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16. ABSTRACT Described are preliminary results of investigations aimed at choosing and/or developing spray nozzles with primary application to cloud seeding with hygroscopic liquids in controlled spray sizes. Several types of nozzles are under investigation, including: air-operated nozzles, self-impinging jet nozzles, target-impinging jet nozzles, fan-type, and solid-cone type nozzles. Air-operated nozzles produce the smallest droplet sizes (less than 20 μm mass median diameter), but tend to have a high noise level and higher initial and operating costs. Self-impinging jets and solid-cone nozzles produce droplets as small as about 50 μm while target-impinging jets produce droplets down to about 25 μm . Tests on fan-type nozzles were too limited for conclusive results. Several methods of liquid injection were also investigated and sampling techniques were developed.			
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March 1974

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UNITED STATES DEPARTMENT OF THE INTERIOR

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PURPOSE

This research is concerned with the investigation of spray nozzles that would be useful in cloud seeding operations. The goal of the research is to make possible the selection and/or development of nozzles that will spray hygroscopic liquids in controlled spray sizes. The purpose of this report is to discuss progress in these investigations.

CONCLUSIONS

1. Although the quantity of useable data was limited by difficulties in sampling, sufficient information was gained to allow reasonable choices of nozzles for specific droplet size requirements.
2. Air-operated nozzles are capable of producing very fine sprays less than about $20 \mu\text{m}$ (microns) for an air pressure of 45 psi (3.2 kg/cm^2). The size is dependent upon relative air and liquid flow rates, and a fair degree of size control is possible. The method of liquid injection affects the resulting droplet size.
3. Resonator caps and deflecting plates have no apparent beneficial effect in reducing the spray size for a given energy expenditure.
4. Air-operated nozzles tend to have a high noise level.
5. Higher costs are associated with nozzles which operate from compressed air.
6. Self-impinging jet nozzles offer an inexpensive technique for producing sprays with mass median diameters down to about $50 \mu\text{m}$. The spray size decreases with increasing liquid pressure. The nozzle developed and tested consisted of two 0.0135-inch (0.34-mm) holes intersecting at the outside surface of the pipe at an angle of 90° .
7. Target-impinging jets can produce sprays with mass median diameters down to about $25 \mu\text{m}$. Again, the droplet size decreases with increasing liquid pressure.
8. Tests of fan-type and solid-cone-type nozzles were very limited, but droplet sizes similar to the impinging-jet nozzle were found for the solid-cone type.
9. Injection of a spray into an aircraft slipstream can cause additional breakup of larger droplets, the limiting size being determined by the velocity of the airstream.

RECOMMENDATIONS FOR FUTURE WORK

1. Droplet size data should be obtained over a wide range of operating conditions for the following devices, in order of priority:
 - a. Self-impinging jets nozzle.
 - b. Target-impinging nozzle.
 - c. Other devices as time and funding permit.
2. Work should continue for development of a laser-drilling technique for production of self-impinging jets nozzles.
3. A portion of the research effort should be directed toward development of radically new concepts for formation of sprays.

APPLICATIONS

The results reported herein have application to cloud seeding technology and to other uses of spray nozzles such as spray drying, fire fighting, and fuel injection.

INTRODUCTION

In November 1970, an interdisciplinary research team was formed at the Engineering and Research Center for investigation and development of nozzles for ice embryo formation and spray applications. The team included the disciplines of theoretical and experimental fluid mechanics; mechanical engineering; compressible flow; evaporation, condensation, and nucleation; economics; physics; meteorology, and weather modification.

The investigations for development of nozzles for ice embryo formation will be reported separately. The subject of this report is development of nozzles for spray applications.

The research team's initial objectives were:

1. Early procurement and evaluation of the air-operated Sonicore nozzles for airborne seeding and spray-drying applications.
2. Review and evaluation of patents and technical literature concerning nozzles and appurtenant equipment that would be useful.

3. Optimization of an impinging-jets nozzle for large-scale drying applications.

4. Optimization of an impinging-jets nozzle for ground seeding, and development of possible appurtenances for reducing droplet size.

These objectives were modified somewhat during the course of the study, but they still provided general guidelines. Considerable effort was spent in developing a satisfactory technique for determining size characteristics of sprays. Also, much laboratory testing was performed on several types of nozzles in addition to those listed in the objectives.

The major emphasis was on the cloud seeding applications. Logistics problems were a major consideration; for example, an air-operated nozzle requiring a large air compressor would not be generally suitable for airborne seeding. The major goal that developed was to establish an inventory of nozzles that could form required droplet sizes according to conditions of updraft speed, cloud base temperature, height above cloud base, etc.

Other potential spray nozzle applications such as spray drying, fire fighting and prevention, outdoor cooling, etc., were considered.

LABORATORY TEST FACILITIES

Pumps and Injection Apparatus

Figure 1 shows the stainless steel tank and tubing used for injection of liquid, including corrosive solutions, into the air-operated nozzles. The tank was filled with liquid, then air pressure applied at the top of the tank forced the liquid into the nozzle at a determined rate. The liquid flow rate was read with a volumetrically calibrated rotameter. Air pressure was monitored with a Bourdon gage. Air for the air-operated nozzles was supplied from a centralized laboratory distribution system.

For high-pressure liquid nozzles, water was used as the test fluid and was supplied by a Moyno pump, belt-driven from a 2-hp (1.5-kw) electric motor, Figure 2. Pressures up to 600 psi (42.2 kg/cm²) were obtained.

A collection hood with fan-assisted venting to the outside was constructed to allow indoor spraying of corrosive solutions, Figure 3.

*Numbers designate references listed at the end of this report.

Sampling

Initial droplet-size data were obtained with an aerosol sampling device developed by Cornell Aeronautical Laboratories,^{7*} Figure 4.

The aerosol was drawn into the instrument by vacuum provided by a blower. Intake speeds were variable to more than 100 miles per hour (160.9 km/hr). A slide-changing device operated to expose a gelatin-coated slide, with exposure times varying from a fraction of a second to unlimited time.

A typical slide is shown in Figure 5. Impact of the water droplet on the slide and dissolution of the gelatin coating, according to several sources, causes a crater approximately twice the diameter of the original droplet. Figure 5 shows several agglomerations of droplets and a preponderance of smaller droplets. Examination, with a stroboscopic light of the spray which produced this slide, suggested that many large drops were not collected. Apparently, collection of spray by withdrawal perpendicular to the stream allowed larger drops to sweep past the end of the sampling tube. On the other hand, directing the stream into the sampling tube introduced more water than the shortest slide exposure time would accommodate. Attempts to baffle the airstream and select only a portion of the spray were largely unsuccessful. Water had a tendency to collect on the baffling, then shed off in the form of very large drops. Thus, the reliability of this method of data collection was very uncertain.

Considerable data were collected by the widely used method of passing a wand-mounted, gelatin-coated slide through the spray, Figure 6. The speed of the wand was very critical in collecting the optimum amount of liquid. Comparison of Figures 7 and 8 demonstrates this.

Samples were obtained by collecting water on a gelatin-coated slide and by collecting ammonium nitrate-urea solution on an uncoated slide. The photographs in Figure 9 fail to show the 2:1 ratio in crater to droplet diameters. The mean diameter for droplets in Figure 9A was 27 μm and that for 9B was 24 μm .

These uncertainties were compounded by the problem of evaporation of the waterdrops and water addition to the hygroscopic ammonium nitrate-urea drops.

Another method attempted was to pass a gelatin-coated cylindrical glass rod through the spray.

The intent of the cylindrical shape was to improve the collection efficiency for smaller droplets. Figure 10 shows the poor definition and considerable agglomeration of droplets. Therefore, this method was rejected.

Obviously, the most reliable means of determining droplet sizes would be to photograph the droplets directly and as close as possible to their origin. The speed of the stream of spray, particularly for the acoustic nozzles, and the density of the spray made such direct photography extremely difficult. However, after much experimentation, a fairly reliable system was developed.

A 10,000-volt spark gap, with a duration of 0.5 microsecond, was used as the light source. The light beam was made parallel by a collimating lens; it was then passed through the spray and a diverging lens to the film plate. A shadowgraph resulted, with magnification determined by the distance from the diverging lens to the film plate. The shutterless camera required operation in a darkroom.

Figure 11 shows the spark-gap and optics setup for 25X magnification. The resulting photographed sample was approximately 0.14 by 0.18 inch (3.6 by 4.6 mm) with a depth of field of 0.03 inch (0.8 mm). The photographs were enlarged four times to produce a 100X magnification.

A typical 25X magnified photograph is shown in Figure 12. Only those droplets in focus are counted.

Slower-moving droplets were exposed by a strobe flash having a duration of about 1.2 microseconds.

A major problem with this technique was the inability to photograph a representative sample of the spray because the spray was not uniform through its cross section. Therefore, a large number of photographs would have been necessary for a satisfactory analysis.

The method finally used consisted of collecting a sample from the entire cross section of the spray in a dish with a shallow depth of Stoddard solvent. However, droplets tended to migrate toward larger droplets to form agglomerates, as shown in Figures 13 and 14. Thus, a delay of more than a few seconds between collection of the sample and photographing the image through the microscope made the sample essentially useless. Addition of hypoid gear lubricant slowed the migration process, and size analysis showed repeatable results.

TESTING OF DEVICES

Air-operated Nozzles

Several types of air-operated nozzles are shown in Figure 15.

Sonic resonators.—For this device, the breakup of drops presumably occurs when the drops are subjected to oscillation in a field of high-frequency sound waves. This field is produced by a so-called resonance cup or chamber in the path of a high-velocity jet of air. The frequency of oscillation can be calibrated and is found to be on the order of 10,000 hz. This principle was first applied by J. Hartmann in the 1920's and has thus been known as the "Hartmann whistle." Other investigators, including Boucher and Kreuter² and Brun and Boucher³ have investigated this device, and numerous patents have been issued on devices consisting of slight modifications of the Hartmann whistle. One such device is the "Sonicore" nozzle marketed by Sonic Development Corporation of Yonkers, New Jersey.

"Sonicore" Models 052, 156, 188, and 312 were obtained for laboratory testing (the model number refers to the nozzle throat diameter in thousandths of an inch). As in other types of aerodynamic nozzles, the droplet size decreased with an increasing ratio of airflow to liquid flow rate. Examples are shown in Figures 16 and 17.

Spray from the Model 156 was analyzed for size distribution with a constant air pressure of 30 psi (2.1 kg/cm²) and liquid flow rates of 0.2, 0.3, and 0.4 gpm (0.013, 0.019, and 0.025 liter/sec). Results are summarized in Table 1.

The data show some inconsistencies, although they were not serious. Also, use of the upstream impinging-liquid injector caused some reduction in droplet sizes.

This type of nozzle exhibited intense noise characteristics. The "Sonicore" 312 nozzle showed intensity levels of 134 decibels (dB) at a distance of 3 feet (0.9 meter) from the nozzle and 118 dB at a distance of 20 feet (6.1 meters) with an air pressure of 40 psi (2.8 kg/cm²) and no liquid injection. Corresponding levels with water injection were 125 dB at 3 feet (0.9 meter) and 118 dB at 20 feet (6.1 meters). Attempts to isolate and muffle the sound had little success. To prevent hearing damage, precautions are required when sound levels reach 95 dB, with

Table 1

Laboratory Test of Sonicore Model 156

Air pressure psi	Liquid flow gpm	Geometric mean diameter, μm	Geometric standard deviation	Median mass diameter, μm	Number of droplets in sample
30	^a 0.2	43.4	1.42	63.0	258
30	0.3	55.5	1.45	83.9	234
30	0.4	55.0	1.53	95.0	148
30	^b 0.2	35.4	1.52	59.6	352
30	0.3	38.5	1.39	53.6	253
30	0.4	50.1	1.51	83.8	444

^a Liquid injected through manufacturer's ports.

^b Upstream impinging injector used, Figure 23.

exposure time of 2 hours, for the frequency range of the nozzle.

The tests further showed that the 188 nozzle gave a marginal sound intensity and the 156 nozzle was below the limit for required protection. The 156 nozzle was therefore chosen for inclusion in a field test spray rig.

Specifications for the field test spray rig required a delivery of approximately 1 gpm (0.06 liter/sec) ammonium nitrate-urea liquid fertilizer with a median mass diameter of about 20 μm . Thus, four "Sonicore" 156 nozzles were required, each delivering 1/4 gpm (0.02 liter/sec) of liquid and operating at an air pressure of 60 psi (4.2 kg/cm²) [about 60 cfm (28.3 liter/sec) of free air].

The use of steam in lieu of compressed air was suggested. However, computations showed that a steam generator would require 119 hp (88.7 kw) to supply 60 cfm (28.3 liter/sec) of dry steam, with the unrealistic assumption of 100 percent efficiency. A 16-hp (11.9 kw) (ideal) air compressor would provide an adequate air supply. Also, the use of steam would involve some safety hazards.

A ground-based liquid fertilizer spray rig was assembled and tested. The rig consisted of a rotary air compressor, four "Sonicore" 156 nozzles with associated air and liquid piping, a flowmeter, a pump capable of handling corrosive liquids, and a motor-generator set for supplying the necessary power.

Figure 18 shows a local test of the rig. The rig worked best under calm conditions; a relatively stiff breeze caused the spray plume to bend toward the ground.

The spray rig was transported to San Angelo, Texas, for further evaluation during the emergency drought-relief cloud seeding program in the summer of 1971. However, very limited opportunities arose for field testing. Further evaluation is planned.

Supersonic nozzles.—The basic mechanism of liquid spray produced in a supersonic nozzle is the interfacial shear developed by the velocity differential between liquid and air. A recent paper by Sherman and Schetz¹⁵ describes the breakup of liquid sheets and jets in a Mach-2.2 free stream. High-speed photography showed that sheets of liquid developed a surface-wave structure with subsequent disintegration into ligaments and droplets. Jet breakup consisted of wave formation followed by gross fracture of the jet. The pieces of fluid then broke down into smaller particles and droplets. The tests also showed that the degree of breakup at a given stream location was inversely proportional to a dynamic pressure ratio q_r :

$$q_r = \frac{\rho_l V_j^2}{\rho_g U^*{}^2} \quad (1)$$

where

ρ_l = liquid density
 ρ_g = gas density
 V_j = liquid injection velocity
 U^* = free-stream velocity

For example, droplet sizes would be decreased by increasing the free-stream velocity or decreasing the liquid injection velocity from a fixed-diameter liquid-injection port.

For the liquid sheet, the wavelength, and thus the droplet size, were functions of the growth rate of surface disturbances. The relationships were not clearly

explained in the paper; however, the test results showed that mean droplet diameters of 21 to 31 μm resulted from a liquid sheet thickness of about 150 μm in a Mach-2.2 airstream. The size distribution showed a marked skewness toward the smaller sizes.

More than 20 years ago, Lane^{1,2} listed three stages in the breakup process:

1. Initiation of small disturbances on the liquid surface.
2. Formation of ligaments and drops by interfacial shear.
3. Additional breakup during movement of air.

These stages correspond to those described by Sherman and Schetz^{1,5} as discussed above.

Lane describes the breakup of droplets in a steady airstream as a formation of a hollow bag which burst to form smaller drops. Experimental results were expressed by the equation:

$$(u - v)^2 d = 612 \quad (2)$$

where

u = critical velocity of airstream required to break drop, m/sec

v = velocity of entrained drop at instant of breaking, m/sec

d = diameter of drop, mm

Thus, higher differential velocities would be required to form successively smaller drops. Lane found that the relationship did not hold for supersonic airstreams, with the rate of decrease in size being less than that predicted by equation (2).

The goal of this investigation was to design a nozzle by which required droplet sizes could be produced with a minimum expenditure of energy.

Two approaches seemed feasible:

1. Control of the wavelength of instability with resulting control of the droplet size.
2. Control of the droplet size before introduction into the supersonic nozzle, thus determining the final droplet size according to a relationship similar to Lane's.

The latter approach was pursued. The problem is complicated by the acceleration of droplets in the airstream. Lane's experiments were simplified in that he subjected the droplets to short duration airblasts, rather than a steady stream. In the supersonic nozzle, the relative velocity of the droplet will vary with time. Intuitively, the accelerating airstream in the expanding part of the nozzle would lead to a uniform drop size. This occurs because shearing action is maintained between air and liquid droplet, providing further breakup. Lane's work suggests 15 μm as a lower limit for the mean diameter caused by breakup in an airstream.

Additional information was found in a paper by Kim and Marshall¹¹. Using air nozzles with liquid injected in an annular shape, they found that a plot of the logarithm of the mass median particle diameter versus the square root of the liquid mass flow rate was linear for a given nozzle and air mass flow rate. They also found that the median mass diameter approached a lower limit as the air/liquid mass flow rate ratio increased. The experiments showed that even with a relatively viscous liquid [8.7 centipoise (cp) (1.82×10^{-4} lb-sec/ft²)] the limiting median mass diameter could be 1 or 2 μm . This suggests that water (≈ 1 cp) (2.09×10^{-5} lb-sec/ft²) could be broken into submicron particles.

Therefore, the problem was to design a nozzle to produce a required uniform, minimum droplet size for a given liquid flow rate, with a minimum expenditure of energy. Larger sizes could then be generated by reducing the airflow rate or, if desirable, increasing the liquid flow rate.

A Mach-1.5 supersonic nozzle, Figures 19 and 20, was designed and fabricated. The air nozzle is annular shaped, and liquid is injected upstream from the nozzle. The deflecting plate forms an adjustable resonance chamber and can be removed completely to allow formation of a hollow, circular jet.

Alternative methods of liquid injection were considered. First, the liquid was injected through a needle valve into a polyvinyl-chloride tee fitting in the line upstream from the air nozzle. It was suspected that some breakup occurred through the needle valve, which maintained a differential pressure ranging from 2 psi (0.1 kg/cm²) at 0.1 gpm (0.01 liter/sec) to 25 psi (1.8 kg/cm²) at 0.4 gpm (0.03 liter/sec). To verify this, a clear plastic tee was fabricated and installed in the line, Figure 21. The photograph shows that, even though some initial breakup took place at the needle

valve, the liquid formed a thin sheet on the surfaces of the tee. Thus, drop formation probably occurred through formations of perturbations on the surface of the sheet, as described by Sherman and Schetz. The resulting water spray, after passage through the supersonic nozzle, is also shown in Figure 22. Several runs were made with varying air pressure, liquid flow rate, and deflecting plate spacing (including no deflector). Results are given in Table 2.

Several tentative conclusions can be drawn from these data:

1. Spray size generally decreased with increased deflecting plate spacing. Smallest sizes were obtained without a deflecting plate.
2. Results were very sensitive to the sample size.

Table 2
Laboratory Test of USBR-1 Nozzle

Air pressure psi (kg/cm ²)	Liquid flow gpm (liters/sec)	Geometric mean diameter, μ m	Geometric standard deviation	Median mass diameter, μ m	Number of droplets in sample
20 (1.4)	0.1 (0.01)	^a 15.0	2.15	86.4	195
20	.3 (0.02)	13.5	2.17	82.1	148
20	.4 (0.03)	16.9	2.63	282.0	200
34 (2.4)	.4	20.3	2.26	148.2	200
45 (3.2)	.1	11.3	2.10	59.6	200
45	.2 (0.01)	7.6	1.97	29.9	200
45	.3	7.4	2.00	31.5	200
20	.1	^b 26.0	1.89	88.1	144
20	.4	15.8	1.89	53.2	198
34	.1	20.0	2.23	136.5	148
34	.2	16.5	2.02	72.4	170
44 (3.1)	.3	29.5	1.86	94.0	88
45	.4	19.0	1.99	72.7	198
20	.1	^c 16.7	1.71	39.5	198
20	.2	20.6	1.89	69.6	188
20	.3	28.4	2.40	282.7	96
20	.4	17.4	1.98	70.1	180
34	.1	12.8	1.68	28.6	198
34	.3	15.4	2.16	91.0	198
45	.1	22.5	2.04	102.9	198
45	.3	16.6	1.98	66.7	198
45	.4	45.3	1.71	107.7	55
20	.2	^d 20.0	1.97	79.9	70
20	.3	17.7	1.54	31.2	151
34	.3	17.4	1.76	45.0	164
34	.4	16.6	1.57	30.5	47
34	.4	12.1	1.87	39.4	198
45	.3	18.0	1.76	47.0	198
45	.4	14.6	1.44	21.7	198

^a deflecting plate spacing = 1/16 inch (1.6 mm).

^b deflecting plate spacing = 1/8 inch (3.2 mm).

^c deflecting plate spacing = 3/16 inch (4.8 mm).

^d no deflecting plate.

3. Using only the larger samples (> 150), there is an ill-defined increase in droplet size for increasing liquid flow rate for an air pressure of 20 psi (1.4 kg/cm²). At air pressures of 34 (2.4) and 45 psi (3.2 kg/cm²) there appears an insensitivity to liquid flow rate, within the range tested.

A different system of liquid injection was devised to cause initial breakup of the drops before entry into the nozzle, with the intention of using the energy of the airstream more efficiently. A drawing of this system is shown in Figure 23.

A supersonic nozzle was also fabricated with a serrated resonator cap and flat deflecting plate, Figure 24. The purpose of the serrations was to provide more shear contact between the air-liquid jet and the surrounding air.

At an air pressure of 34 psi (2.4 kg/cm²) and a liquid flow rate of 0.3 gpm (0.02 liter/sec), the geometric mean droplet size was 44 μ m and the median mass diameter was 53 μ m. The deflecting plate was set so that the points of the serrations rested on the downstream end of the nozzle section. Additional deflector spacing and air-to-liquid flow rates were tested visually with a high-intensity light source. The results showed no advantage over the simpler USBR-1 nozzle described earlier.

Figure 25 shows a conventional Prandtl-Meyer supersonic nozzle, which consists of a sudden 45° expansion downstream from the nozzle throat. Operation of this nozzle, with the tee of Figure 21, showed a coarser spray than the other air-operated nozzles. Figure 26 shows the operation. At an air pressure of 34 psi (2.4 kg/cm²) and a liquid flow rate of 0.1 gpm (0.01 liter/sec), the geometric mean droplet size was 30 μ m, with a mass median diameter of 75 μ m. Thus, the spray is approximately twice as large as that for the USBR-1 nozzle with a 3/16-inch (4.8-mm) deflecting plate spacing under identical operating conditions.

A test of the Sprayco No. 6K nozzle, Figure 15F, was performed after use of the nozzle in an operational hygroscopic cloud seeding program in Oklahoma. The nozzle was designed so that the liquid was introduced into the center of a swirling airstream and mixed before leaving the exit port. Laboratory tests were performed to duplicate conditions used in the cloud seeding operation. Air pressure was set at 32 psi (2.2 kg/cm²), and liquid flow was set for 0.3 gpm (0.02 liter/sec). Geometric mean diameter of the spray was 43 μ m and median mass diameter was 64 μ m. Additional data taken with air pressure set at 45 psi

(3.2 kg/cm²) and liquid flow rate ranging from 0.2 to 0.4 gpm (0.01 to 0.02 liter/sec) provided geometric mean diameters between 25 to 45 μ m and median mass diameters varying from 55 to 80 μ m. No apparent correlation was observed between droplet size and liquid flow rate for these tests.

Liquid-pressure Nozzles

Several types of nozzles operated by liquid pressure only are shown in Figure 27.

Self-impinging jets.—Dombrowski and Hooper⁶ describe the mechanisms of breakup of impinging jets. The impinging jets produce a flat sheet in a plane perpendicular to that containing them. Formation of aerodynamic or hydrodynamic waves on the surface of the sheet then causes additional breakup.

Dombrowski and Hooper maintained laminar flow over a range of Reynolds numbers up to 12,000. Insertion of wires at the tube entrances was used to produce turbulent flow. Tests were carried out for both cases, with impingement angles of 50° to 140° and jet velocities of 730 to 1,950 cm/sec (24 to 64 ft/sec). Their results showed that, for both laminar and turbulent jets, a minimum geometric mean drop size of about 100 μ m occurred for an impingement angle of 140° and a jet velocity of 1,950 cm/sec (64.0 ft/sec). The laminar flow actually reached the minimum drop size at about 1,200 cm/sec (39.4 ft/sec) for impingement angles of 110° to 140°, then began to increase with an increase in velocity. However, the turbulent case is of practical interest. The results, though terminated at 1,950 cm/sec (64.0 ft/sec) suggested that there would be no further reduction of drop size with increasing jet velocity. One purpose of the present tests was to verify this conclusion.

The impinging jet nozzles hold promise both for cloud seeding with hygroscopic liquids and for large-scale spraying-drying applications. Thus, it was necessary to obtain a rapid means of drilling large numbers of hole pairs and at the same time to maintain good control of hole alignment, size, and shape.

Figure 28 shows a series of impinging jets formed by punching plastic pipe with a No. 10 needle. As the photo shows, some jets were misaligned and others were plugged. Tests were also performed with holes formed by a No. 80 [(0.0135-inch (0.3-mm)] drill bit. Problems with plugging continued, even during operation at several hundred psi. Figure 29 shows material forced into the pipe interior during drilling. The problem of plugging was finally greatly reduced by using tap water and a 5-micron cartridge filter.

Test nozzles were formed in 1/2-inch (12.7-mm), Schedule No. 40 and 80 PVC pipe, using a No. 80 drill [0.0135 inch (0.3 mm)]. Impingement angles of 90° to 110° were chosen to minimize splash back onto the pipe surface and to allow proper aeration of the jets.

A special shop jig was made to ensure proper alignment of the holes. However, it was found that misalignment of the jets occurred for certain pressure ranges, Figures 30 to 32. The misalignment was caused by jet instability, not drilling technique.

Numerous trials finally resulted in a pair of 90°, 0.0135-inch (0.3-mm) diameter holes which properly impinged over the range of test pressures, Figures 33 to 35. The holes intersected at the outside surface of the pipe.

Figure 36 shows the variation of median mass diameter and geometric mean diameter with pressure. The scatter of data, though not serious, is believed to be caused by agglomeration of droplets before the sample photograph was taken. The curves suggest limiting mass median and geometric mean diameters of about 50 and 25 μm , respectively, for this particular nozzle. Laboratory tests showed no significant change in head loss with hole size. However, investigations by others suggest that hole diameters less than about 0.01 inch (0.3 mm) are impractical because of liquid filtering problems and viscous effects.

A review of technical literature on pulsed laser drilling suggested this as a possible technique for drilling large numbers of hole pairs to close specifications. A pilot test showed that the technique holds promise and should be developed. Plans call for fabrication of a tube holder and development of a beam splitter to simultaneously drill two holes with a single laser beam.

Target-impinging jets.—In this nozzle type, a high-pressure, high-velocity liquid jet impinges on a fixed target. A typical nozzle of this type is manufactured by Bete Fog Nozzle, Inc., and is shown in Figure 37. The nozzle has an advantage in simplicity of design. However, the target can be easily knocked out of alignment, which is a critical factor. Also, as Figure 37 shows, filaments of relatively large drops tend to form at the target support. The particular nozzle tested had an orifice diameter of 0.018 inch (0.46 mm), with a target of approximately the same size. Difficulties in sampling did not provide reliable data for presentation here, but a minimum geometric mean diameter of about 45 μm was suggested.

Another nozzle of the target-impinging type is the "Mee" nozzle, manufactured by Mee Industries, Inc.

The particular nozzle tested had an orifice and target size of about 0.007 inch (0.18 mm).

Figure 38 shows the variation in droplet diameter and nozzle flow rate with liquid pressure. The data scatter for mass median diameter in the smaller sizes is believed to be caused by agglomeration of smaller drops into larger drops. Therefore, the curve fit to the data was tempered by this observation.

Geometric standard deviation varied from about 1.3 to 1.8 in the analysis, with a slight decrease with increasing liquid pressure and flow rate.

The limiting droplet size is indicated by the curves to be about 20 μm . Comparison with the minimum size of droplets produced by the Bete nozzle (45 μm) suggests that the minimum size might be directly related to the orifice size. Figure 39 shows the appearance of the spray for liquid pressures of 40, 300, and 575 psi (2.8, 21.1, and 40.4 kg/cm^2).

Target-impinging nozzles obviously are capable of producing smaller droplets at much lower liquid pressures and flow rates than the self-impinging jets. However, the relative costs of constructing or purchasing each type must be considered when dealing with large quantities of fluid.

Fan Type.—The Spraying Systems 1/8-K5 nozzle, Figure 27B, was tested in the summer of 1972 during a program of hygroscopic cloud seeding in Oklahoma. Measurements were made with spraying of water from a parked aircraft and of ammonium nitrate-urea solution from a low-flying aircraft. Test results are summarized in Table 3.

The large difference in median mass diameter between sampling at the tail and sampling at downwind locations was a result of larger droplets striking the ground a short distance downwind from the aircraft. The larger droplets were not included in the collected sample.

During the airborne low passes, mostly large droplets were collected. Even considering the hygroscopic growth, particles were probably over 800 μm median mass diameter when released from the aircraft.

Later laboratory tests showed that an airspeed of 236 ft/sec (71.9 meters/sec) should reduce the median mass diameter to about one-half of that for still-air operation of the nozzle. Limited laboratory tests also showed that increasing the liquid pressure from 20 psi (1.4 kg/cm^2) to 100 or 200 psi (7.0 or 14.1 kg/cm^2) would reduce the spray size considerably.

Table 3
FIELD TESTS OF SPRAYING SYSTEMS
1/8-K5 NOZZLE

Sampling location	Aircraft configuration	Geometric mean diameter, μm	Geometric standard deviation	Median mass diameter, μm
Tail section	Parked—engines off	21.1	3.18	1,166.8
30 feet (9.1 meters) downwind	Parked—engines on	12.5	2.35	110.6
45 feet (13.7 meters) downwind	Parked—engines on	13.2	2.41	134.0
On runway	Airborne—low passes	180.1	2.07	876.1

Injection pressure was 20 psi (1.4 kg/cm²) for all tests.

Solid-cone type.—The Monarch solid-cone nozzle, Figure 27D, was given a very limited test, using a liquid pressure of 400 psi (28.1 kg/cm²). A sample of 482 droplets gave a geometric mean diameter of 50.4 μm , a geometric standard deviation of 1.52, and a median mass diameter of 85.1 μm . The geometric mean diameter is similar to that for the impinging-jets nozzle, Figure 33, but the median mass diameter is considerably smaller. Also, the spray from the solid-cone nozzle is considerably larger than that for the target nozzle at the same pressure.

Miscellaneous Devices

Jet injected into slipstream.—Based on the findings of Sherman and Schetz¹⁵, Lane¹², and others, it seemed that appreciable drop breakup could be accomplished by injecting a solid liquid jet into an aircraft slipstream. Some field investigations had also suggested this possibility.

Assuming a 202 ft/sec (61.6 meters/sec) slipstream, application of equation (2) would yield:

$$d = \frac{612}{(u-v)^2} = \frac{612}{3,600} = 0.17 \text{ mm}$$

$$= 170 \mu\text{m}$$

the minimum size drop which could be further broken by this air velocity.

Figure 40 shows the laboratory apparatus used in checking this conclusion. The air pipe is at the right of the photograph; airflow is from right to left. The liquid was injected perpendicular to the stream through a 1/16-inch-diameter (1.6-mm) orifice into a calibrated 202 ft/sec (61.6 meters/sec) airstream.

The resulting droplets were not collected but were estimated to range between 100 and 500 μm in size.

Propeller spray generator.—A propeller spray generator, Figure 41, was loaned to the laboratory by the Sierra Research Corporation. However, time did not permit testing of the device. Liquid is introduced to the propeller through a series of tiny holes located in the circular ring around the propeller shaft. The blades possessed different shapes, and the leading edges were attached to the hub at different positions. The tips of the blades appeared to be different also. Some contained a groove from leading edge to trailing edge, while others were flat. All blades contained grooves along the trailing edge, eliminating the possibility of a smooth convergence of flow from either side of the blade and increasing the degree of vorticity. The degree of turbulence produced by this propeller would be extremely high compared with a propeller with conventional blading and should produce considerable liquid droplet breakup.

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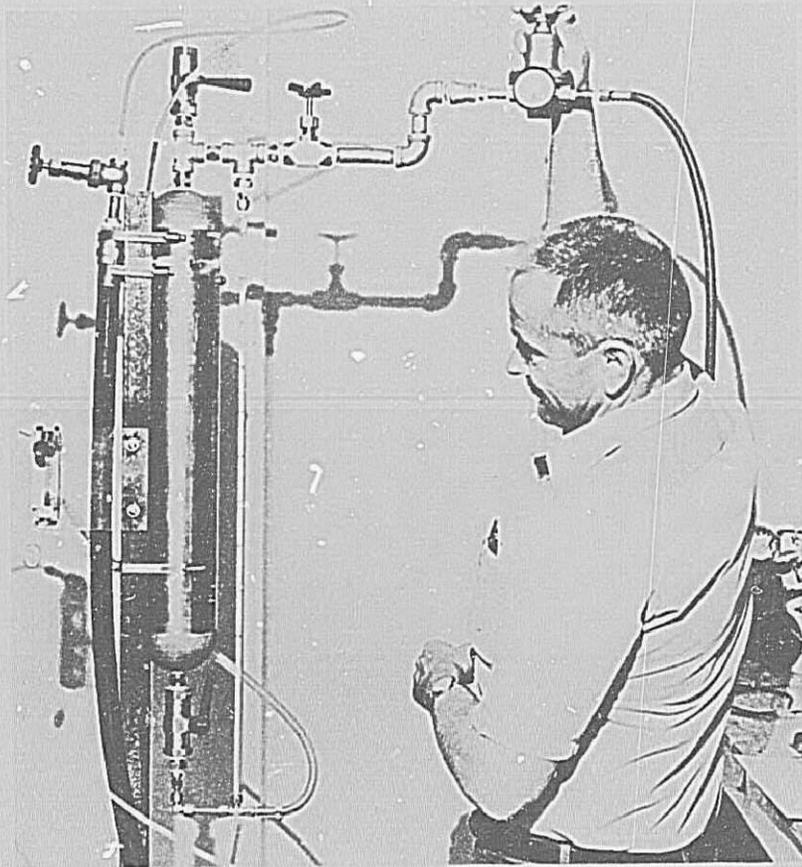


Figure 1. Apparatus for injection of liquid into air-operated nozzles. Photo P801D-74365

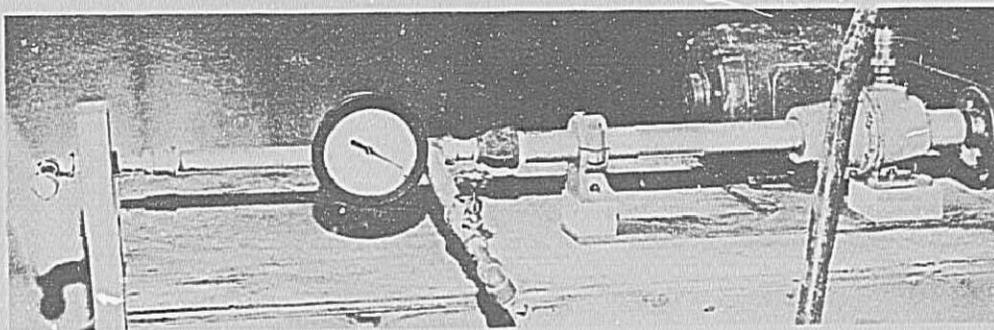


Figure 2. Equipment for injection through liquid nozzles. Photo P801D-74366 NA

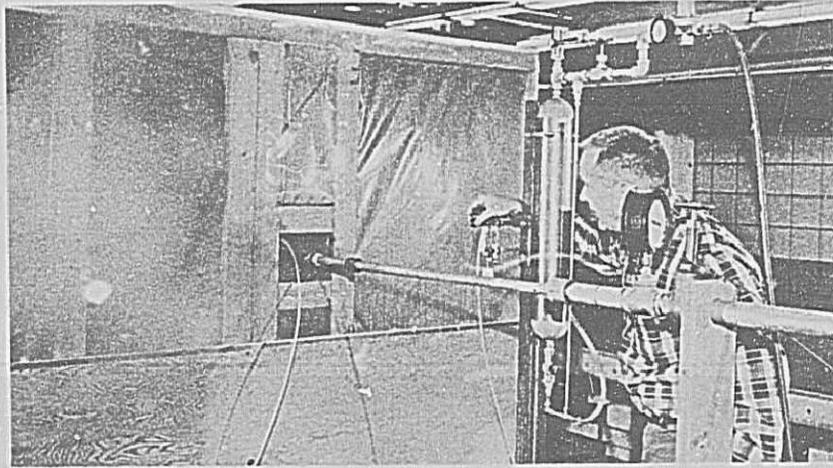


Photo P801D-74367 NA



Figure 3. Vented collection hood for indoor spraying of corrosive liquids. Photo P801D-74368 NA

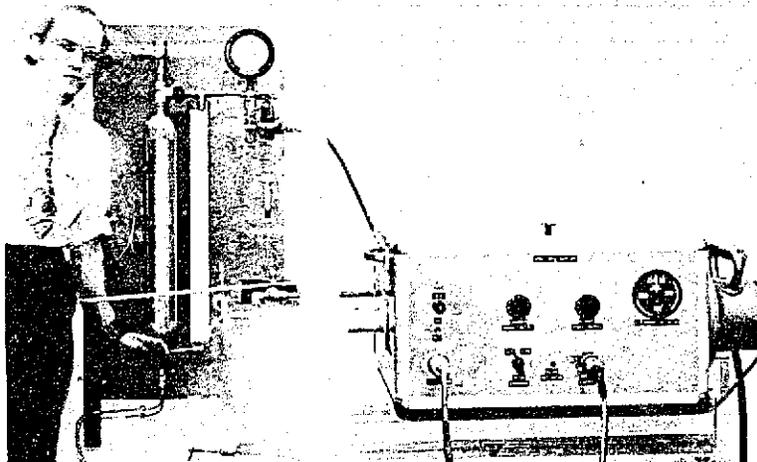


Figure 4. Cornell droplet sampler. Photo P801D-74369NA

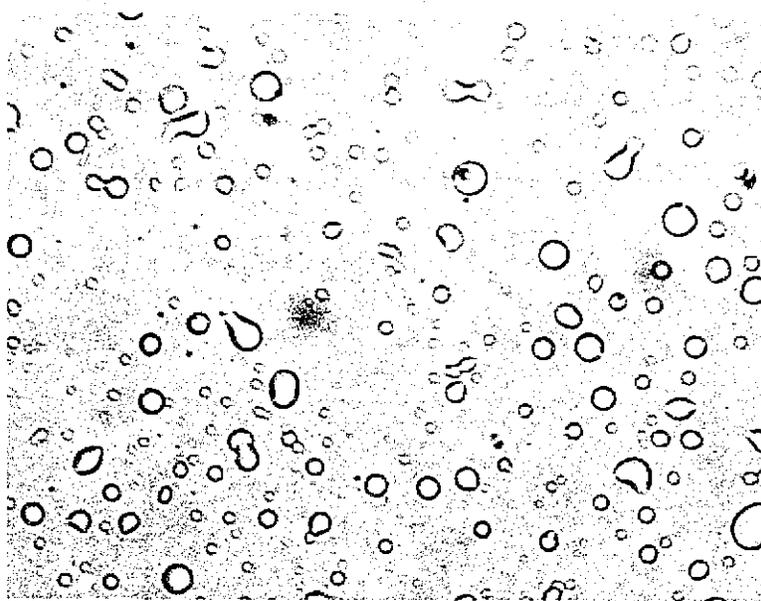


Figure 5. Water droplets collected on gelatin-coated slide with Cornell sampler (50X magnification). Photo P801D-74370NA

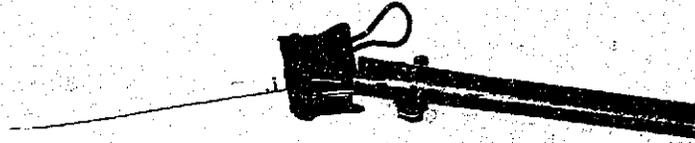


Figure 6. Gelatin-coated slide mounted in wand. Photo P801D-74371NA

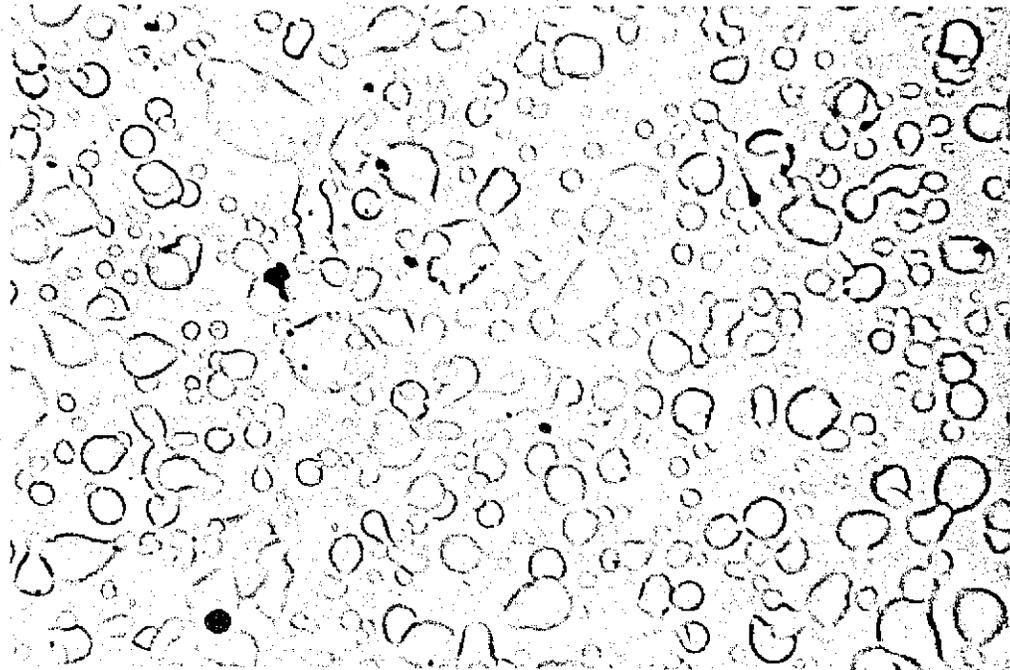


Figure 7. Poor slide specimen. Photo P801D-74372NA

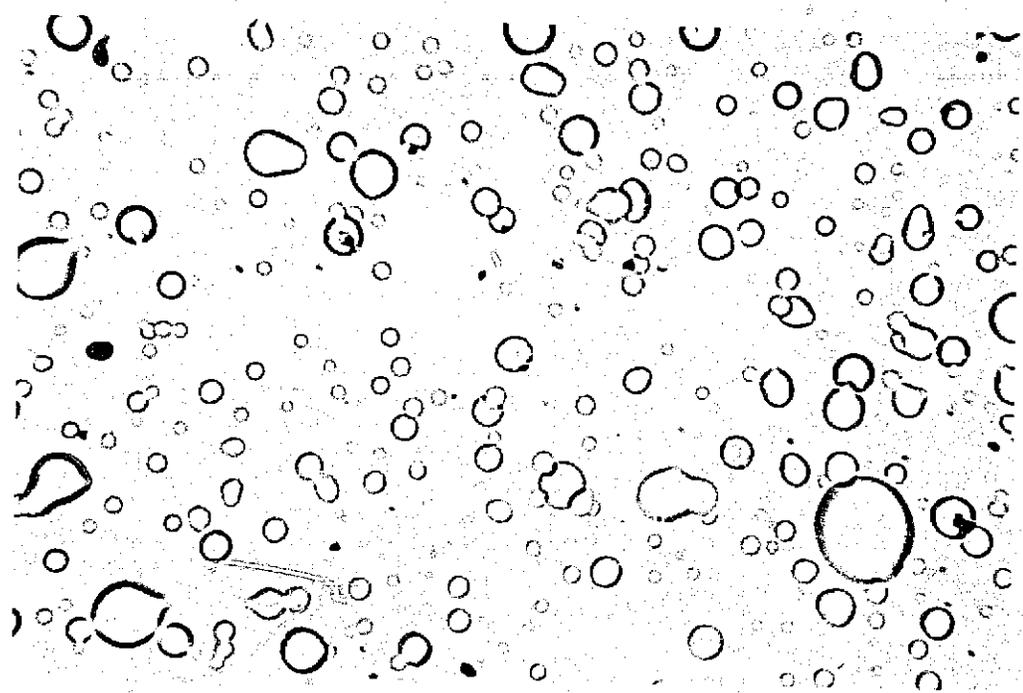
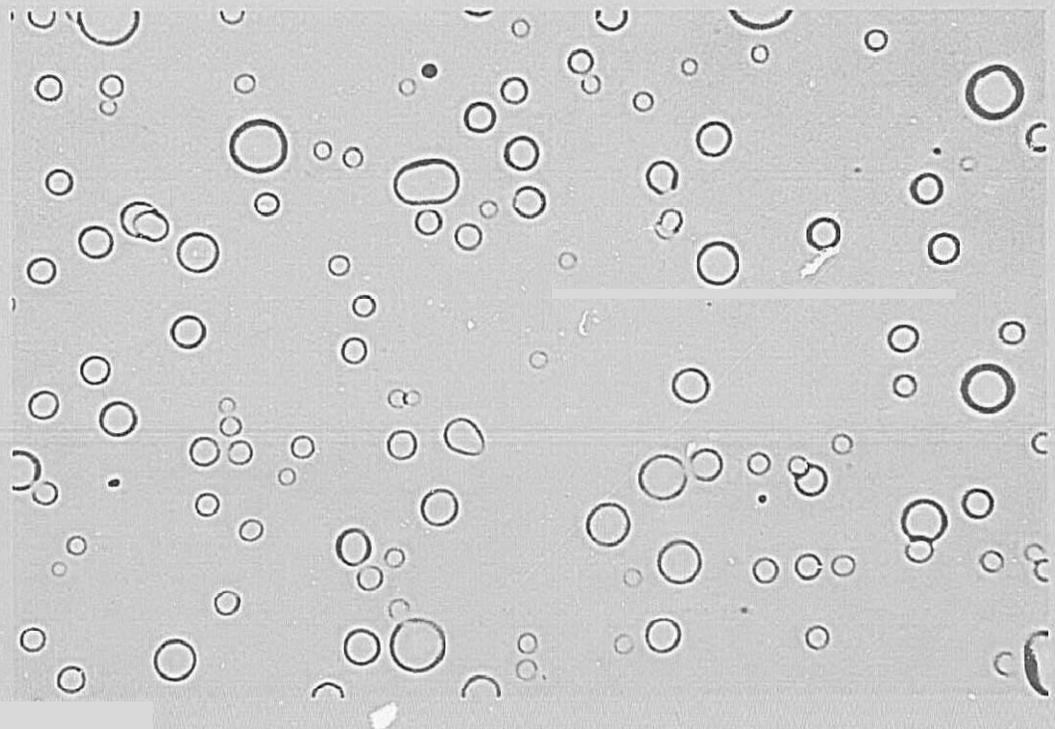
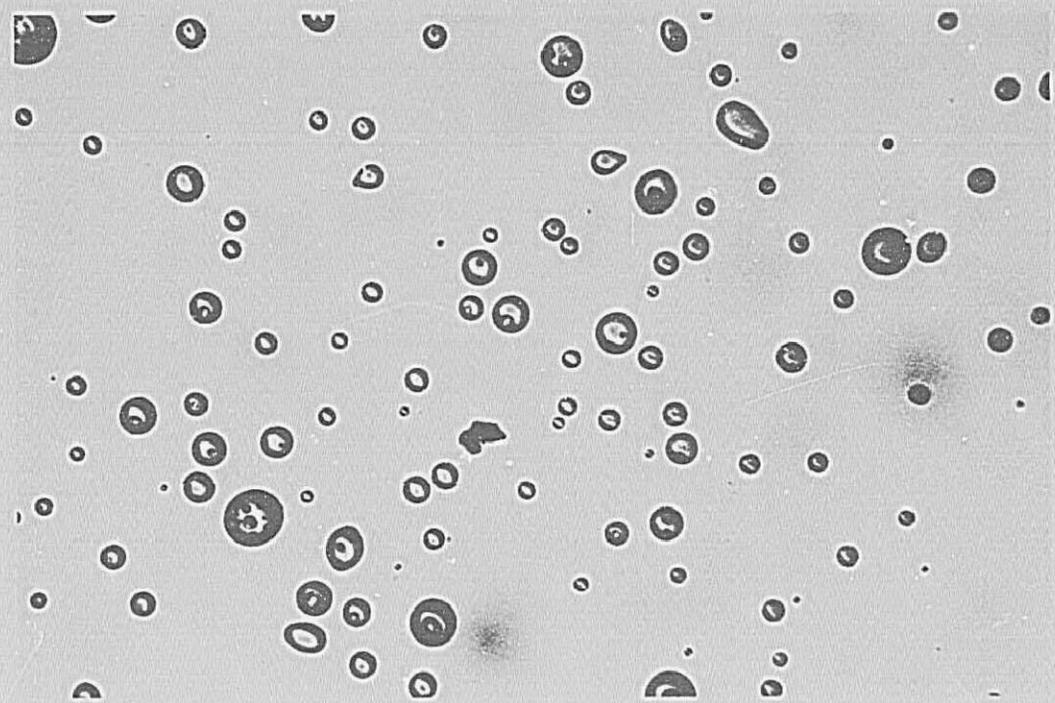


Figure 8. Better slide specimen. Photo P801D-74373



A. Water droplet craters on gelatin-coated slide. Photo P801D-74374 NA



B. Ammonium nitrate-urea droplets on uncoated slide. Photo P801D-74375 NA

Figure 9. Comparison of droplets on coated and uncoated slides

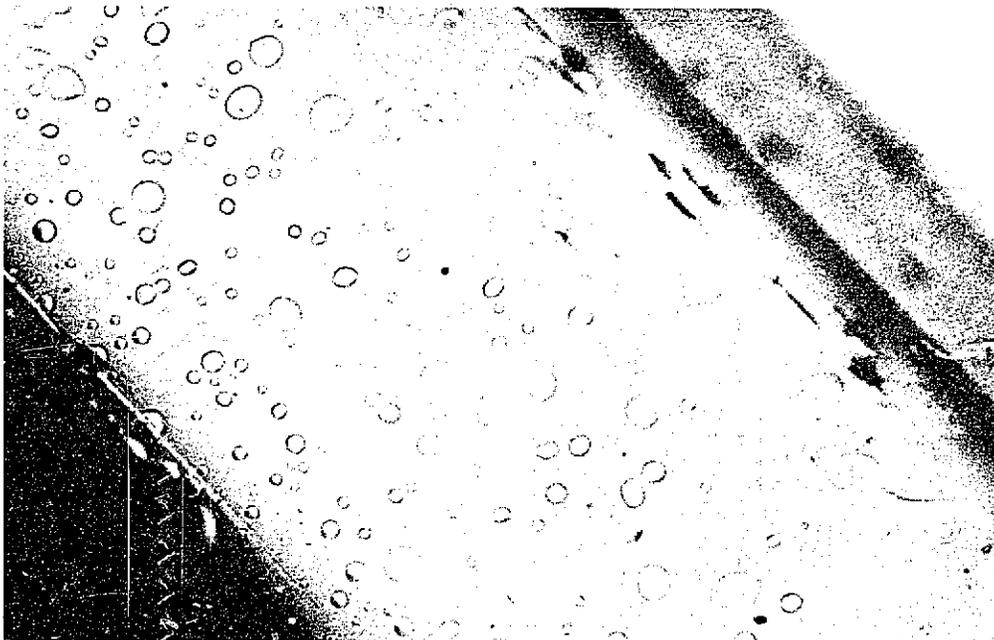


Figure 10.: Water droplets collected on gelatin-coated cylindrical glass rod. Photo P801D-74376 NA

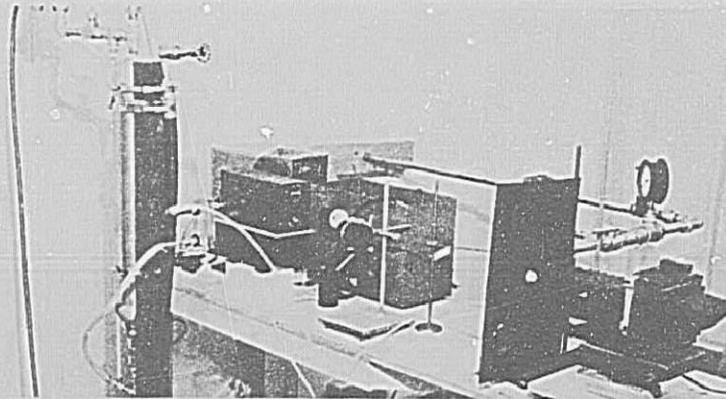


Figure 11. Spark-gap light source and optics for photographing airborne droplets. Photo P801D-74377 NA

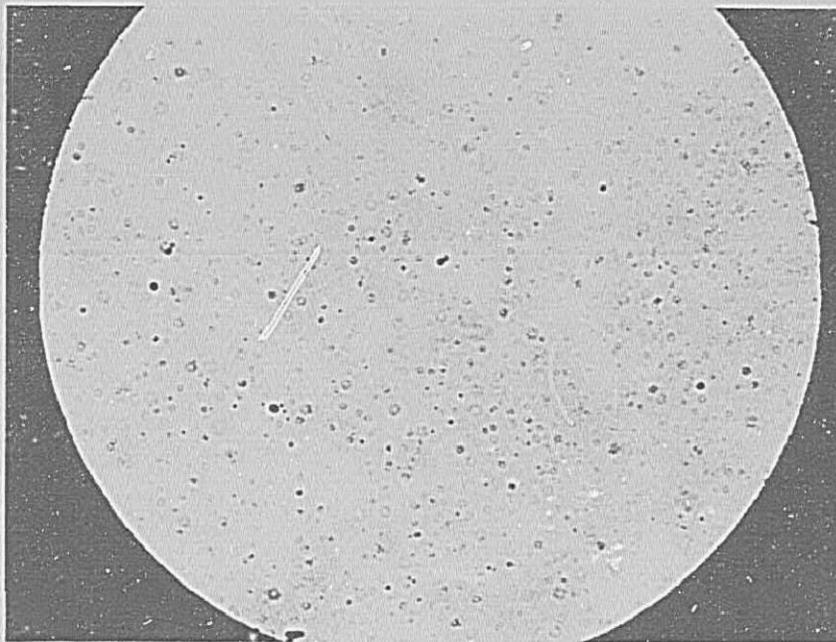


Figure 12. Typical high-speed photograph of airborne droplets (25X magnification). Photo P801D-74378

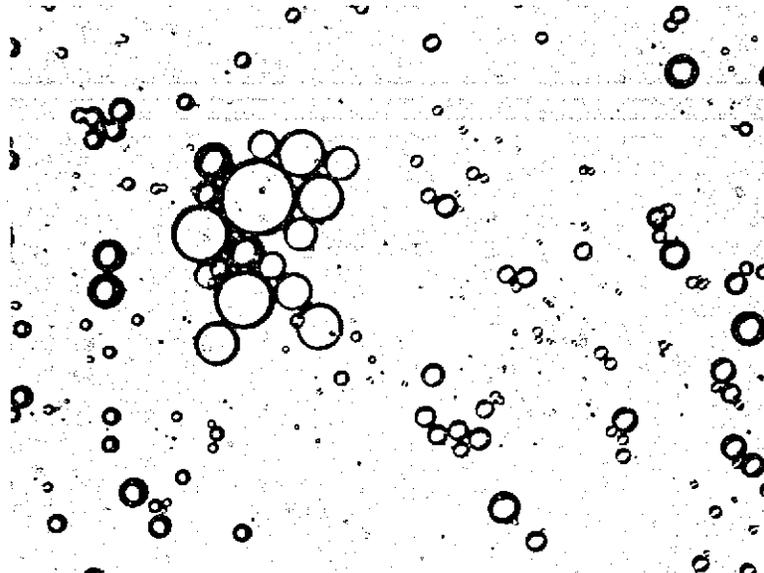


Photo P801D-74379 NA

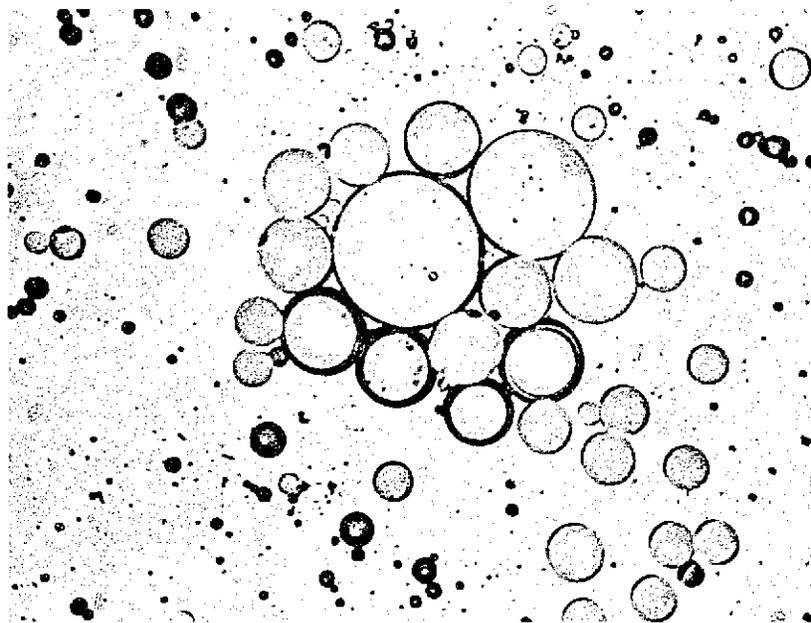


Figure 13. Photomicrographs showing agglomeration of water droplets in Stoddard solvent. Photo P801D-74380 NA

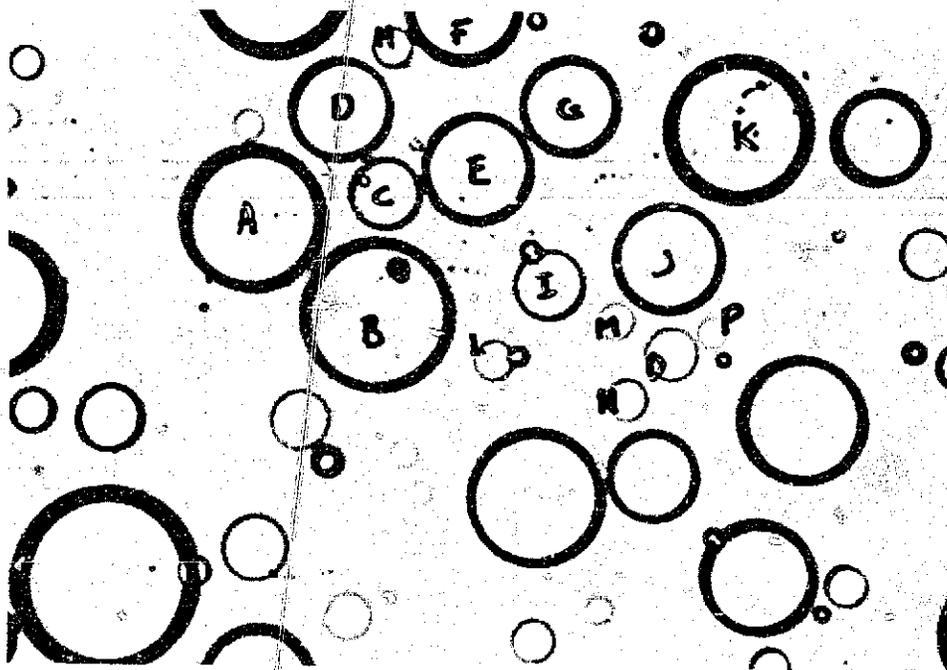


Photo P801D-74381 NA

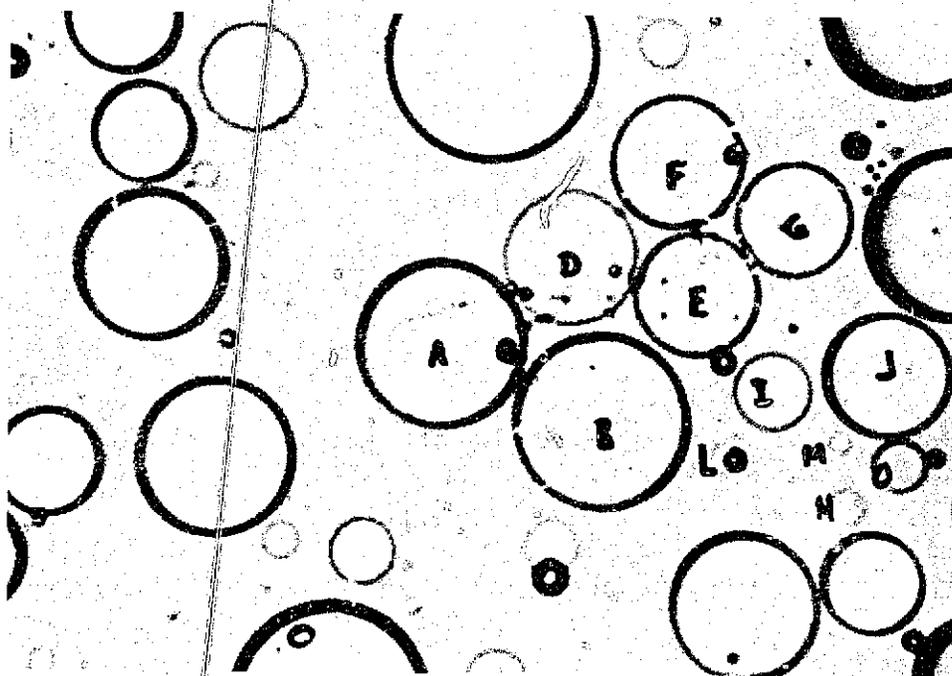


Figure 14. Photomicrographs showing migration and agglomeration of water droplets in Stoddard solvent. Individual droplets are identified by alphabetic characters. Photo P801D-74382 NA

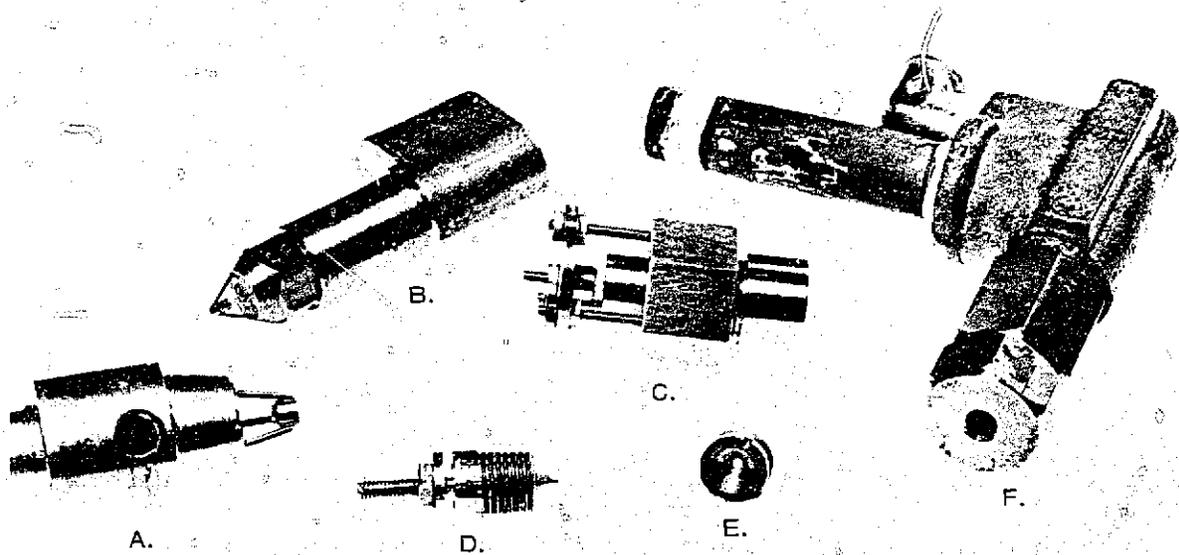


Figure 15. Air-operated nozzles. Photo P801D-74383NA

- A. "Sonicore" No. 188
- B. "Sonicore" No. 052
- C. USBR-2
- D. USBR-1
- E. Prandtl-Meyer
- F. Sprayco No. 6K

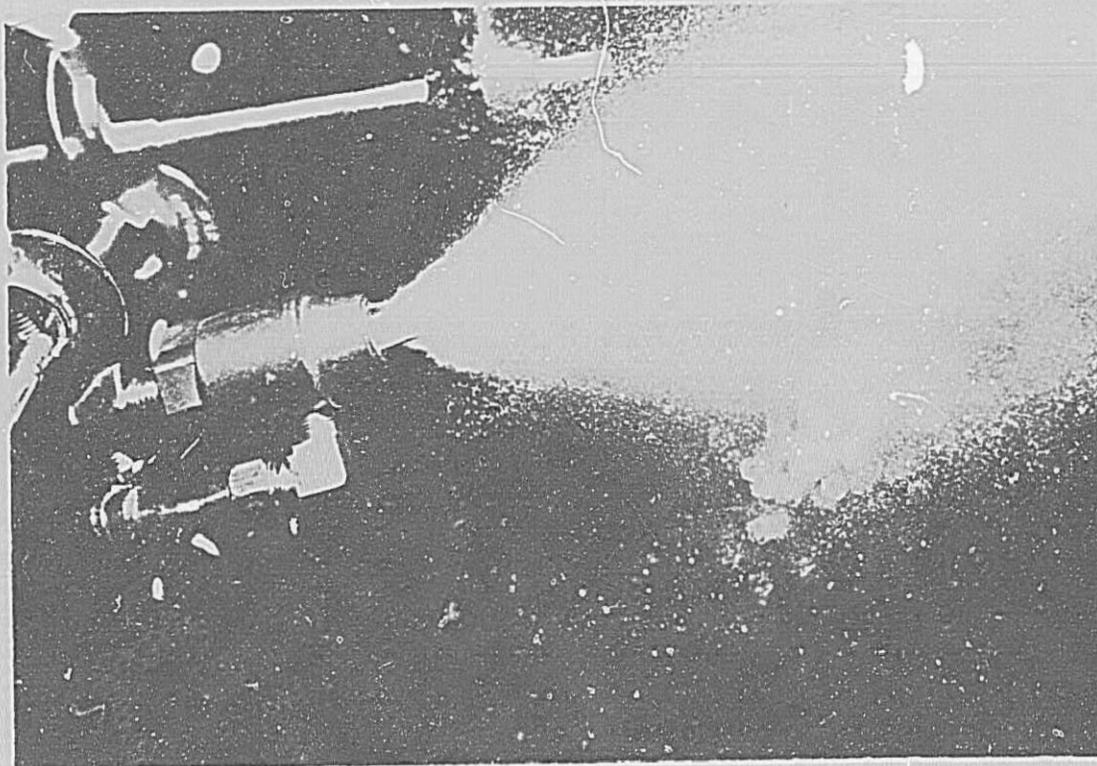


Figure 16. "Sonicore" No. 188 nozzle with air pressure = 10 psi (0.7 kg/cm²) water pressure = 60 psi (4.2 kg/cm²). Photo P801D-74384 NA

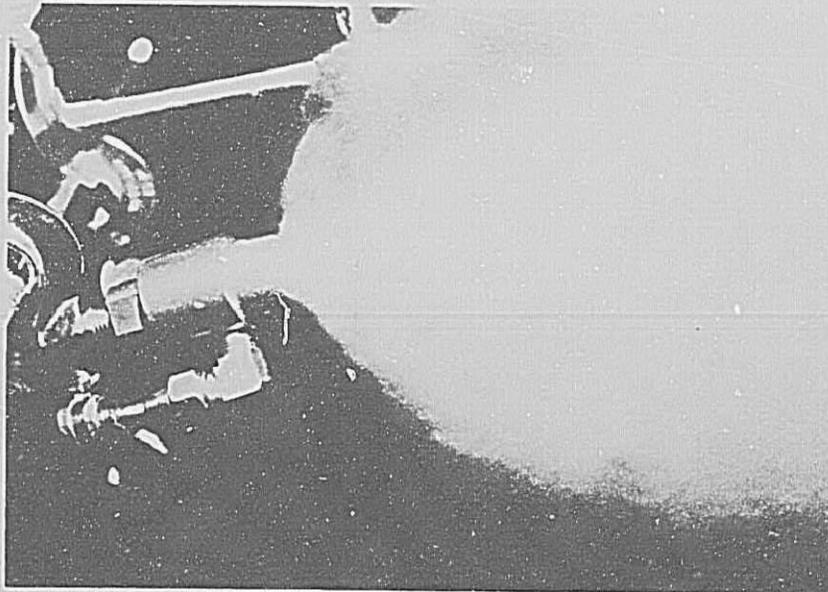


Figure 17. "Sonicore" No. 188 nozzle with air pressure = 60 psi (4.2 kg/cm²), water pressure = 10 psi (0.7 kg/cm²). Photo P801D-74385 NA



Figure 18. Ground-based spray rig using "Sonicore" nozzles for hygroscopic cloud seeding. Photo P801D-68982 NA

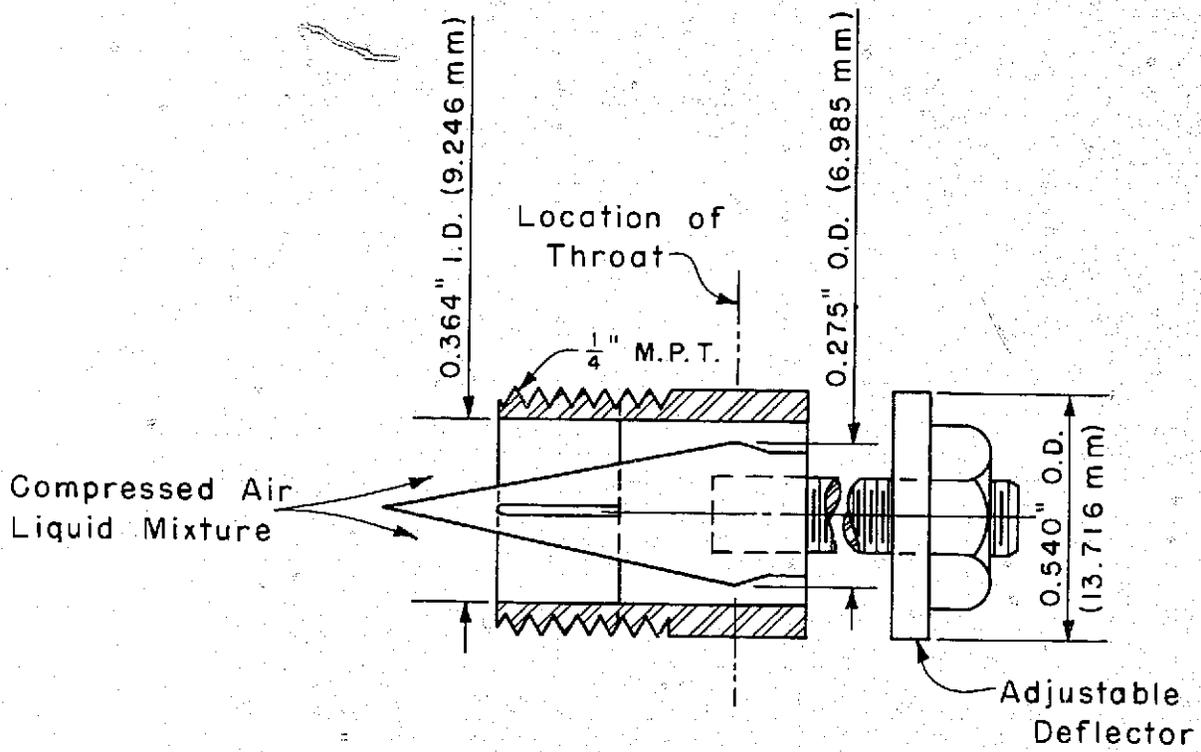


Figure 19. Cross section of Mach-1.5 supersonic nozzle (USBR-1).

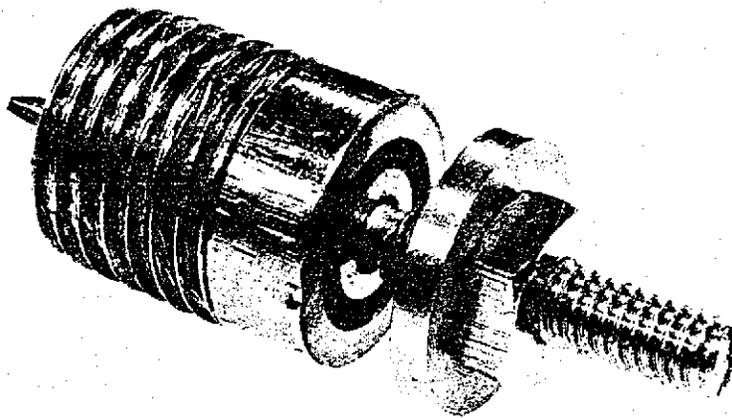


Figure 20. Mach-1.5 supersonic nozzle (USBR-1). Photo P801D-74386NA

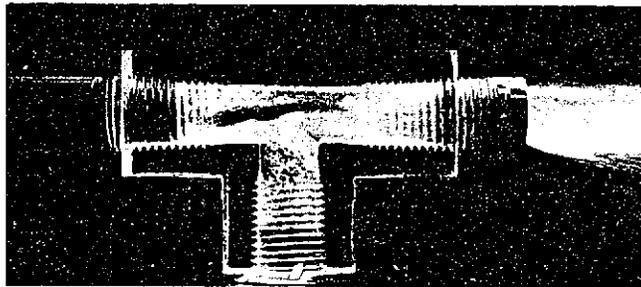


Figure 21. Transparent tee and nozzle in operation. Photo P801D-74387NA

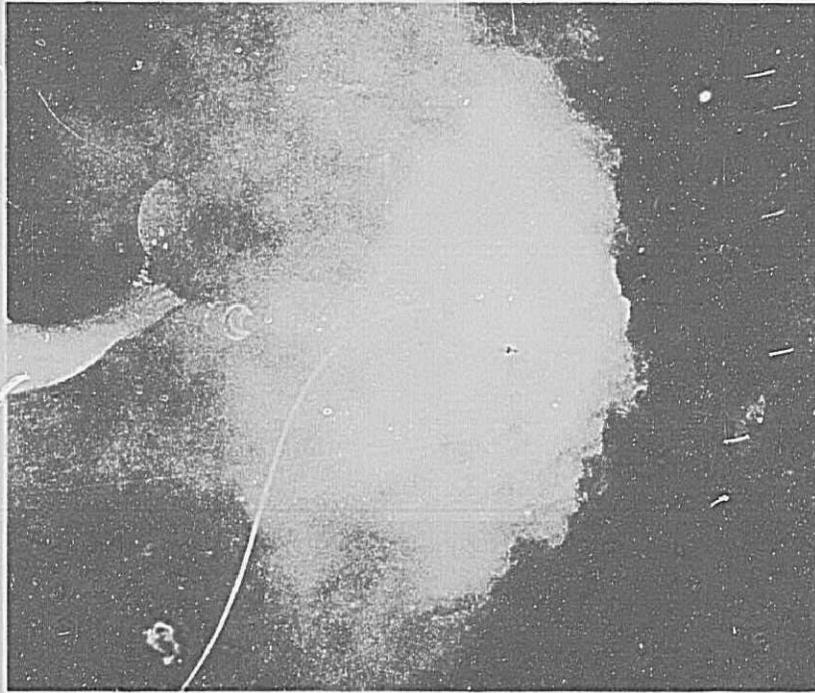


Figure 22. Mach-1.5 nozzle (USBR-1) with deflecting plate. Photo P801D-74388NA

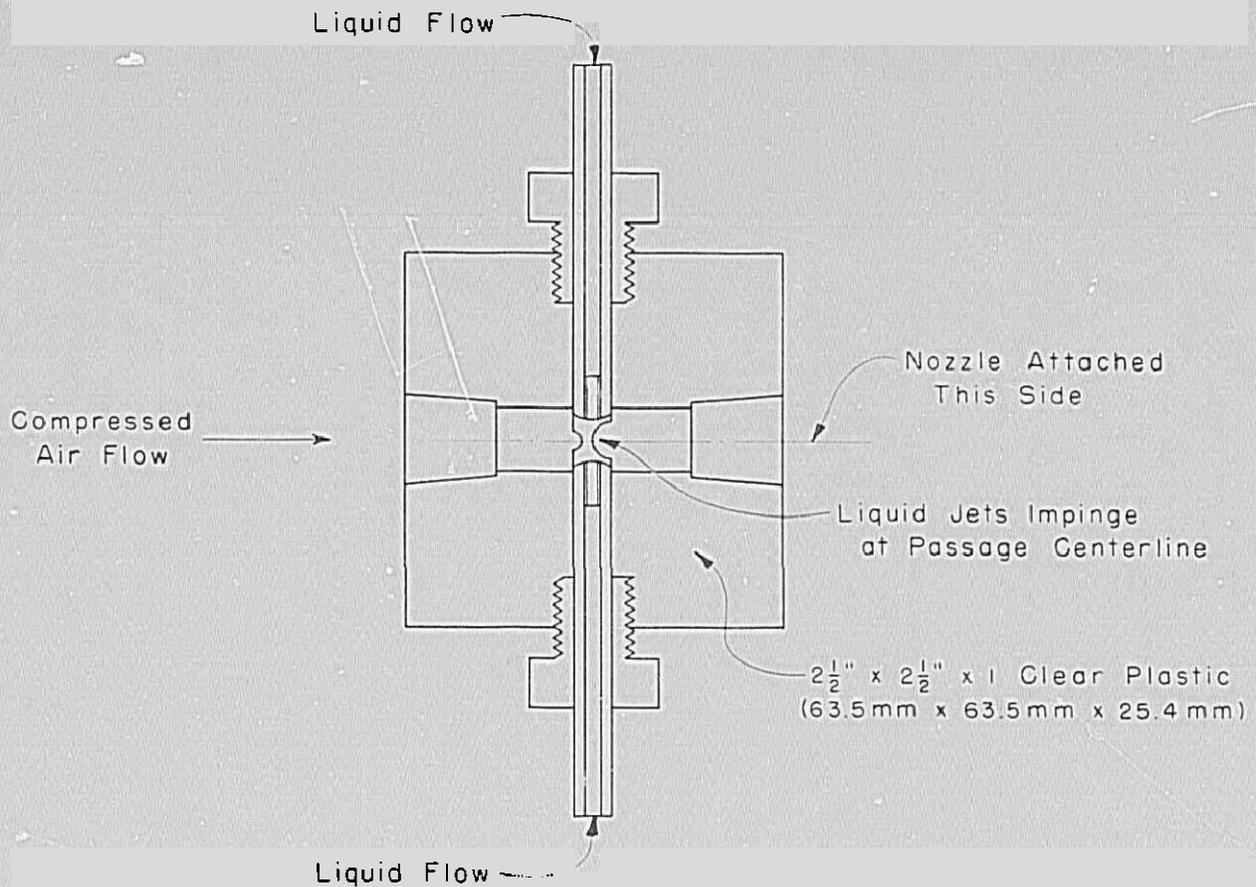


Figure 23. Device for injection of liquid upstream from air nozzle.

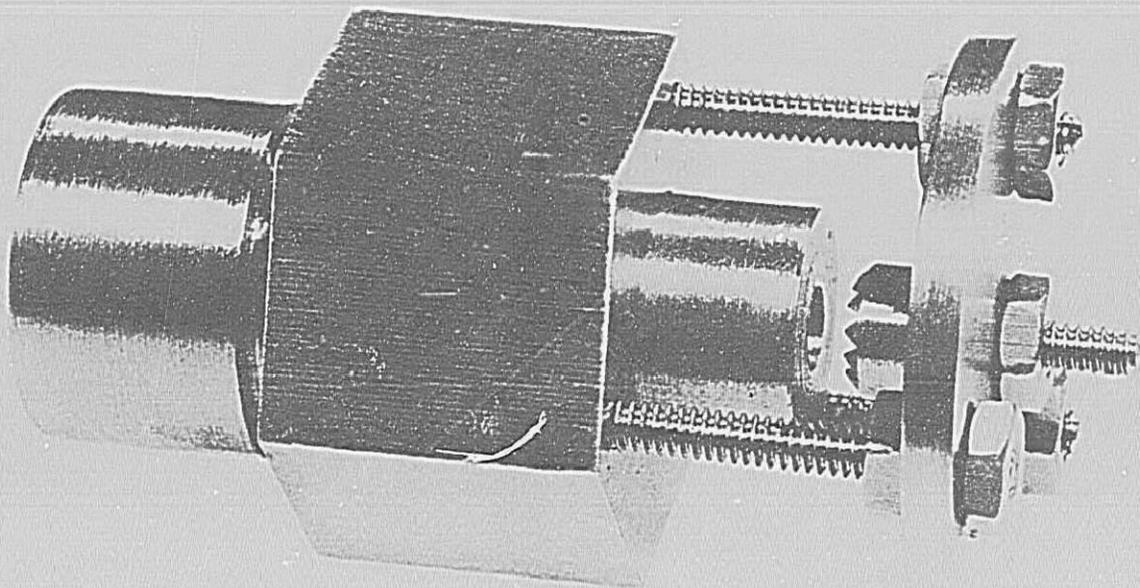
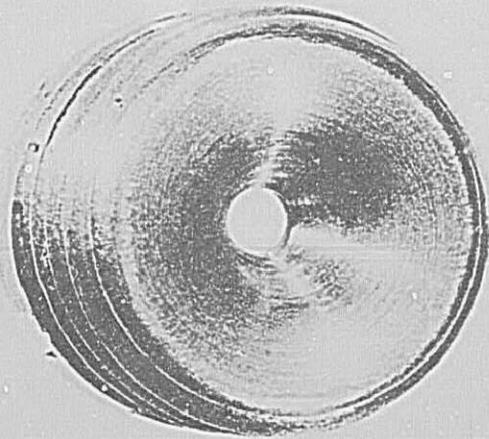
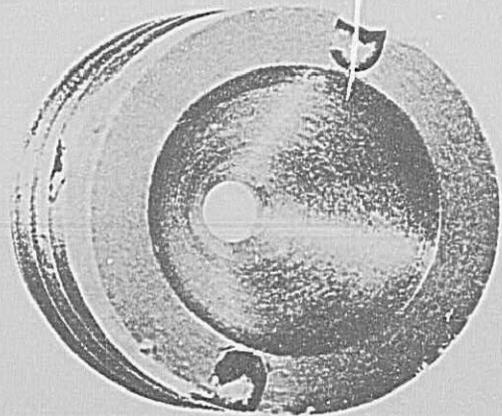


Figure 24. Supersonic nozzle with serrated resonator cup and deflecting plate (USBR-2). Photo P801D-74389NA



entrance



exit

Figure 25. Prandtl-Meyer supersonic nozzle. Photo P801D-74390NA

Photo P801D-74391NA

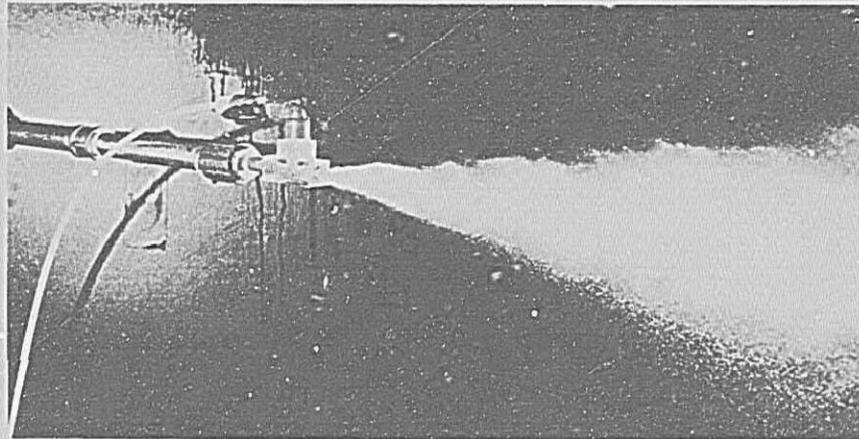


Figure 26. Prandtl-Meyer nozzle in operation. Photo P801D-74392NA

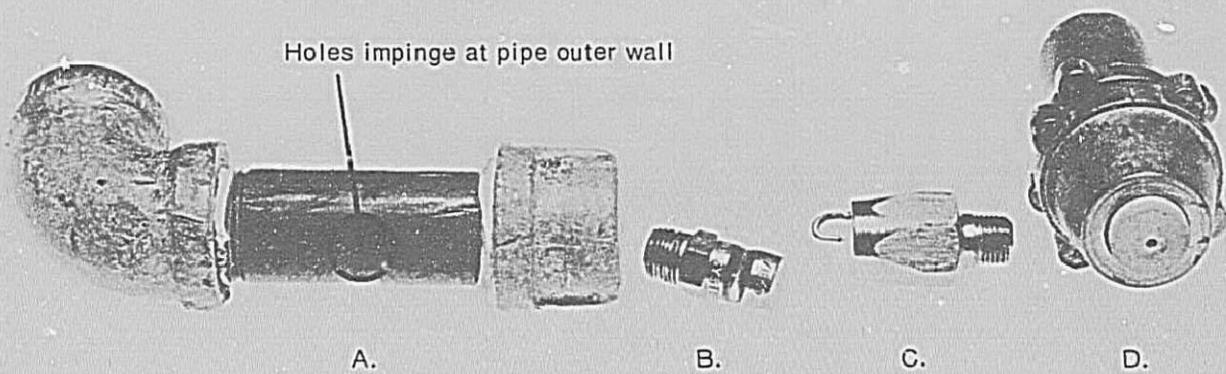


Figure 27. Nozzles operated by liquid pressure only. Photo P801D-74393NA

- A. Self-impinging jets (USBR)
- B. Fan-type (Spraying Systems, 1/8-K5)
- C. Target-impinging jet (Bete)
- D. Solid-cone (Monarch)

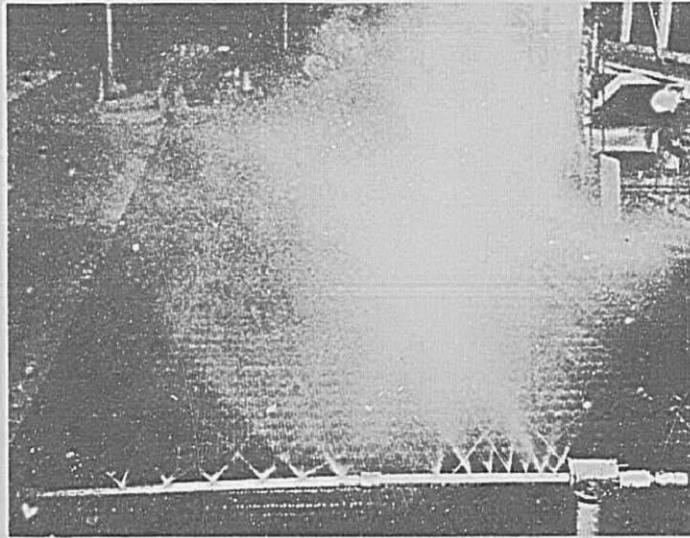


Figure 28. Series of self-impinging jet nozzles in operation. Photo P801D-74394NA

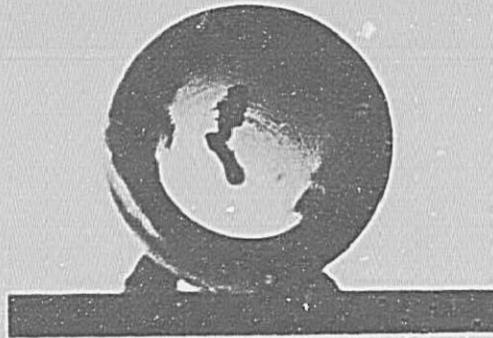


Figure 29. Interior of PVC pipe showing residue of material removed during mechanical drilling. Photo P801D-74395NA

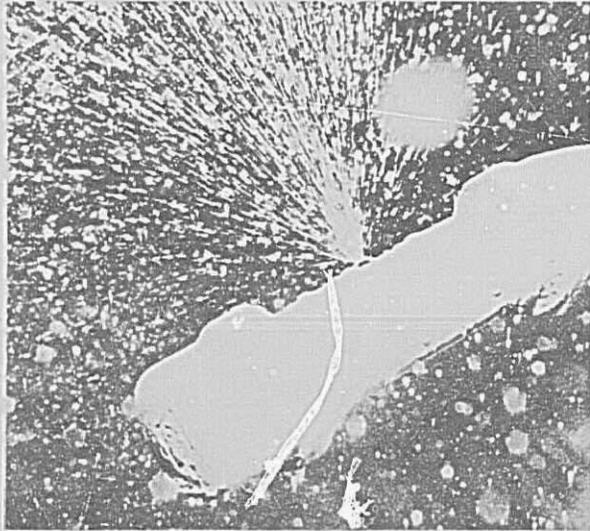


Figure 30. Self-impinging jets at 45 psi (3.2 kg/cm²).
Photo PX-D-71167NA

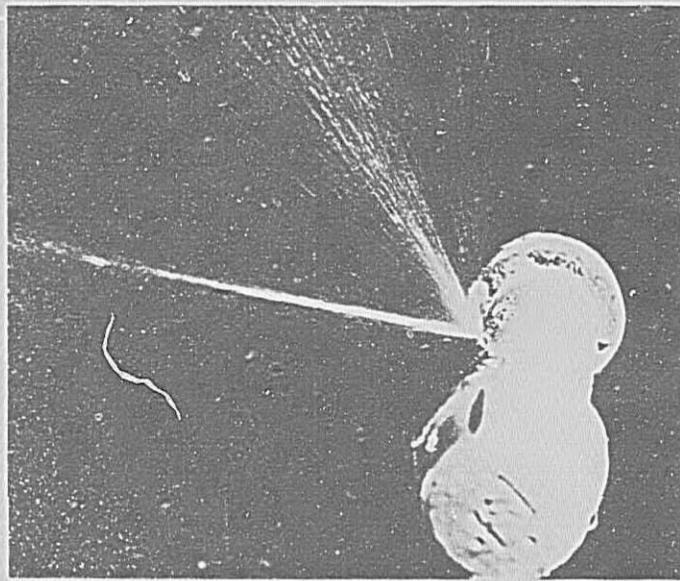


Figure 31. Self-impinging jets at 150 psi (10.6 kg/cm²). Photo
P801D-74397NA

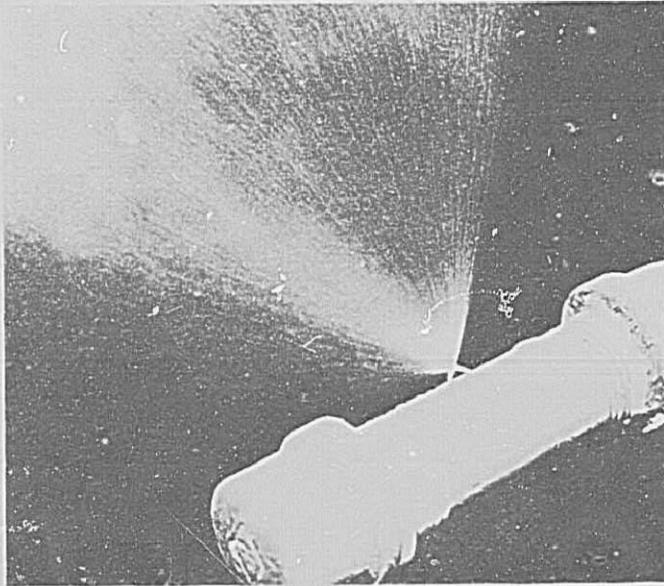


Figure 32. Self-impinging jets at 500 psi (35.2 kg/cm²). Photo P801D-74398NA

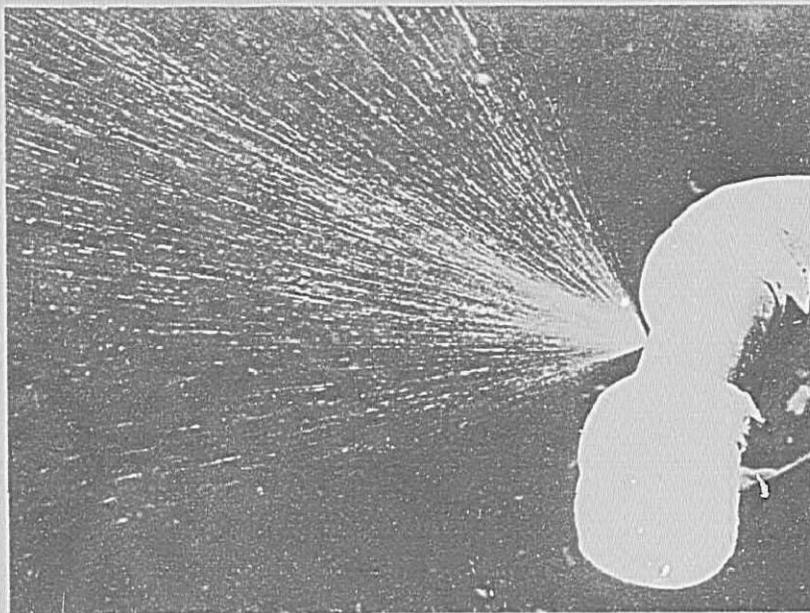


Figure 33. Self-impinging jets at 40 psi (2.8 kg/cm²). The holes intersect at outer surface of pipe. Photo P801D-74399NA

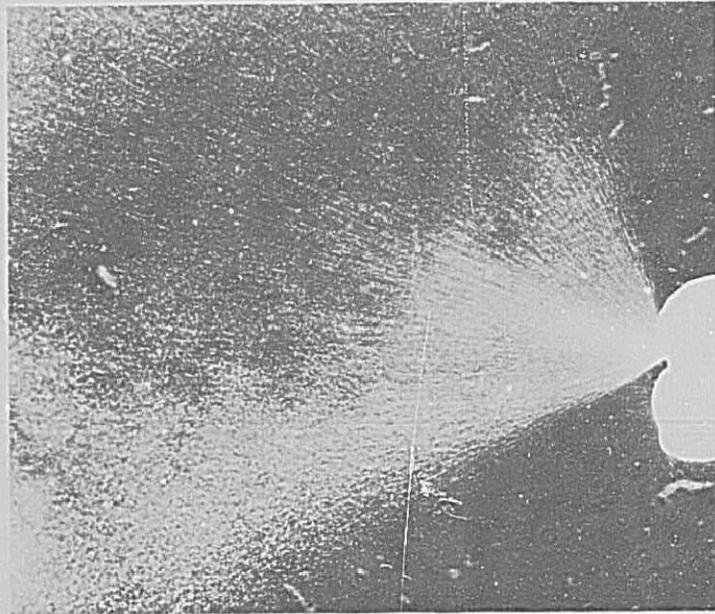


Figure 34. Self-impinging jets at 300 psi (21.1 kg/cm²). The holes intersect at outer surface of pipe. Photo P801D-74400NA.

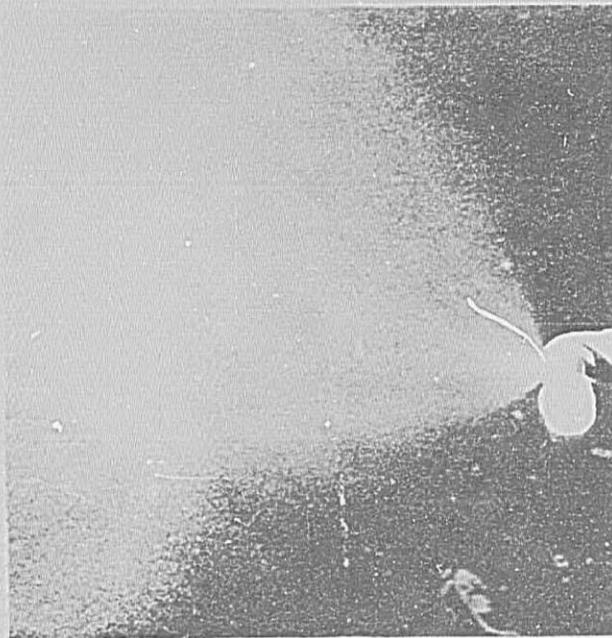


Figure 35. Self-impinging jets at 550 psi (38.7 kg/cm²). The holes intersect at outer surface of pipe. Photo P801-D-74401NA.

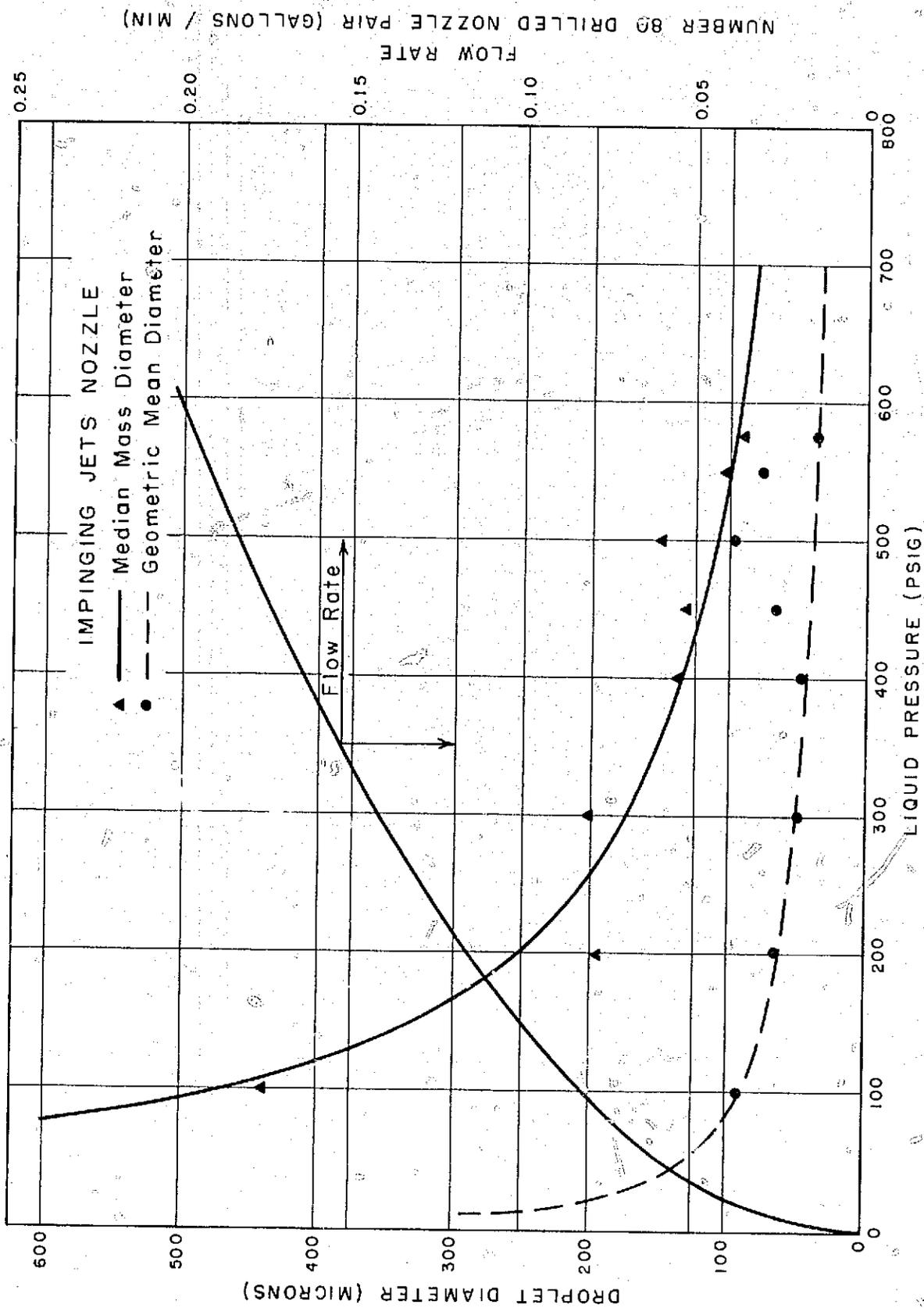


Figure 36. Characteristics of an impinging jets nozzle.

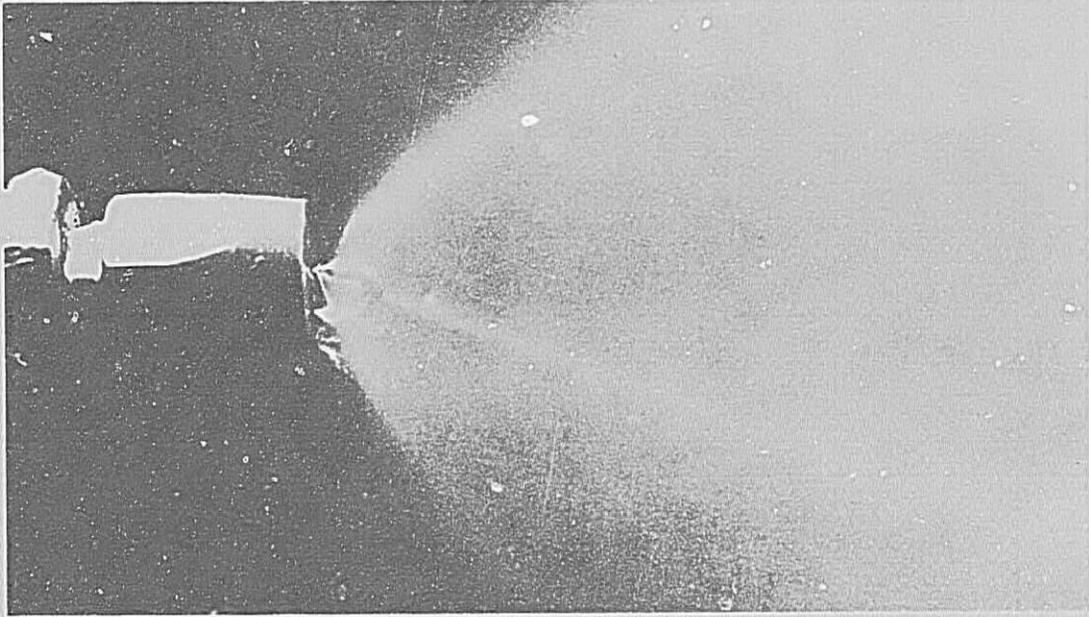


Figure 37. "Bete" target-impinging jet nozzle. Photo P801D-74402NA

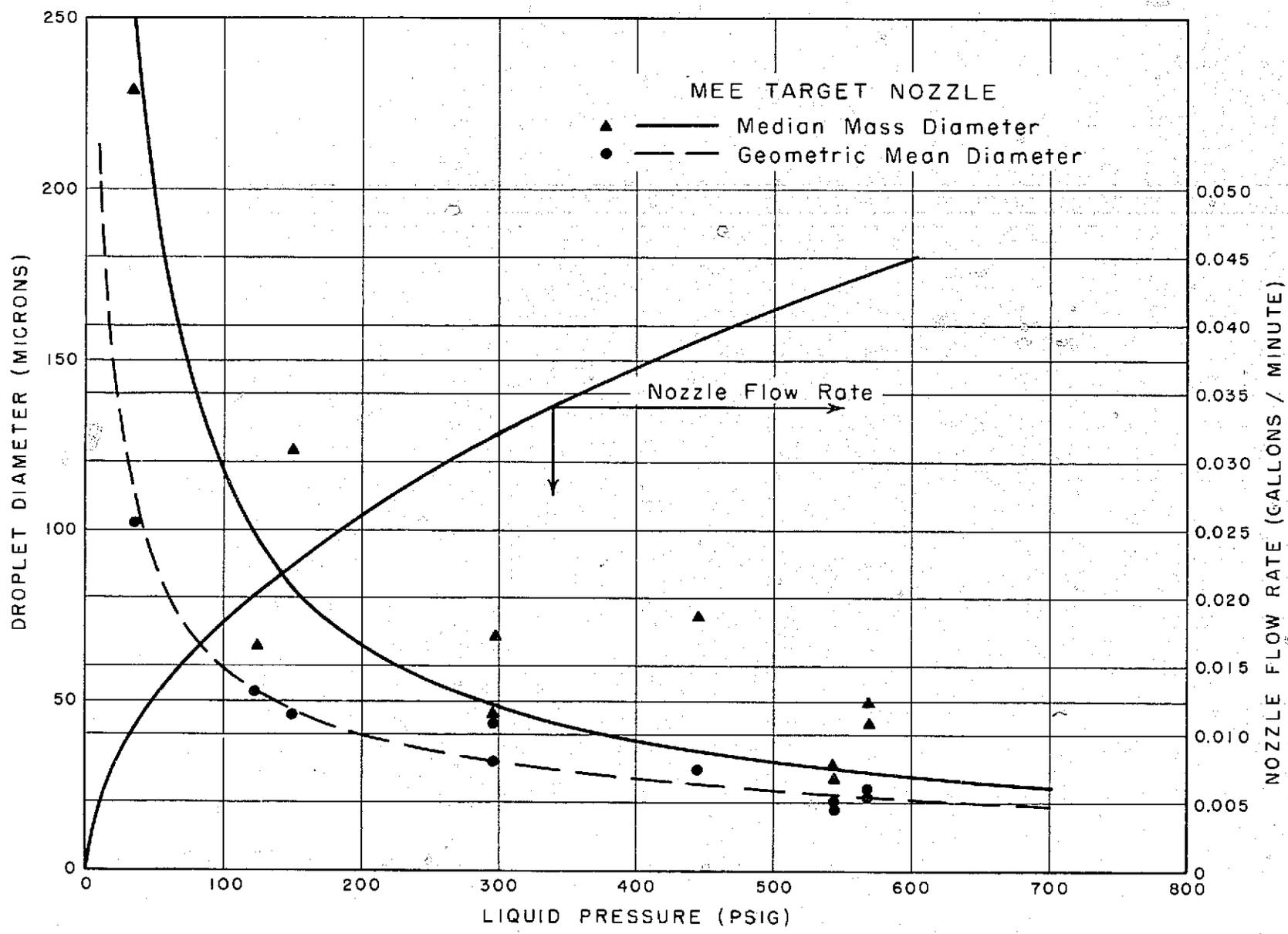
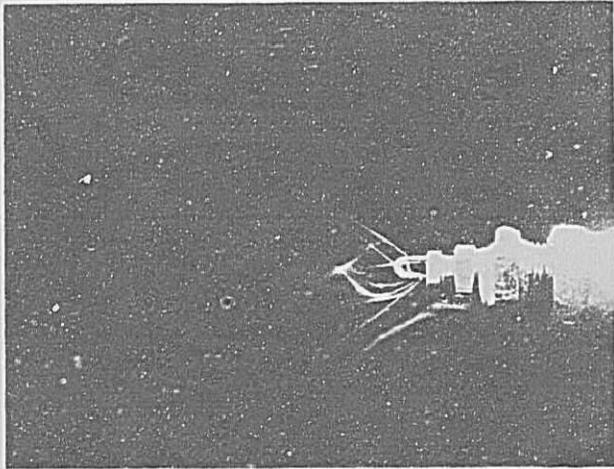
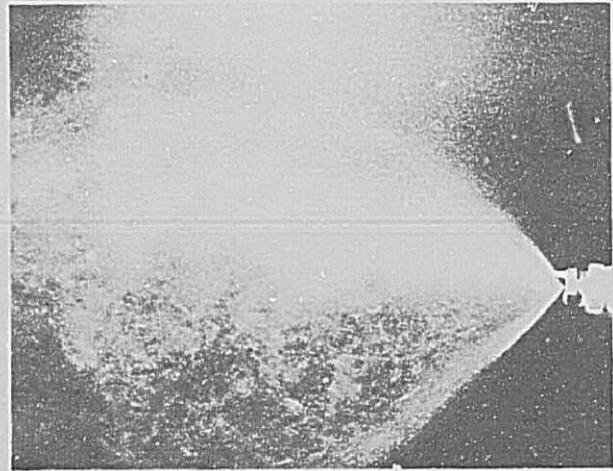


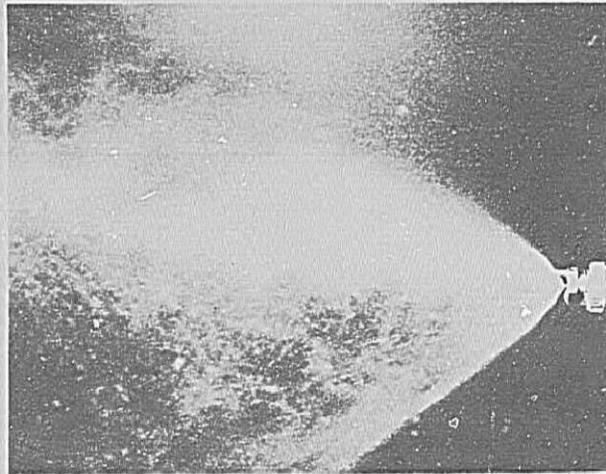
Figure 38. Characteristics of "Mee" target-impinging nozzle.



A. 40 psi (2.8 kg/cm²). Photo P801D-74403 NA



B. 300 psi (21.1 kg/cm²). Photo P801D-74404 NA



C. 575 psi (40.4 kg/cm²). Photo P801D-74405 NA

Figure 39. "Mee" target-impinging nozzle.

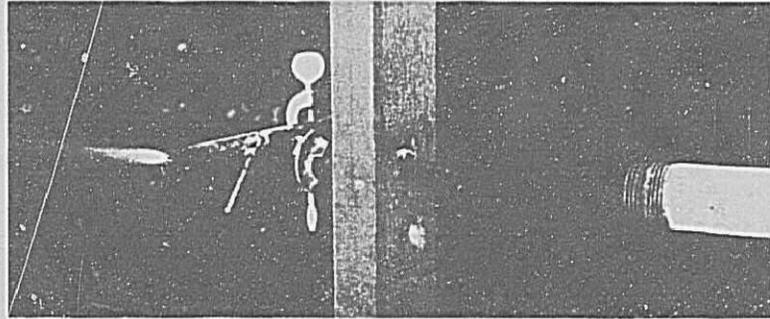


Figure 40. Breakup of liquid jet in airstream. Photo P801D-74406NA

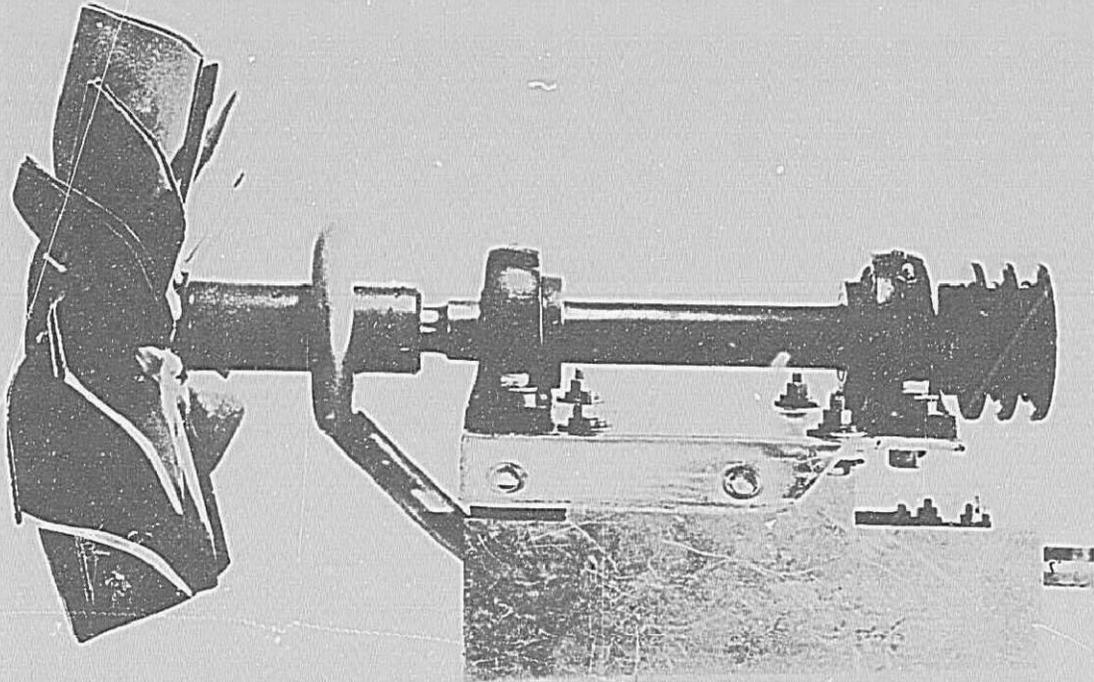


Figure 41. Propeller spray generator. Photo P801D-74407NA

CONVERSION FACTORS—BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-68) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg, that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
LENGTH		
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
Inches	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
Feet	0.3048 (exactly)*	Meters
Feet	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
Miles	1.609344 (exactly)	Kilometers
AREA		
Square inches	6.4516 (exactly)	Square centimeters
Square feet	*929.03	Square centimeters
Square feet	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	*0.40469	Hectares
Acres	*4.0469	Square meters
Acres	*0.0040469	Square kilometers
Square miles	2.58999	Square kilometers
VOLUME		
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
CAPACITY		
Fluid ounces (U.S.)	29.5737	Cubic centimeters
Fluid ounces (U.S.)	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
Liquid pints (U.S.)	0.473166	Liters
Quarts (U.S.)	*946.358	Cubic centimeters
Quarts (U.S.)	*0.946331	Liters
Gallons (U.S.)	*3.785.43	Cubic centimeters
Gallons (U.S.)	3.78543	Cubic decimeters
Gallons (U.S.)	3.78533	Liters
Gallons (U.S.)	*0.00378543	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
Gallons (U.K.)	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	*764.55	Liters
Acre-feet	*1,233.5	Cubic meters
Acre-feet	*1,233,500	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
Short tons (2,000 lb)	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
Pounds per square inch	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
Pounds per square foot	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
Pounds per cubic foot	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
Inch-pounds	1.12985 x 10 ⁶	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
Foot-pounds	1.35582 x 10 ⁷	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
Feet per second	0.3048 (exactly)*	Meters per second
Feet per year	*0.965873 x 10 ⁻⁶	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
Miles per hour	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second ²	*0.3048	Meters per second ²
FLOW		
Cubic feet per second (second-feet)	*0.028317	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	*0.453592	Kilograms
Pounds	*4.4482	Newtons
Pounds	*4.4482 x 10 ⁵	Dynes

Table II—Continued

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	*0.252	Kilogram calories
British thermal units (Btu)	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	*1.35582	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft ² degree F (k, thermal conductivity)	1.442	Milliwatts/cm degree C
Btu in./hr ft ² degree F (k, thermal conductivity)	0.1240	Kg cal/hr m ² degree C
Btu ft/hr ft ² degree F	*1.4880	Kg cal/hr m ² degree C
Btu/hr ft ² degree F (C, thermal conductance)	0.568	Milliwatts/cm ² degree C
Btu/hr ft ² degree F (C, thermal conductance)	4.882	Kg cal/hr m ² degree C
Degree F hr ft ² /Btu (R, thermal resistance)	1.761	Degree C cm ² /milliwatt
Btu/lb degree F (c, heat capacity)	4.1868	J/g degree C
Btu/lb degree F	*1.000	Cal/gram degree C
ft ² /hr (thermal diffusivity)	0.2581	cm ² /sec
ft ² /hr (thermal diffusivity)	*0.09290	m ² /hr
WATER VAPOR TRANSMISSION		
Grains/hr ft ² (water vapor) transmission]	16.7	Grams/24 hr m ²
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	*304.8	Liters per square meter per day
Pound-seconds per square foot (viscosity)	*4.8824	Kilogram second per square meter
Square feet per second (viscosity)	*0.092903	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candle)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Milliuries per cubic foot	*35.3147	Milliuries per cubic meter
Milliamps per square foot	*10.7639	Milliamps per square meter
Gallons per square yard	*4.527219	Liters per square meter
Pounds per inch	*0.17858	Kilograms per centimeter

ABSTRACT

Described are preliminary results of investigations aimed at choosing and/or developing spray nozzles with primary application to cloud seeding with hygroscopic liquids in controlled spray sizes. Several types of nozzles are under investigation, including: air-operated nozzles, self-impinging jet nozzles, target-impinging jet nozzles, fan-type, and solid-cone type nozzles. Air-operated nozzles produce the smallest droplet sizes (less than $20\ \mu\text{m}$ mass median diameter), but tend to have a high noise level and higher initial and operating costs. Self-impinging jets and solid-cone nozzles produce droplets as small as about $50\ \mu\text{m}$ while target-impinging jets produce droplets down to about $25\ \mu\text{m}$. Tests on fan-type nozzles were too limited for conclusive results. Several methods of liquid injection were also investigated and sampling techniques were developed.

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REC-ERC-74-4

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Bur Reclam Rep REC-ERC-74-4, Div Gen Res, Mar 1974. Bureau of Reclamation, Denver, 38 p, 41 fig, 3 tab, 16 ref

DESCRIPTORS—/ weather modification/ *cloud seeding/ flow characteristics/ fluid mechanics/ jets/ supersonic flow/ compressible flow/ *nozzles/ *sprays/*particle size/ measurement/ research and development

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