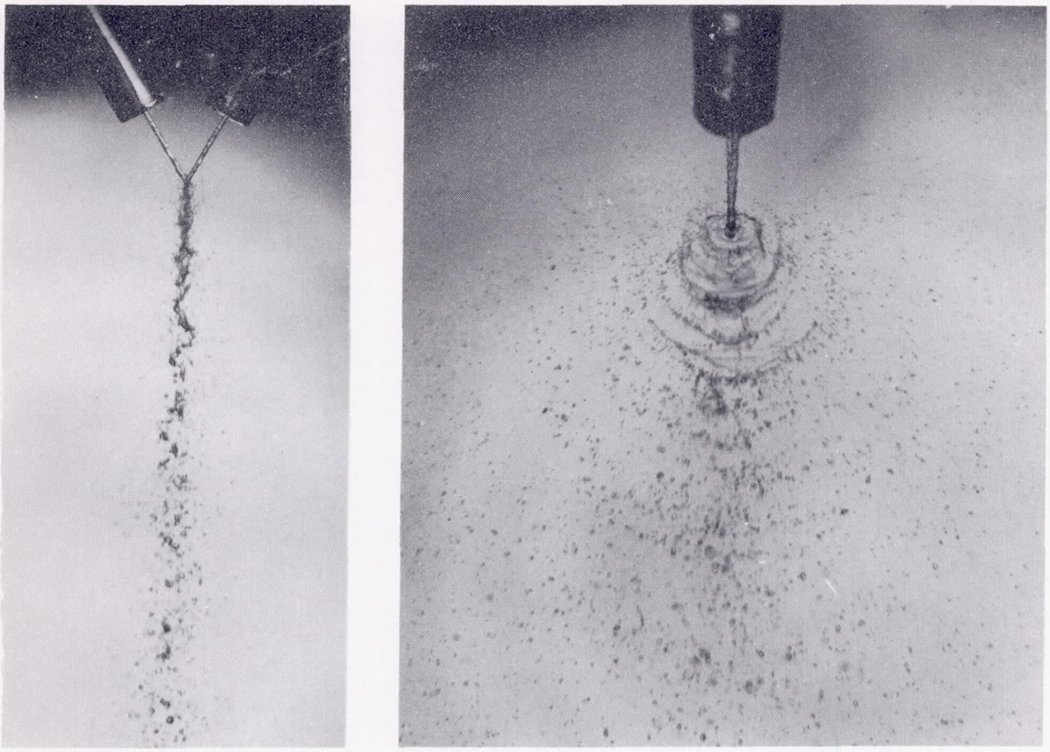

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Figure 3. - Microflash photographs of formation of spray by two impinging jets of water. Views perpendicular and parallel to plane of jets are shown.

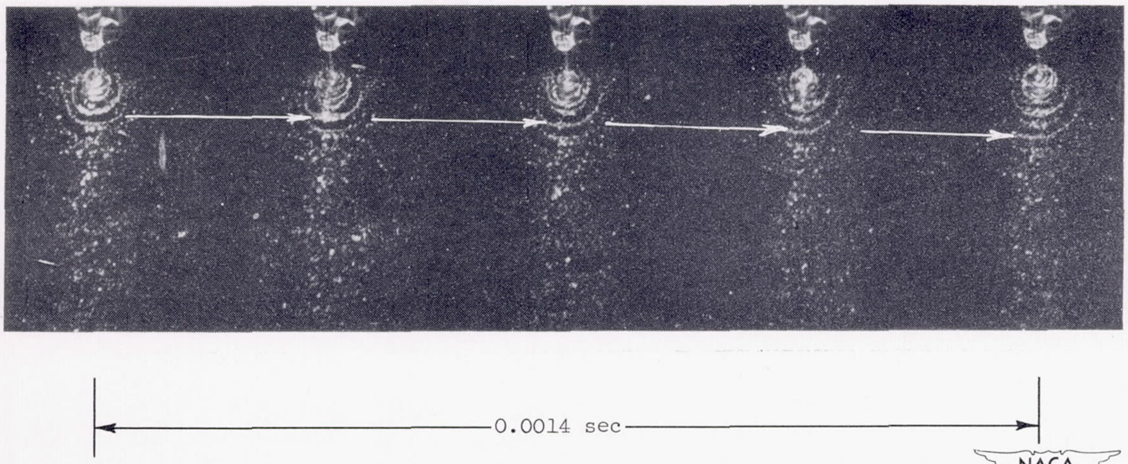

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Figure 4. - Successive frames from high-speed motion pictures of formation of spray from two impinging jets of water.

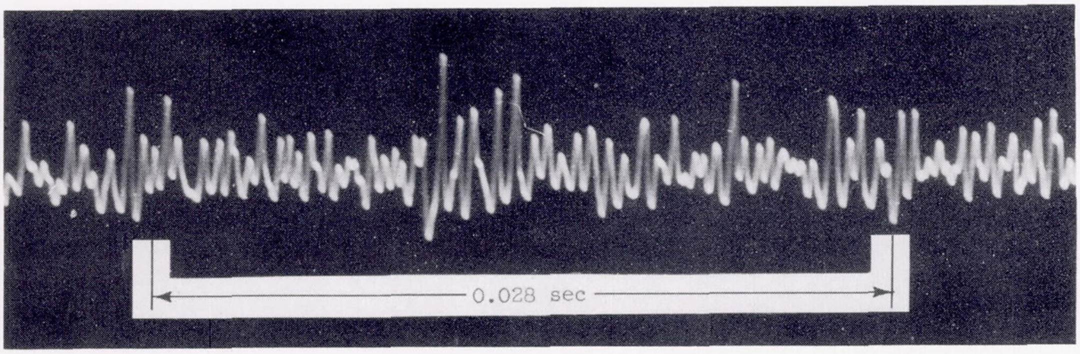

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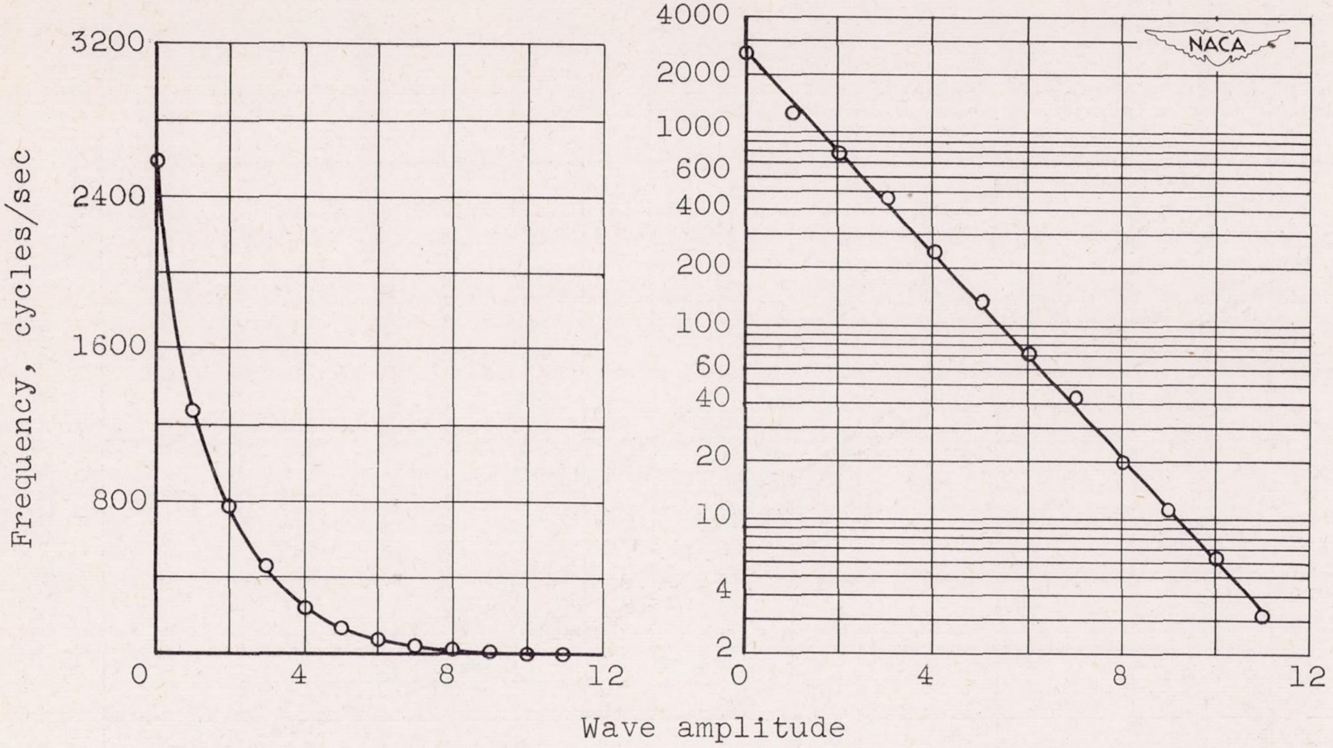
Figure 5. - Oscilloscope trace of photoelectric-cell signal resulting from intermittent disintegration of sheet of liquid formed by two impinging jets.



(a) Linear coordinates.

(b) Semilogarithmic coordinates.

Figure 6. - Typical wave amplitude and frequency characteristic for fluctuations resulting from impingement of two liquid jets. Frequency shown represents frequency of waves of amplitude greater than given amplitude.

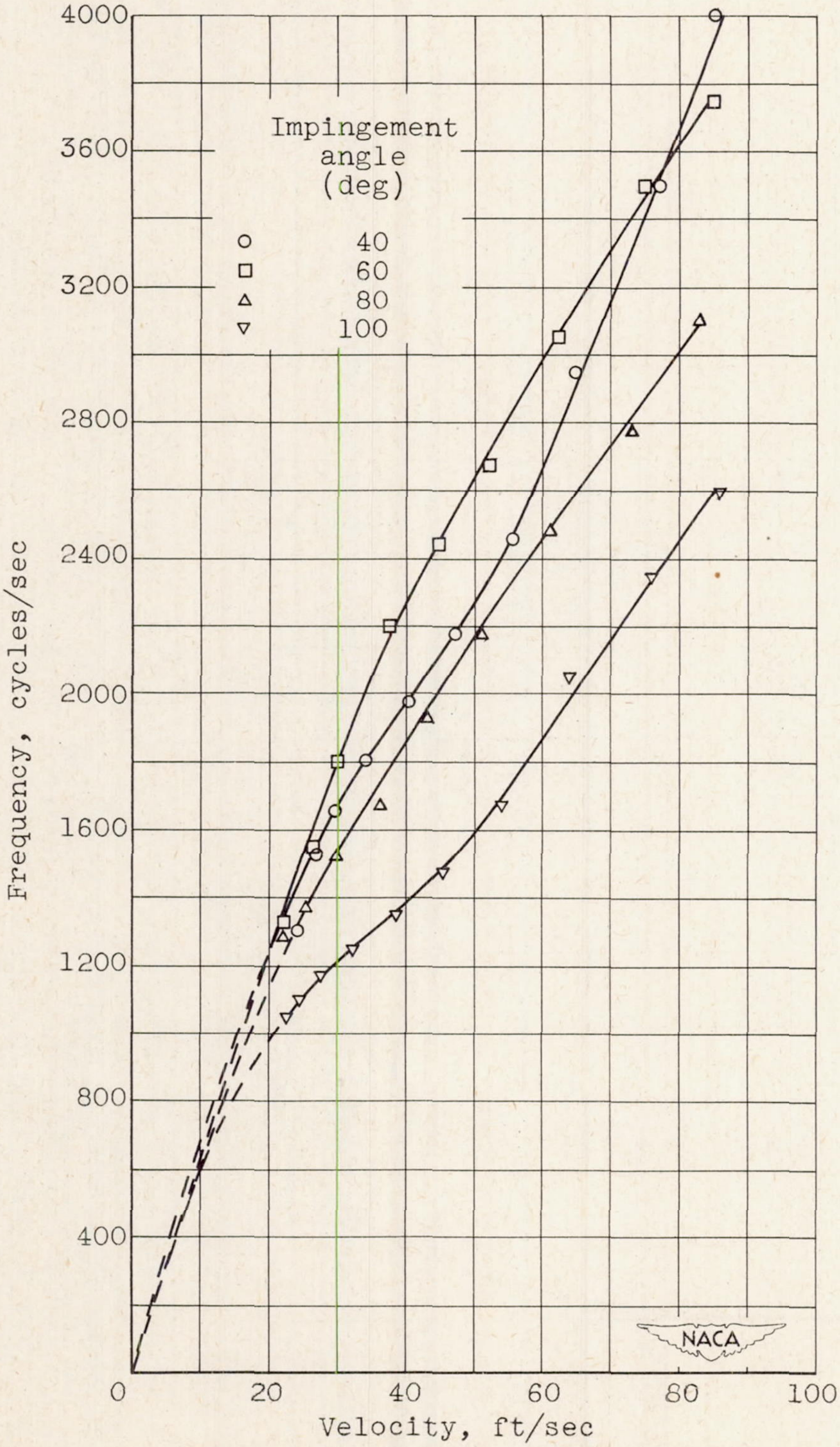


Figure 7. - Effect of jet velocity on wave frequency for several impingement angles. Effect is shown for impinging jets 0.025 inch in diameter.

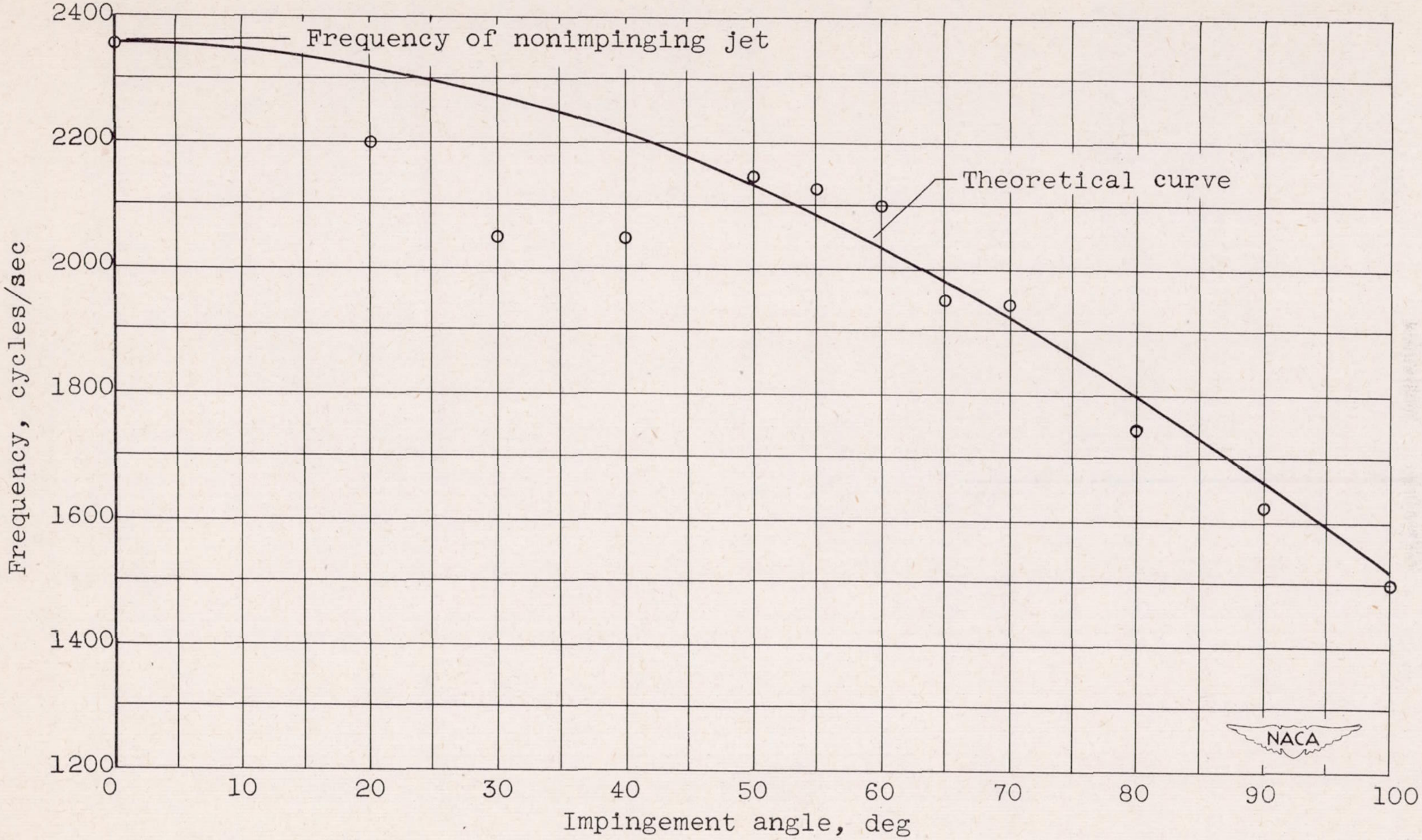


Figure 8. - Effect of impingement angle on wave frequency for 0.040-inch-diameter jets at velocity of 40 feet per second.

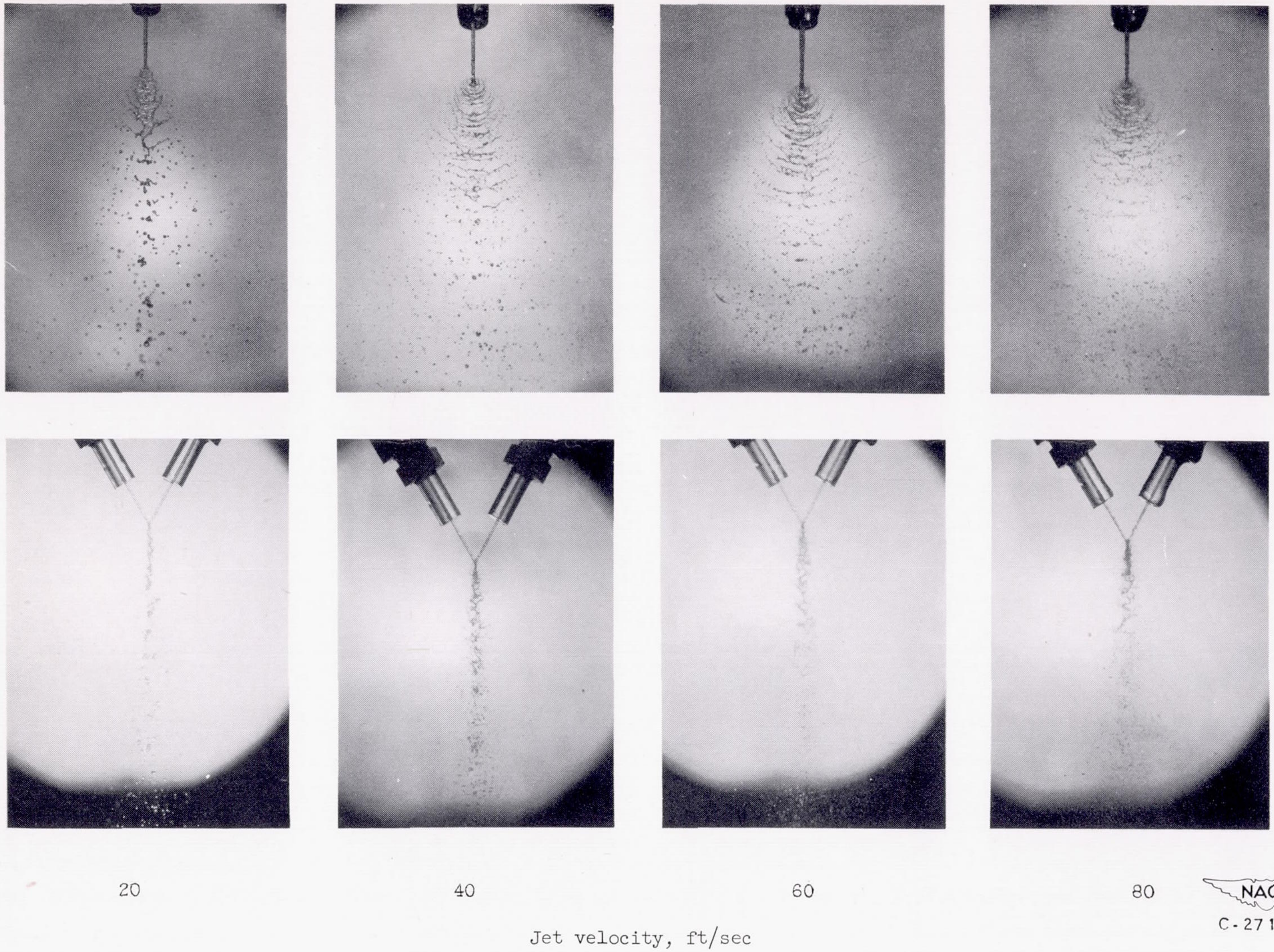


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Figure 9. - Effect of jet velocity on spray pattern. Conditions: jet diameter, 0.025 inch; impingment angle, 60°.

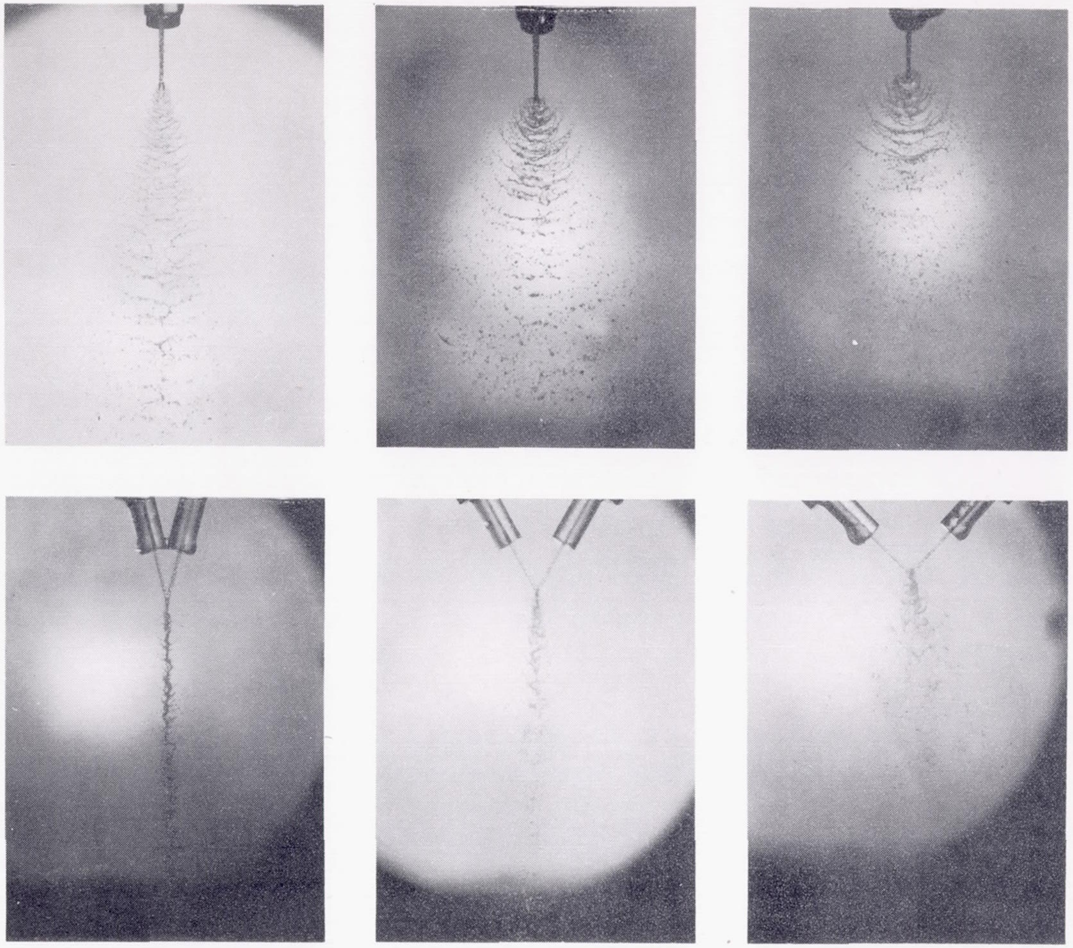

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Figure 10. - Effect of impingment angle on spray pattern. Conditions: jet diameter, 0.025 inch; jet velocity, 60 feet per second.

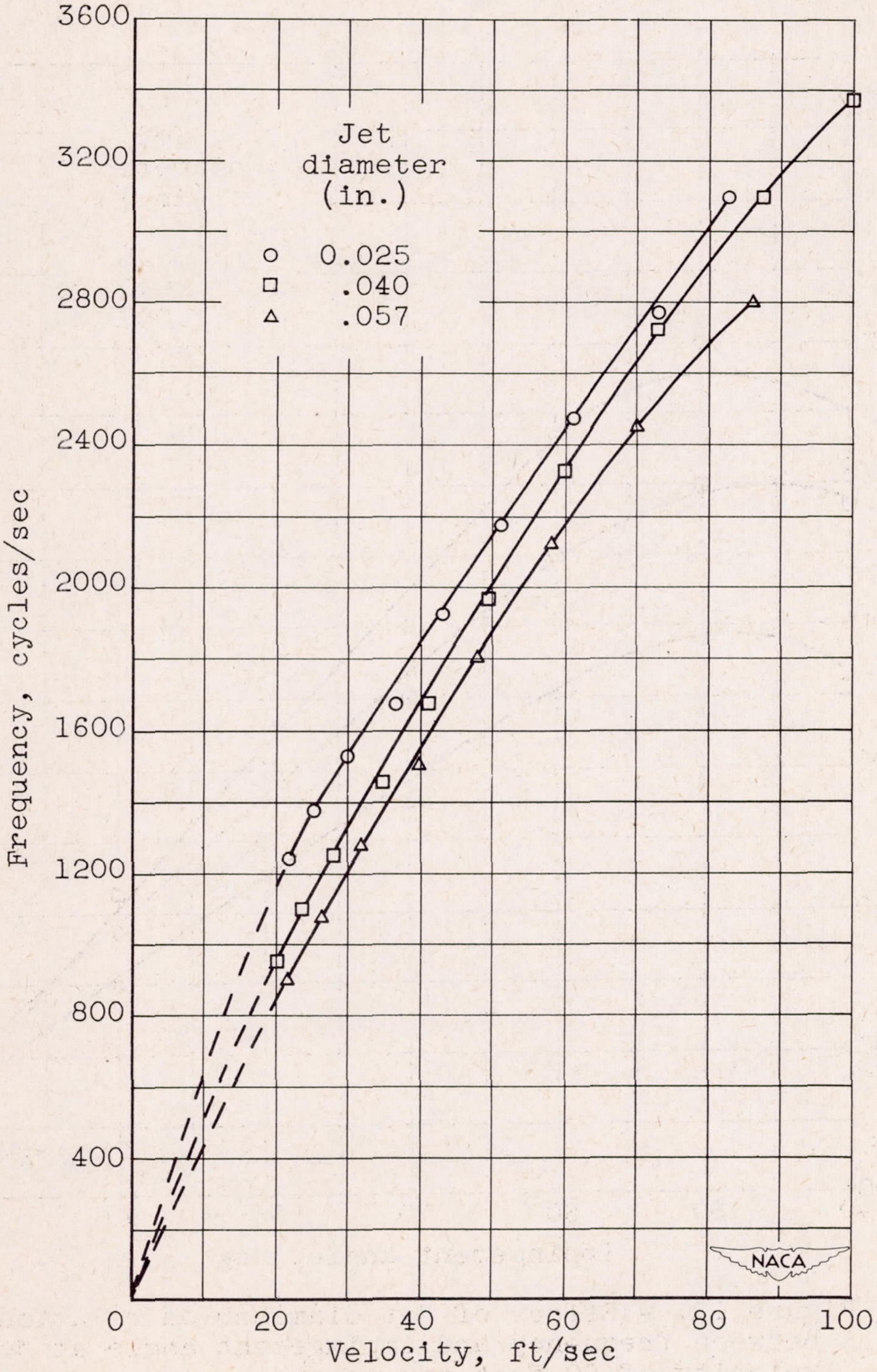


Figure 11. - Effect of jet diameter on relation between frequency and jet velocity at impingement angle of 80°.

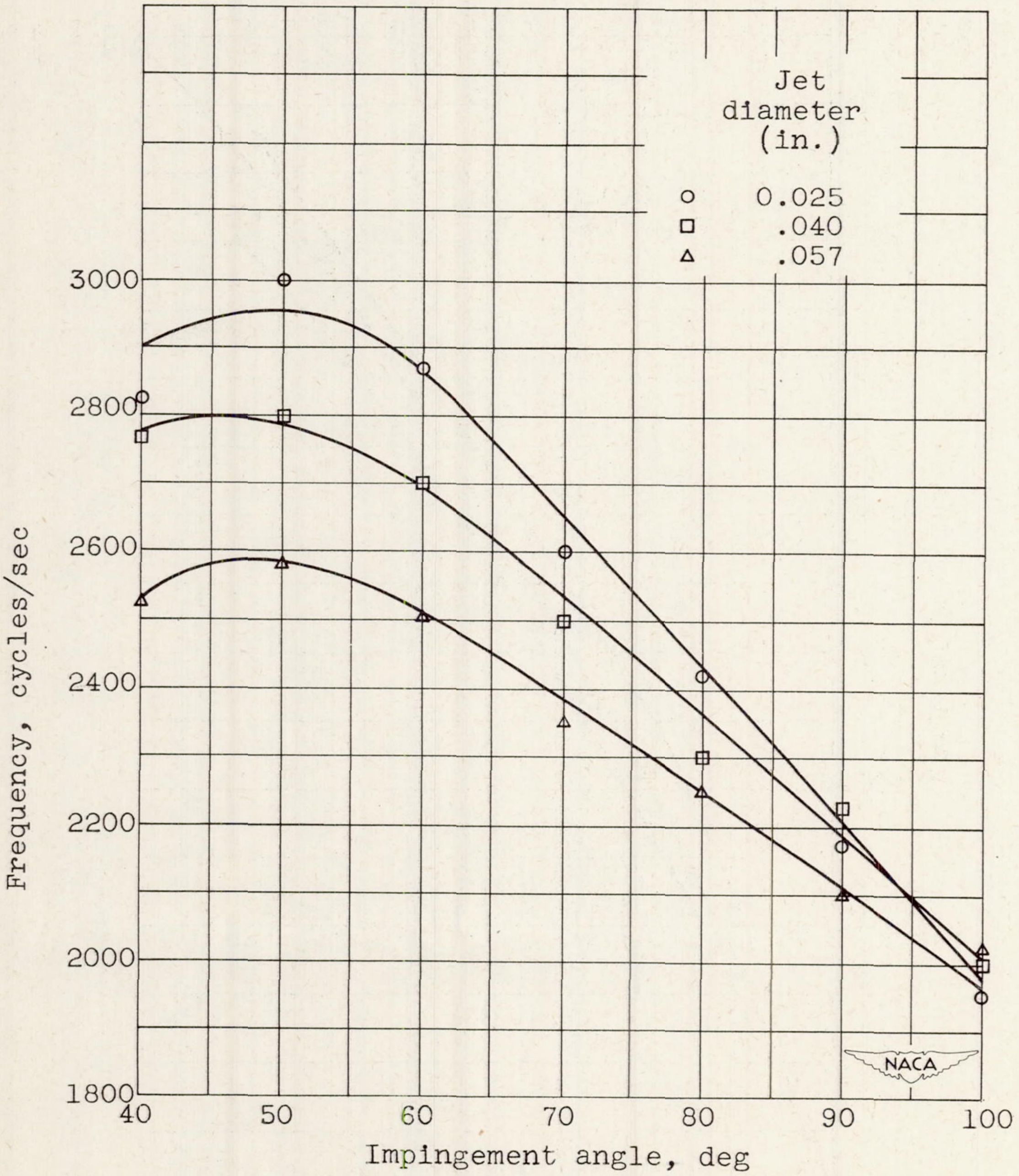
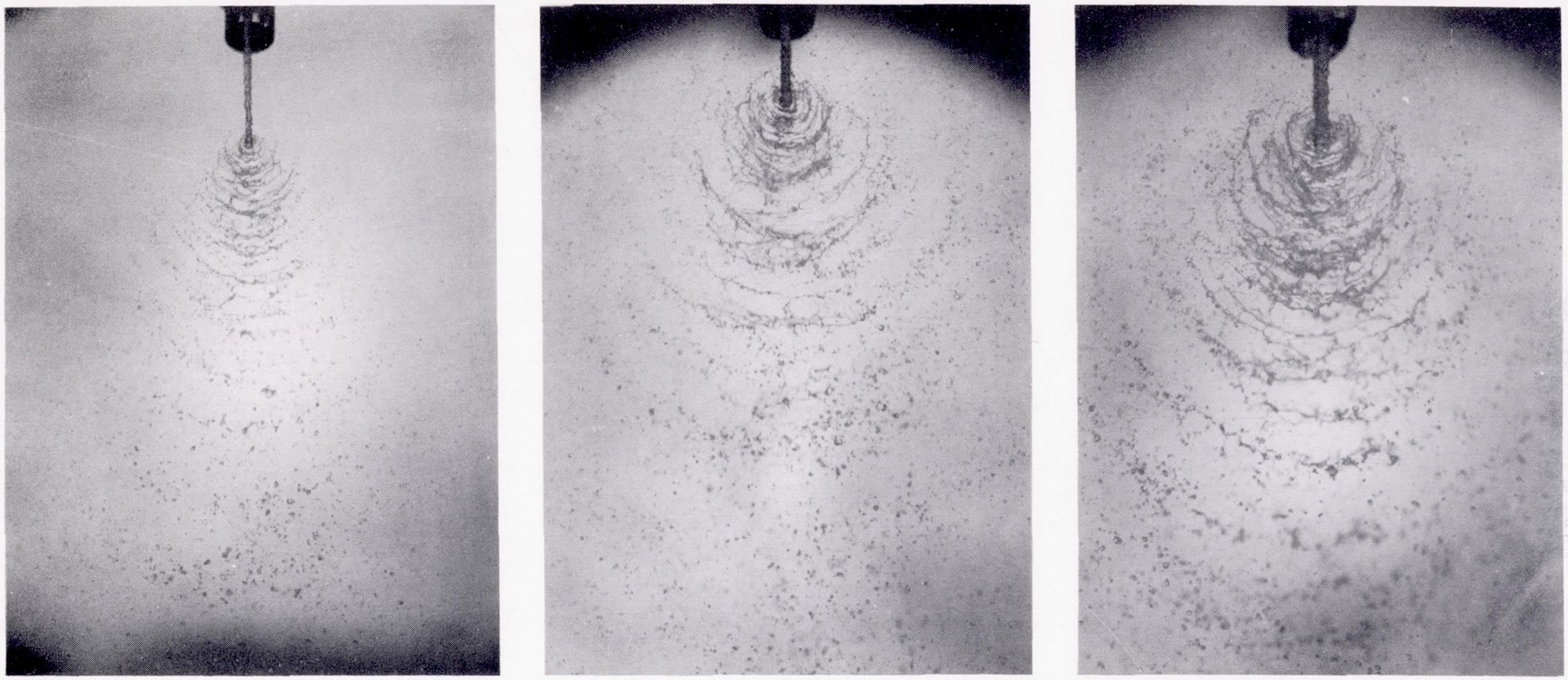


Figure 12. - Effect of jet diameter on relation between frequency and impingement angle at jet velocity of 60 feet per second.



0.025

0.040

0.057

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Jet diameter, in.

Figure 13. - Effect of jet diameter on spray pattern. Conditions: jet velocity, 50 feet per second; impingment angle, 70°.

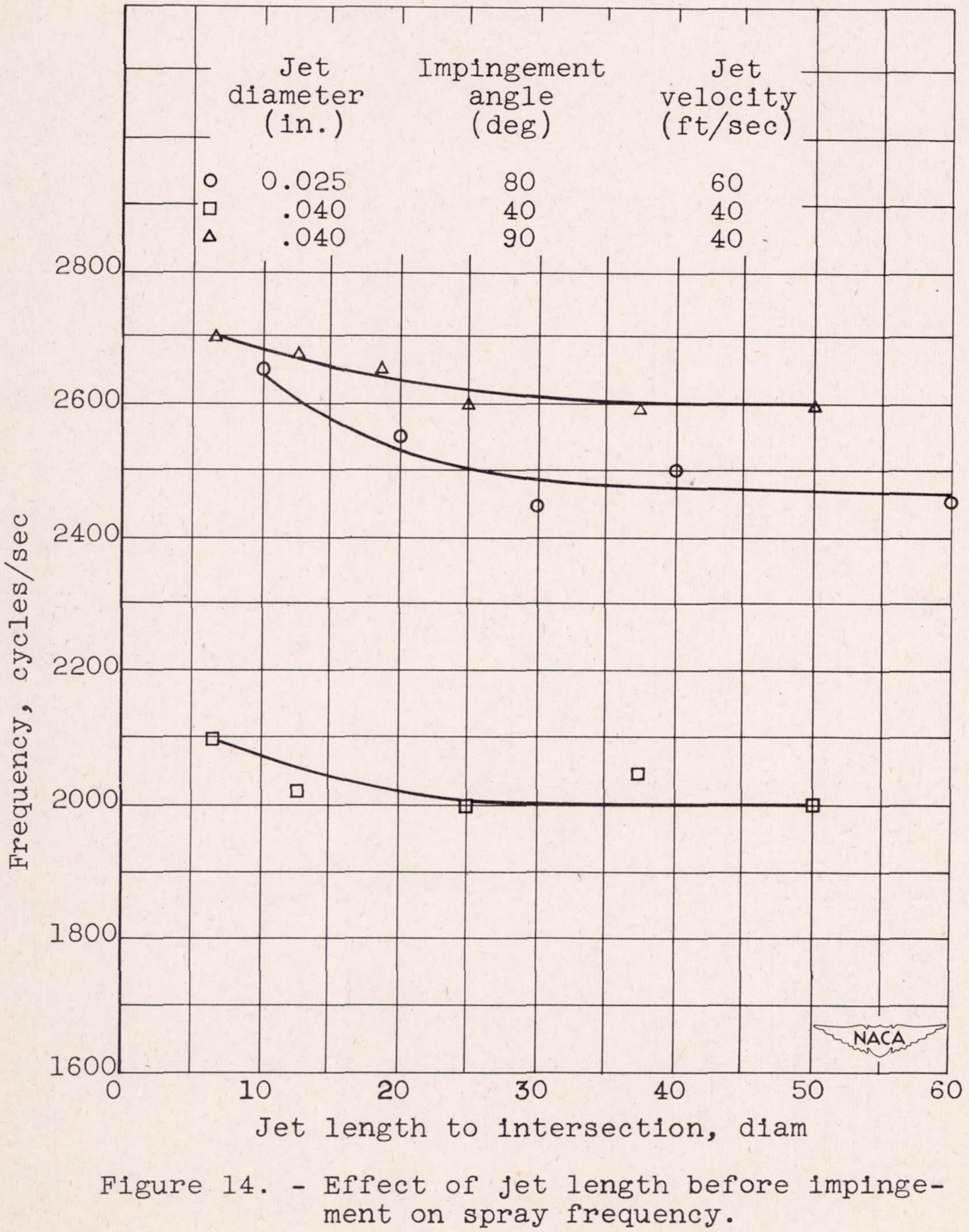
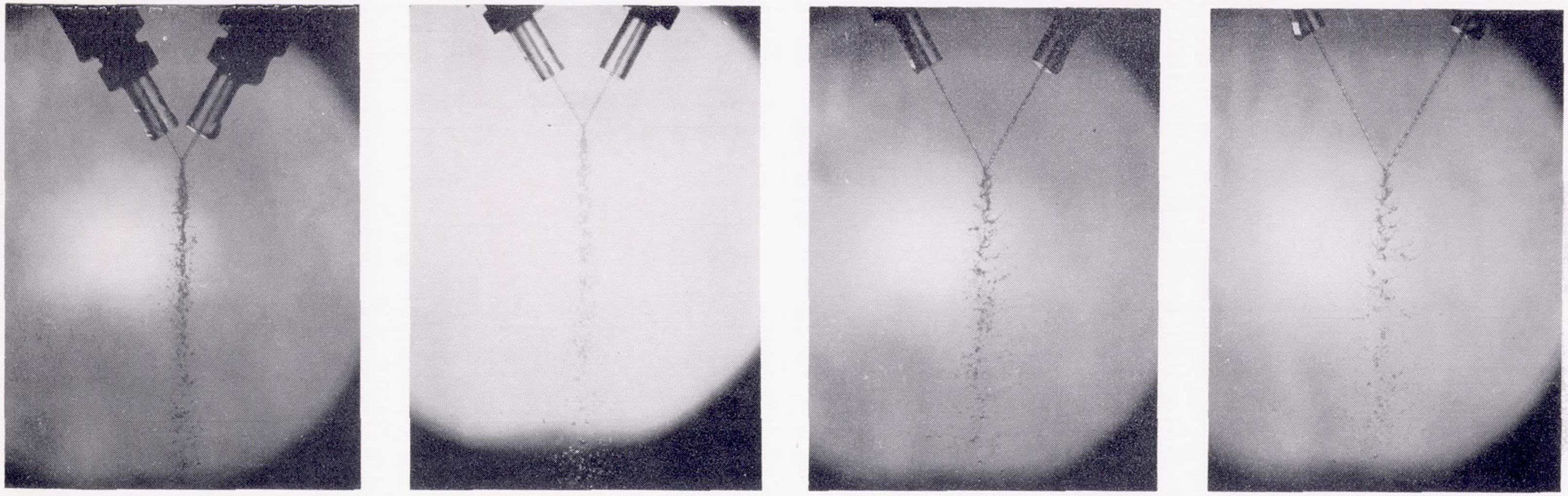


Figure 14. - Effect of jet length before impingement on spray frequency.



10 20 40 60

$\frac{\text{Jet length}}{\text{Jet diameter}}$

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Figure 15. - Effect of ratio of jet length to jet diameter on spray pattern. Conditions: jet diameter, 0.025 inch; jet velocity, 40 feet per second; impingment angle, 60°.