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AN OIL-STREAM PHOTOMICROGRAPHIC AEROSCOPE FOR OBTAINING CLOUD LIQUID-WATER CONTENT AND DROPLET SIZE DISTRIBUTIONS IN FLIGHT

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SUMMARY

An airborne cloud aeroscope by which droplet size, size distribution, and liquid-water content of clouds can be determined has been developed and tested in flight and in wind tunnels with water sprays. In this aeroscope the cloud droplets are continuously captured in a stream of oil, which is then photographed by a photomicrographic camera. The droplet size and size distribution can be determined directly from the photographs. With the droplet size distribution known, the liquid-water content of the cloud can be computed from the geometry of the aeroscope, the airspeed, and the oil-flow rate.

The aeroscope has the following features: Data are obtained semiautomatically, and permanent data are taken in the form of photographs. A single picture usually contains a sufficient number of droplets to establish the droplet size distribution. Cloud droplets are continuously captured in the stream of oil, but pictures are taken at intervals. The aeroscope can be operated in icing and nonicing conditions. Because of mixing of oil in the instrument, the droplet-distribution patterns and liquid-water content values from a single picture are exponentially weighted average values over a path length of about 3/4 mile at 150 miles per hour.

The liquid-water contents, volume-median diameters, and distribution patterns obtained on test flights and in the Lewis icing tunnel are similar to previously published data.

INTRODUCTION

The determination of liquid-water content and droplet size distribution of natural and artificial clouds has received considerable attention in recent years in connection with cloud-physics studies and, in particular, with aircraft icing studies. A knowledge of the liquid-water content and droplet size distribution in clouds is of fundamental importance in evaluating aircraft operation problems such as rate and area of ice formation on various aircraft components, rate and area of erosion by cloud droplets of various aircraft surfaces such as radomes, reduction of pilot's visibility, and attenuation of radar. A knowledge of liquid-water content and droplet size distribution is also of importance in establishing the basic mechanisms of cloud formation and precipitation.

Numerous methods and techniques for determining liquid-water content or droplet size or both have been proposed in recent years (refs. 1 to 18), but each method suffers from one or more limitations, which, in some cases, become severe when measurements are attempted from an airplane. The three most common techniques that have been used are rotating multicylinders, cloud cameras, and oil-covered slides.

The rotating-multicylinder technique for supercooled clouds (refs. 19 to 23) has provided data that have been valuable in designing ice-protection systems for airplanes, but there are limitations to the technique for aircraft icing studies and for cloud-physics studies in general. The method is based upon the impingement of droplets on cylinders where the air flow past the cylinders is ideal nonviscous laminar flow, which is not the case in practice (ref. 24). Also, the method is applicable only in clouds where the temperature is below 0° C; however, at temperatures slightly below freezing there may be considerable error in liquid-water content and droplet size measurements due to loss of water by run-off before freezing occurs (ref. 25). The method does not lend itself to automatic recording of data, and droplet size distributions obtained are only approximations.

The use of cameras to directly photograph droplets in a cloud is basically a fundamental and sound technique, but there are practical difficulties. Because of the high magnification required, the volume of field photographed is extremely small. As a result, a large number of photographs are required to establish the droplet size distribution and liquid-water content, because the average number of droplets per picture is usually less than 1 for clouds of moderate liquid-water contents. Furthermore, since the magnification required is high, it is difficult to design a camera so that the object plane is outside the undisturbed airstream about an airplane.

The oiled-slide technique where a glass slide covered with a suitable oil is exposed to an airstream carrying cloud droplets and is then photographed through a microscope has been frequently used to determine droplet size distributions. Although this method yields good photographs with a large number of droplets per picture from which droplet sizes can be measured, there are some practical limitations that are difficult to overcome. The droplet size distribution determined from the photographs must be corrected for variations in collection efficiencies of the slide for droplets of various sizes in order to obtain the true droplet size distribution of a cloud. The collection efficiencies generally used for this correction are based upon those of a ribbon in ideal two-dimensional flow, which is not the case in actual practice. In order not to saturate the slide with droplets, the oiled slide cannot be exposed for more than a fraction of a second. This requires that the slide be moved rapidly or that a protective covering be opened and closed rapidly. This motion disturbs the air-flow field in the vicinity of the slide; therefore, the collection efficiencies of the slide are not the same as for a ribbon in ideal flow. This technique does not lend itself to automatic operation either.

Since all the methods proposed and tested have limitations when used in an airplane, a direct method that eliminates or substantially reduces these limitations is needed. As a result of this need, the oil-stream photomicrographic aeroscope has been developed and tested at the NACA Lewis laboratory. A description of this aeroscope is presented herein along with some cloud data obtained.

SYMBOLS

The following symbols are used in this report. Any consistent set of dimensions or mixed dimensions with numerical conversion factors can be used in the solution of equations presented herein.

A area of pickup hole

C number of droplets per unit volume of oil

d droplet diameter

F volume flow rate of oil

l sample path length

m mass of individual droplet

N number of droplets of uniform size per picture

n number of droplets of uniform size entering pickup hole per unit time

P fraction of total number of droplets in picture

t time

U airspeed

V_c cloud volume

V_M mixing volume

V_p volume of oil photographed

v_{cr} critical velocity

W_p total mass of water per picture for nonuniform droplet distribution

w liquid-water content of cloud in mass per unit volume

ρ_w density of water

PRINCIPLE OF OPERATION OF AEROSCOPE

Basically, the aeroscope continuously captures cloud droplets in a stream of oil that is caused to move through a thin channel where photomicrographs of the oil and water droplets are taken. The droplet size and distribution are determined by measuring the images on the photographs. After the droplet distribution is known, the liquid-water content of the cloud is calculated from the geometry of the instrument, the airspeed, and the oil-flow rate.

The principle of operation can best be described by reference to a schematic diagram (fig. 1). The aeroscope is composed of five main parts: droplet-pickup probe, circulating pumps for oil and air, transparent plastic photographic cell, light source, and a photomicrographic camera.

The droplet-pickup probe consists of a small-diameter tube with a small hole, which faces upstream to the air flow carrying the droplets. Oil is forced by a pump through the pickup probe in the direction indicated in the sketch. Oil is prevented from flowing out of the hole by means of the air pump. As the oil passes the small hole, any water droplets that enter are trapped in the oil. The oil containing the droplets then flows through the transparent plastic cell where the droplets are photographed with a photomicrographic camera. The channel through the plastic cell narrows at the point where the pictures are taken so that all the droplets are approximately in the object plane of the camera. After leaving the plastic cell the oil passes through a filter and trap where the water droplets are removed. The oil is then recirculated.

The air pump prevents oil from escaping by reducing the pressure in the small chamber at the top of the plastic cell with respect to the pressure at the pickup hole. This pressure difference causes air to enter the pickup hole and thus prevents oil from escaping. The air flow into the oil stream also aids the water droplets in entering. The air is entrained in the oil in the form of large bubbles, which are separated from the oil and water droplets in the funnel-shaped chamber at the top of the plastic cell. The air bubbles rise to the free oil surface where they burst. Under conditions where the pickup probe is exposed to a moving airstream, the dynamic pressure at the pickup hole is usually large enough to drive air into the oil stream if the plastic cell is vented to static pressure. However, with moderate airspeeds the pressure difference is so large that too much air enters the system. This causes violent turbulence in the air-separator chamber in the plastic cell with some air bubbles continuing through the photographic section. The air pump is therefore employed to act as a metering device that allows just enough air to enter the pickup hole to prevent oil from escaping.

BASIC THEORY FOR DETERMINING DROPLET SIZE, CLOUD-SAMPLE VOLUME, AND LIQUID-WATER CONTENT

In order to develop the basic theory for determining droplet size, size distribution, and liquid-water content of a cloud, the following assumptions are made:

(1) All droplets in the volume swept out by the projected area of the hole in the pickup probe enter the hole; that is, the collection efficiency of the hole is 100 percent.

(2) Droplets do not break when they graze the edge of the hole, enter the oil, or strike the rear surface on the inside of the probe.

(3) Droplets do not coalesce when entrained in oil.

(4) Droplets do not change size by diffusion or evaporation after they are entrained in the oil.

(5) Droplets maintain their relative positions while they are being entrained in the oil and being transported to the photographic region in plastic cell.

The validity of these assumptions and other possible errors are evaluated in a later section.

Droplet Size

The determination of the droplet size and size distribution is a straightforward procedure. The droplet-image diameters are measured on the negative or enlargement with a suitable scale. The image size is divided by the over-all magnification to give the actual droplet size. The frequency of occurrence of droplets of a given size or size range can be tabulated, and other computations can be made from the tabulation.

Cloud-Sample Volume

Under assumption (5) the droplet distribution obtained from a picture represents the droplet distribution in a given small volume of cloud. This cloud volume V_c is related to the volume occupied by the droplets in the photographic cell V_p where the picture is taken by

$$V_c = \frac{AUV_p}{F} \tag{1}$$

The quantity AU/F can be looked upon as a concentration factor. It is equal to the ratio of the volume occupied by a given number of droplets in air to the volume occupied by the same droplets in oil V_c/V_p.

Because of mixing in the air-separator chamber and other factors, the droplet size distribution and liquid-water content derived from a given picture represent average values for a much larger volume of cloud than that given by equation (1). The effect of mixing and other factors on the sample volume is discussed in a later section.

Liquid-Water Content

If a cloud is composed of droplets of uniform size, the number of droplets that enter the pickup hole per unit time is given by

$$n = \frac{w}{m} (AU) \tag{2}$$

Dividing equation (2) by the oil volume flow rate F gives the number of droplets per unit volume of oil C:

$$C = \frac{n}{F} = \frac{w}{m} \frac{AU}{F} \tag{3}$$

The number of droplets per picture is obtained by multiplying equation (3) by the volume of oil photographed (focal volume of camera). The result is

$$N = CV_p = \frac{w}{m} \frac{AUV_p}{F} \tag{4}$$

Solving equation (4) for the liquid-water content w gives

$$w = \frac{mNF}{AUV_p} \tag{5}$$

In equation (5) the product Nm is the total mass of water represented by the picture. For clouds with a nonuniform droplet size distribution, the total mass of water in a picture W_p is given by

$$W_p = \frac{1}{6} \pi\rho_w \sum n_i d_i^3 \tag{6}$$

Substitution of equation (6) into equation (5) for Nm gives

$$w = \frac{\frac{1}{6} \pi\rho_w F \sum n_i d_i^3}{AUV_p} \tag{7}$$

which is the liquid-water content for a cloud with a nonuniform droplet size distribution.

DESCRIPTION OF TEST MODEL OF AEROSCOPE

A cloud aeroscope based upon the operating principles and theory outlined in the preceding sections was constructed and tested in a two-engine transport aircraft and in wind tunnels with water sprays at the NACA Lewis laboratory. Photographs of the instrument installed on the airplane are presented in figures 2 and 3. Figure 2 shows the main part of the instrument, which is located inside the cabin. Figure 3 shows the pickup probe mounted on a streamlined strut on the outside of the fuselage. The mounting strut is slightly off center on top of the fuselage and approximately 10 feet behind the windshield.

Pickup Probe

A high collection efficiency of the pickup hole requires that the probe size be small. One probe consists of a piece of 1/8-inch-outside-diameter tubing with 1/32-inch wall, which is bent in the form of a "U." The pickup hole is 0.040 inch in diameter and is located on the outside of one of the legs of the "U" about midway between top and bottom. This probe was used in wind tunnels at temperatures above freezing. A second probe was constructed in the form of an airfoil with a chord length of 1/2 inch and maximum thickness of 5/32 inch. The length of the probe is 4 inches, and the pickup hole is 0.040 inch in diameter and is located $1\frac{1}{2}$ inches from the top of the probe on the leading edge of the airfoil.

This probe contains a U-shaped channel through which the oil is circulated. A heater element consisting of about 8 inches of number 26 Nichrome wire is located between the oil passages. The maximum heat output is approximately 22 watts. This probe was used in flight in icing and nonicing conditions. In icing conditions the heater voltage was adjusted so that the probe temperature was about 40° F. Schematic drawings of the two probes are presented in figure 4. The pickup probe was mounted on a streamlined strut on the airplane so that the pickup hole would be in the undisturbed airstream (fig. 3). The distance from fuselage to pickup hole was about 18 inches.

Pickup probes of tubing smaller than 1/8-inch outside diameter were constructed and used successfully. However, some difficulties arise when the probe is too small in diameter. If the pickup hole is large compared to the probe tubing, the edges of the hole extend in a circumferential direction into the low-pressure region of the flow. As a result, oil is sucked out through the pickup hole. However, if the hole is small, the number of droplets entering is very low.

Photographic Cell

The photographic cell is composed of two pieces of transparent plastic and is divided into two main parts, the air-separator chamber and the photographic region. The cover plate is attached to the body of the cell by machine screws along the edges. The cover plate could be removed from the body so that the internal channels could be cleaned without disturbing the focus. The details of construction of the cell are presented in figure 5. The oil, water, and air mixture is conducted from the pickup probe to the cell through approximately 100 inches of 1/16-inch-inside-diameter copper tubing. The mixture enters the cell near the bottom of the V-shaped air-separator chamber (fig. 5). The air bubbles, being very much less dense than the oil, rapidly rise to the free oil surface where they burst. The air is removed from the chamber by the air pump. In rising to the top the bubbles are tumbled by the steplike protuberances so as to detach any water droplets that might be suspended at the oil-air interface. Most of the droplets, however, because of their original direction of velocity and because they are slightly denser than the oil, move straight downward towards the photographic region, which is located below the air-separator chamber. In the photographic region the oil and water droplets flow through a thin channel so that all droplets are confined to the focal volume of the camera. The channel dimensions in the test model of the aeroscope are 0.008 inch in the direction of the optical axis and 0.1 inch at right angles.

Camera

The camera is composed of a microscope and a film-transport mechanism. In the test model the microscope with a 32-millimeter objective and a 12.5-power hyperplane eyepiece is mounted inside a cone-shaped metal housing (fig. 2), which is attached to the film transport mechanism from a K-24 aerial camera. This combination of lenses and other geometry gives an over-all magnification of X45 at the film. With this magnification the entire droplet-channel width, 0.1 inch, is photographed. The camera is focused by sliding the plastic cell on two rods that are rigidly attached to the cone-shaped metal housing of the camera. These rods also support the light source.

Light Source

The light source consists of a condensing lens and a high-pressure mercury lamp. The lamp is powered by a high-voltage power supply. The light source and condensing lens are arranged for bright field illumination, with the light source focused onto the central portion of the objective lens of the camera. The light source is operated as a flash unit with the main peak of illumination lasting about 4 microseconds. A flash is used instead of a shutter because the droplet velocity through the object field is so high that a shutter cannot stop the droplet motion. Droplets move about 0.7 micron during the 4-microsecond flash.

Intervalometer

An aircraft-camera intervalometer is used to flash the light source and to advance the film in the camera. The intervalometer can be set to take pictures at any time interval from 1 to 80 seconds. However, the minimum time interval at which pictures can be taken is about 10 seconds, as this is the time required for the condenser in the light-source power supply to recharge.

Filter and Water Trap

The filter and water trap consists of a chamber of about 2-cubic-inch capacity filled with cotton. The cotton removes solid particles from the oil such as dust and impedes the motion of droplets in a horizontal direction so that they settle to the bottom of the chamber where they are trapped. The effectiveness of the trap and filter was checked in tunnel operation of the aeroscope by taking pictures after the spray was turned off.

Oil Pump

The oil pump is a specially designed positive-displacement, constant-volume, low-flow-rate pump, consisting of three metallic bellows connected in series with stopcock valves between them. A cam and lever arrangement changes the internal volume of the bellows and positions the stopcock valves in such a manner as to produce uniform positive inflow and outflow. The pump is designed so that by changing gear ratio between motor and pump, flow rates from 2.08 to 12.46 cubic centimeters per minute could be obtained. The volume flow rate used in the test-model aeroscope was 5.34 cubic centimeters per minute. This low flow rate was chosen as a compromise between the number of droplets per picture (eq. (4)) and the time required to move the oil from the pickup hole to the plastic cell. The pump is driven by a 1/50-horsepower 110-volt 60-cycle motor. The weight of the pump and motor is less than 10 pounds, which is considerably less than commercially available constant-volume, uniform-low-flow-rate pumps that are usually designed to deliver fluid at high pressures.

Air Pump

The air pump is a fluid-metering pump designed to deliver 2 gallons per hour. It is equipped with a 24-volt direct-current motor, but in the aeroscope it is operated on a variable alternating current over a range from 6 to 24 volts. The flow rate of this pump is adjusted so that enough air enters the pickup hole to prevent oil from flowing out. Loss of oil is detected by a lowering of the oil level in the air-separator chamber in the plastic cell. The air pumping rate, however, is kept sufficiently low that no violent turbulence is caused in the separator chamber. The air pump is exhausted into the oil reservoir, because during charging of the aeroscope with oil some oil flows through this pump.

Oil

The oil used in the aeroscope is a mixture composed of the following components: four parts of SAE number 20 motor oil, four parts of Varisol, and one part of 10-centistoke silicone oil. This mixture has a fairly low viscosity, which allows the air bubbles in the separator chamber to escape rapidly, and has a density less than that of water.

Charging Aeroscope with Oil

The system is charged with oil by turning the three-way stopcock (fig. 1) so that the oil pump is connected to the reservoir as well as to the filter and trap. Because of the restricted channel through the plastic cell, most of the oil entering the oil pump comes from the reservoir. During the charging process the air-separator chamber may fill up. The excess oil is then removed by the air pump. When charging an empty system, some air may be trapped in the filter and water trap. This trapped air can cause air bubbles to travel in the reverse direction through the plastic cell when the air pressure is reduced at the droplet-pickup hole, such as during ascent in an aircraft. Most of this air can be removed, however, by increasing the flow capacity of the air pump during the charging process.

EVALUATION OF ASSUMPTIONS AND POSSIBLE ERRORS

Collection Efficiency of Pickup Hole

The assumption that all the droplets in the volume swept out by the projected area of the pickup hole enter the hole is not strictly true. However, for small pickup probes such as the ones described herein, the over-all collection efficiency of the hole is high. For example, the collection efficiency of a 0.040-inch-diameter hole on the leading edge of a piece of 1/8-inch-outside-diameter tubing at an airspeed of 150 miles per hour, temperature of 20° F, and 5000-foot pressure altitude for 5-micron droplets is between 0.78 and 0.81; for 10-micron droplets, between 0.88 and 0.91; and for 20-micron droplets, between 0.94 and 0.97. These values are based on droplet trajectory data presented in reference 2 for impingement of droplets on a cylinder.

The collection efficiencies of the pickup hole in the small airfoil probe used on the flight model of the aeroscope for these same conditions are approximately 0.82, 0.91, and 0.96, respectively. These values are based on unpublished data for droplet impingement on a 36-percent-thick Joukowski airfoil. The values are approximate because the pickup probe is not a true Joukowski airfoil, and it is only 31-percent thick. A factor that may increase the collection efficiency of the pickup hole over that for a cylinder or airfoil is the slight flow of air into the hole. The magnitude of this effect is unknown, however. With the collection efficiencies of the pickup hole known for various droplet sizes, the droplet-size-distribution pattern obtained from a picture can be corrected to give the true droplet distribution.

Droplet Breakup

There are two possible causes of droplet breakup: Droplets may strike the edge of the pickup hole and be shattered, or they may break upon penetrating the oil-air interface. Calculations indicate that droplets of cloud size at moderate airspeed do not have enough inertia to travel through the oil and strike the rear surface of the oil channel with enough force to cause breakup.

What happens to a droplet when it strikes the edge of the pickup hole is not known. This source of possible droplet breakup is not too serious, however, since for a large pickup hole compared to cloud droplet size the percentage of total number of droplets in the path of the hole that enter without striking the edge is high. The percentage of droplets that enter a 0.040-inch-diameter hole without striking the edge as a function of droplet diameter is presented in figure 6. These percentages are based upon straight-line droplet trajectories in the volume swept out by the pickup hole. If droplets are broken, the possibility is very high that the portion of the original droplet nearest the center of the pickup hole will enter the hole; and, since there is a slight air flow into the hole, it is possible that some of the remainder will enter also.

Little is known about droplet breakup as droplets penetrate an oil-air interface. A study of water droplets penetrating kerosene is reported in reference 26. The range of droplet diameters covered in this study was from 400 to 125 microns. The relation between critical velocity of impact and droplet diameter was found to be

$$v_{cr} = \frac{1725}{d}$$

where the critical velocity in meters per second is the velocity above which droplets of diameter d in microns break up. If it is assumed that the oil mixture used in the test-model aeroscope is similar to kerosene (Varisol is a hydrocarbon similar to kerosene) and the previous relation for critical impact velocity holds true for smaller droplets, then droplet breakup for the aeroscope can be expected to occur for droplets larger than 27 microns. The impact velocity was based upon velocities of impact at a stagnation point of a cylinder as given in reference 1 for a 1/8-inch cylinder traveling at 150 miles per hour at a 5000-foot altitude and a temperature of 20° F. Reference 26 indicates that at velocities slightly above critical the droplets break into two parts, a comparatively large mass accompanied by a very small satellite; as the impact velocity is further increased, the satellite becomes larger and larger until the two droplets are the same size. At this point another small satellite appears. Whether or not the results of reference 26 are applicable to the present instrument is further complicated by the fact that in the aeroscope the droplets enter the pickup hole with a small volume of air, whereas in the experimental investigation the droplets penetrated the oil surface directly. This small volume of air may produce a cushioning effect, which would retard droplet breakup.

Droplet breakup, if present, should not appreciably affect liquid-water-content measurements, but would affect the droplet-distribution patterns if a large number of large droplets were present in the cloud. Liquid-water-content calculations could be in error if the breakup resulted in a large number of droplets that are too small to be seen on the photographs. Determination of errors in droplet size distribution and liquid-water content caused by droplet breakup is difficult, because there is no good independent method of measuring these quantities. Errors due to breakup should not be any more serious with this instrument than with the oiled-slide technique, and they are probably less serious.

Droplet Coalescence

Coalescence of droplets in the oil is not very likely, because the space between droplets is large compared to the droplet size. Wide spacing of droplets is accomplished by proper choice of oil-flow rate, size of pickup hole, and airspeed. Visual observations of droplets settling in still oil showed that droplets could come in contact without coalescing.

Diffusion and Evaporation

Change of size of droplets by diffusion and evaporation after entrainment in oil is probably negligible in the aeroscope for two reasons: First, the oil in the system is probably saturated with water because it is recirculated after droplets have been removed by the filter and trap; second, the time between a droplet's entering the oil and the taking of a picture is less than a minute. Furthermore, the oil is enclosed in a tube, which protects it from a dry atmosphere that would promote evaporation such as occurs on oiled slides in a heated room.

Sample Volume

If the dimension of the pickup hole is very small in the direction of the oil flow and there is no change of relative position of droplets after they are entrained in the oil, then equation (1) gives the volume of cloud space that the droplets in a picture occupy. Since the area of the pickup hole is constant and known, equation (1) may be reduced to a sample path length l by dividing by the area of the pickup hole. The result is

$$l = \frac{UV_p}{F}$$

which gives for the test-model aeroscope at an airspeed of 150 miles per hour a sample path length of about 3.6 feet. However, because of three inherent features of the aeroscope, the sample path length is longer than this value, and the droplet distribution obtained from a picture is an average value over this longer path length. The reasons for this averaging process are: finite size of pickup hole in direction of oil flow, different settling velocities of water droplets of different sizes in oil, and mixing of oil and droplets in the air-separator chamber.

The pickup hole produces an averaging effect because droplets that enter the pickup hole near the downstream side of the hole are entrained in the oil with droplets that entered the hole on the upstream side a short time before. However, this averaging effect is very small. For the test-model aeroscope the sample path length becomes 4.9 feet.

In the region from the pickup hole to the air-separator chamber in the transparent plastic cell, different settling velocities for droplets of different sizes are the major cause of change of relative positions of droplets. For the test-model aeroscope the averaging effect produced by this factor is somewhat larger than that caused by the pickup hole. For example, the settling velocity of a 100-micron-diameter droplet in the oil used is of the order of 1 inch per minute. The velocity of the oil, water droplets, and air bubbles is probably 200 inches per minute or more. The absolute velocity depends upon the amount of air entrained in the oil. The velocity for oil alone is 107 inches per minute. The distance from pickup hole to air-separator chamber is about 100 inches. Thus, the time of transit of a droplet is approximately 30 seconds. Therefore, a 100-micron droplet would arrive at the air-separator chamber 1/2 inch ahead of the oil that it entered at the pickup hole. In other words, it would arrive at the air-separator chamber with oil that passed the pickup hole 0.005 minute before the droplet entered. If a small droplet entered the oil at time zero and traveled with the oil, a 100-micron-diameter droplet that entered 0.005 minute later would arrive at the air-separator chamber at the same time. If the airspeed is 150 miles per hour, the original distance in the cloud between the large and small droplets was 66 feet.

When the oil carrying the water droplets and air bubbles enters the air-separator chamber, some mixing occurs that further increases the path length over which the droplet distribution is averaged. If complete mixing occurs in the air-separator chamber, for any picture the fraction of the total number of droplets in the picture P that have been in the chamber for a period of time t or less is given approximately by

$$P = 1 - e^{-\frac{F}{V_M} t} \tag{8}$$

The total volume of the air-separator chamber is approximately 0.17 cubic inch. In operation, however, the oil level is adjusted so as to fill about half this volume. Visual observation of the aeroscope in operation indicates that most of the mixing occurs in the volume of oil between the entrance tube and the exit at the bottom. This volume is about 0.03 cubic inch. The mixing, however, is not complete in this region either, because most of the droplets are projected straight downward towards the exit because of their initial velocity of entrance into the chamber. This direction of motion is also aided by the difference in density of oil and water. The greatest mixing occurs for the very small droplets. However, if it is assumed that complete mixing occurs in a volume of 0.03 cubic inch and the oil-flow rate is 0.326 cubic inch per minute, then equation (8) becomes

$$P = 1 - e^{-10.8\ t}$$

This equation is plotted in figure 7, which shows that 0.95 of the droplets in a picture were in the air-separator chamber 0.3 of a minute or less. Some of the droplets, however, may theoretically have been in the chamber for an infinitely long time. Three-tenths of a minute at 150 miles per hour gives a path length of 3/4 mile from which 0.95 of the droplets in a picture were captured. This mixing in the air-separator chamber produces an exponentially weighted average value over a much longer sample path length than the other two factors considered; therefore it can be considered as the only factor.

The averaging distance or sample path length can be made smaller by decreasing the mixing volume or increasing the oil-flow rate. Decreasing the mixing volume is probably possible. The only limitation is that the volume be large enough that air bubbles can escape before they are pulled into the photographic area. Increasing the oil-flow rate is possible, but as oil-flow rate is increased the number of droplets per picture is reduced.

Limitations of Camera

The magnification of the camera in the test-model aeroscope was checked by photographing fine wires of known diameter. The magnification was X45 with an error of approximately ±2.5 percent. The resolving power and circle of confusion for the objective lens of the camera are about 5 microns. These values are calculated from theory and are based on a depth of field of 0.008 inch.

The focal volume of the aeroscope is defined by the dimensions of the channel through the plastic cell and the size of the picture in the direction of oil flow. For the test model, the focal volume was 88×10^{-6} cubic inches with a probable error of ±3 percent.

Other Errors

Other sources of error that may affect liquid-water-content measurements are variations in oil-flow rate, size of pickup hole, and variations in airspeed during sampling period. In the test model of the aeroscope, the oil-flow rate is 0.326 cubic inch per minute with a probable variation of ±2 percent. The size of the pickup hole may be slightly larger than the specified 0.040 inch, since it was drilled with a 0.040-inch drill and was not measured.

Over-All Accuracy of Liquid-Water-Content Measurements

The over-all accuracy of liquid-water-content measurements depends upon the accuracy with which the several parameters of equation (7) can be determined or measured. The accuracy of most of these parameters has been discussed in the preceding sections. Determination of the possible error in the total water content represented by a picture $\left(1/6\ \pi\rho_w \sum n_i d_i^3\right.$ of eq. (7)$\left.\right)$, however, is difficult because there are several sources of error, some of which are: failure to measure and count droplets, error in measuring droplet diameters, and grouping of droplet sizes into class intervals for summation.

Failure to measure a droplet will usually occur with small droplets, 5 microns or less. This source of error is not too serious if the droplet size distribution is broad, with a volume-median diameter of the order of 15 microns. Errors in measuring droplet diameters may be either random or systematic, or both. Systematic errors in measured diameters may be due to error in determining the over-all magnification or to bias on the part of the analyst in determining the edges of a droplet image. A systematic error would be greatest in percent for small droplets, but again the error in total water would be small if the droplet size distribution is broad with a fairly large volume-median diameter. The magnitude of the error caused by grouping droplet sizes into class intervals for summation depends upon the shape of the droplet size distribution. This error can be either positive or negative.

An evaluation of the probable random error in liquid-water-content measurement was made for typical droplet size distributions and was found to be ±8 percent with a highest possible value of probable random error of ±17 percent. These values were based upon known and estimated probable errors for each of the various parameters involved in equation (7).

PROCEDURE FOR OBTAINING AND REDUCING DATA TO USEFUL FORM

Liquid-water-content and droplet size-distribution measurements were made with the aeroscope in the NACA Lewis icing tunnel and in flight with a two-engine transport aircraft. The in-flight measurements were made on routine cross-country flights. The instrument was put into operation in clear air and a few pictures were taken. These pictures were later used to determine permanent images that might be mistaken for droplets. These pre-cloud pictures also served to indicate whether there were any air bubbles being pulled through the cell into the area being photographed. After sprays were turned on, or after entry into clouds, a series of 5 to 10 pictures was taken at intervals of 10 seconds. A series of pictures is hereinafter referred to as a "run." While the pictures were being taken automatically, the average flight speed, altitude, air temperature, time, and other general conditions were recorded. Runs were made in the icing research tunnel for various spray conditions. In flight runs were made when it was noted that conditions had changed or when conditions were thought to have changed. This procedure was adopted in order to conserve film and still obtain representative data from widely separated positions in the cloud and under different conditions. The oil flowed continuously between runs.

After the film was developed, negatives were selected for making enlarged prints. The over-all magnification of the enlarged glossy prints was made X101.6, so that 0.02 inch on the print was equivalent to 5 microns. The droplet-image diameters were measured to the nearest 0.02 inch from these prints by means of a scale with 0.02-inch divisions after the permanent images had been checked off. All images less than 5 microns were grouped in the 5-micron class. After the droplet-distribution pattern for a picture was established, the liquid-water content was calculated by equation (7). Some typical droplet pictures are presented in figure 8.

DROPLET SIZE DISTRIBUTIONS AND LIQUID-WATER-CONTENT MEASUREMENTS

Icing Tunnel

Droplet size distributions in the form of cumulative liquid-water-content curves for three spray conditions in the icing tunnel are presented in figure 9. Also presented in the figure are droplet distributions obtained by the dye-tracer technique described in reference 24. Although the droplet distributions obtained by the two methods are for the same spray conditions (air-water pressure ratios), there is not complete agreement. The best agreement occurs for the 0.6 and 0.8 pressure ratios. For the 0.8-pressure-ratio conditions, the aeroscope gives for any droplet size slightly higher values of cumulative liquid-water content than the dye-tracer technique; whereas, for the 0.6-pressure-ratio conditions, the reverse is true. The greatest disagreement occurs for the 0.5-pressure-ratio condition. For this spray condition the cumulative liquid-water content for a given droplet size as given by the aeroscope is about 0.1 gram per cubic meter less than that given by the dye-tracer technique. This disagreement appears to be a result of the fact that the large droplets (32 to 50 microns) indicated by the dye-tracer technique were not detected by the aeroscope. The disagreement between droplet distribution obtained by the two methods is probably due to the difference in size of the volume of cloud sampled. The projected frontal areas of the blotter paper used in the dye-tracer technique is extremely large compared to the pickup hole in the aeroscope probe. As a result, any local inhomogeneities in droplet size distribution in the spray cloud will be masked in the dye-tracer technique, since it obtains data from a much larger volume of cloud than the aeroscope.

The distribution curves of figure 9 are not extended to zero droplet size, because both methods are unreliable in the small-droplet size range. The aeroscope is unreliable for droplets less than 5 microns in diameter, whereas the minimum droplet diameter for which the dye-tracer technique is reliable is of the order of 10 microns.

In-Flight

Twenty-one droplet-size-distribution patterns and liquid-water-content determinations obtained on three flights are presented in tables I and II along with other pertinent information. Table I gives the droplet-size-distribution patterns in the form of frequency of occurrence of droplets in a given size range. Values of liquid-water content, volume-median droplet size, and median droplet diameter for the 21 droplet distributions are presented in table II. Also presented in table II are the flight and meteorological conditions. Each droplet size distribution presented in table I is based upon a single picture. The data presented in tables I and II were not corrected for collection efficiency of the pickup probe. An interesting feature of the data presented in table II is the consistency of the median droplet diameter for any particular day, while the liquid-water content and volume-median droplet diameter vary over a fairly wide range. (The median droplet diameter is that diameter for which 50 percent of the total number of droplets are larger; whereas, the volume-median droplet diameter is that for which 50 percent of the total liquid-water content is in larger droplets.) The volume-median droplet diameters for the three flights are in the same range as previous measured values (refs. 19 to 23). The volume-median droplet diameter of 37.0 microns for flight 1, run 3, picture 2, is rather large and is the result of two large droplets. Liquid-water contents and volume-median droplet diameters for supercooled clouds (flight 3) are in the same range as values obtained by rotating multicylinders (refs. 19 to 23). The liquid-water-content values measured on October 27, 1954 (flight 1) are rather high compared with the values obtained on the other two flights, but they are not unreasonable, since the temperature was 8° to 10° C above freezing. Theory indicates that the maximum water content of a cloud increases with increasing temperature.

The free-air temperature indicator was inoperative on flight 3, so that temperature values given in table II for this flight are approximate, as they were calculated from pickup-probe temperature at the base of the clouds after the de-icing heater was turned off.

The droplet distributions of table I are presented as dimensionless cumulative volume distributions in figure 10. The distributions were made dimensionless by dividing the droplet diameter by the volume-median diameter, and the cumulative liquid-water content by the total liquid-water content. Also shown in figure 10 for comparison are two hypothetical droplet distributions proposed by Langmuir in reference 1 for use with rotating multicylinders. The hypothetical distributions shown are "B" and "E." Most of the data for the three test flights fall in between these two distributions except a few distributions for flight 1 which were somewhat broader. The hypothetical volume distributions contain a single modal value, whereas some of the flight data have more than one modal value.

CONCLUDING REMARKS

Determination of droplet size and liquid-water content with the aeroscope described herein is a direct procedure; therefore, data obtained by it are probably more reliable than those obtained by indirect methods such as rotating cylinders. The probable random error in liquid-water content measurement is estimated to be ±8 percent. The aeroscope concentrates the droplets from a small volume of cloud into a much smaller volume of oil to such an extent that one picture usually contains enough droplets to establish a distribution. Because of mixing in the air-separator chamber the liquid-water content and droplet size distributions arrived at from a single picture are average values over a sample path length of approximately 3/4 mile. Values of liquid-water content and droplet size obtained on test flights are similar to values obtained by other methods. The aeroscope may be operated at any altitude and temperature and over a large range of airspeeds.

The test model of the aeroscope occupies about 6 cubic feet and weighs about 100 pounds. These values could be greatly reduced in future designs, since little attention was paid to weight and volume in the design of the test model. The test model of the aeroscope is semiautomatic in that pictures are taken automatically by the use of an intervalometer. The aeroscope could be made more fully automatic by photographing on the same film as the droplets an instrument panel containing a clock, airspeed indicator, altimeter, and temperature indicator.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 24, 1955

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TABLE I. - DROPLET FREQUENCY DISTRIBUTIONS

Flight	Run	Picture	Number of droplets																		
			Droplet size range, microns																		
			0-7.5	7.6-12.5	12.6-17.5	17.6-22.5	22.6-27.5	27.6-32.5	32.6-37.5	37.6-42.5	42.6-47.5	47.6-52.5	52.6-57.5	57.6-62.5	62.6-67.5	67.6-72.5	72.6-77.5	77.6-82.5	82.6-87.5	87.6-92.5	92.6-97.5
1 (10/27/54)	1	3	148	293	225	85	16	2	1		1										
	2	5	94	243	220	95	25	3		1											
	3	1	45	161	155	57	21	3	4	3					1						
		2	32	166	173	77	20	3	1	2	1									1	1
		6	43	191	183	63	16	4	1												
	4	1	47	99	104	43	14	5	1												
		4	58	124	127	65	13	2													
	5	1	99	306	219	99	27	7	4	1	1					1					
		2	81	326	248	103	29	4	2	1	2	1					1				
		3	97	269	203	84	15	1	2	1	2	1	1								
		4	128	256	236	110	21	4	1						1						
		5	171	345	313	104	18	3	2				1								
2 (12/1/54)	5	1	68	79	32	14	6	2													
		2	83	91	42	12	7	1													
		3	116	125	23	13	9	2			1										
		4	76	94	32	14	9	1	1												
3 (1/19/55)	1	1	41	49	10																
		4	45	79	8																
	3	2	86	139	16	2															
		3	94	142	31	1															
	4	1	50	88	12																

TABLE II. - SUMMARY OF FLIGHT DATA

Flight	Pressure altitude, ft	Cloud type (a)	Run	Time, e.s.t.	Air-speed, mph	Temperature, °C	Picture	Total number of drop-lets	Liquid-water content, g/cu m	Median droplet diameter, microns	Volume-median droplet diameter, microns	Location and remarks
1(10/27/54)	5300	Cu	1	6:25 a.m.	135	10	3	771	1.6	11.6	17.7	Runs 1 to 4 were taken over eastern Ohio and western Pennsylvania, run 5 over south central Pennsylvania. Flight was in warm sector ahead of cold front. Runs 1 to 3 were in cumulus buildup from broken strato-cumulus layer, the top of which was estimated at 4000 ft. Tops of cumulus towers appeared to be in a higher overcast layer, which was estimated at 8000 ft. Light rain was encountered during run 3. Clouds were thin during run 4. Run 5 was probably in a prefrontal squall line, as the turbulence was from light to moderate. No rain was encountered during run 5.
			2	6:35 a.m.	145		5	681	1.5	12.5	18.5	
			3	6:43 a.m.	140	8	1	450	1.5	12.9	21.8	
							2	477	2.5	13.6	37.0	
							6	501	1.2	12.8	17.9	
		Sc	4	7:00 a.m.	143	8	1	313	0.8	12.8	19.4	
							4	389	.9	13.0	18.7	
		CuCon	5	7:25 a.m.	145	9	1	764	2.1	12.3	20.7	
							2	798	2.3	12.4	20.7	
							3	676	1.7	12.1	19.4	
							4	757	1.8	12.5	18.9	
							5	957	1.9	12.2	17.7	
2(12/1/54)	6700	Sc	5	8:21 a.m.	150	10	1	201	0.3	9.2	18.8	Eastern Ohio - Post-cold-front strato-cumulus clouds. Light snowfall was occurring from clouds based at 2700 ft at takeoff from Cleveland at 8:01 a.m. Light aircraft icing was occurring during run 5.
							2	236	.3	9.4	17.3	
							3	289	.4	8.1	21.9	
							4	227	.3	9.2	20.4	
3(1/19/55)	3000	Sc	1	2:00 p.m	190	≈-10	1	100	0.04	8.1	11.7	Erie, Pennsylvania to Cleveland, Ohio - Post-cold-front strato-cumulus clouds. Cloud tops over Erie, 3500 ft, with temperature about -10° C. Clouds very thin during run 1. Clouds during runs 3 and 4 appeared thicker than during run 1. Cloud base at Cleveland was 1800 ft and surface temperature was ≈-2° C.
							4	132	.06	7.8	10.3	
	2700	Sc	3	2:05 p.m.	175	≈-8	2	243	0.17	7.9	11.3	
							3	268	.15	8.5	12.1	
	2900	Sc	4	2:09 p.m.	165	≈-9	1	150	0.08	8.2	11.3	

[a]Cu, cumulus; Sc, strato-cumulus; CuCon, cumulus congestus.

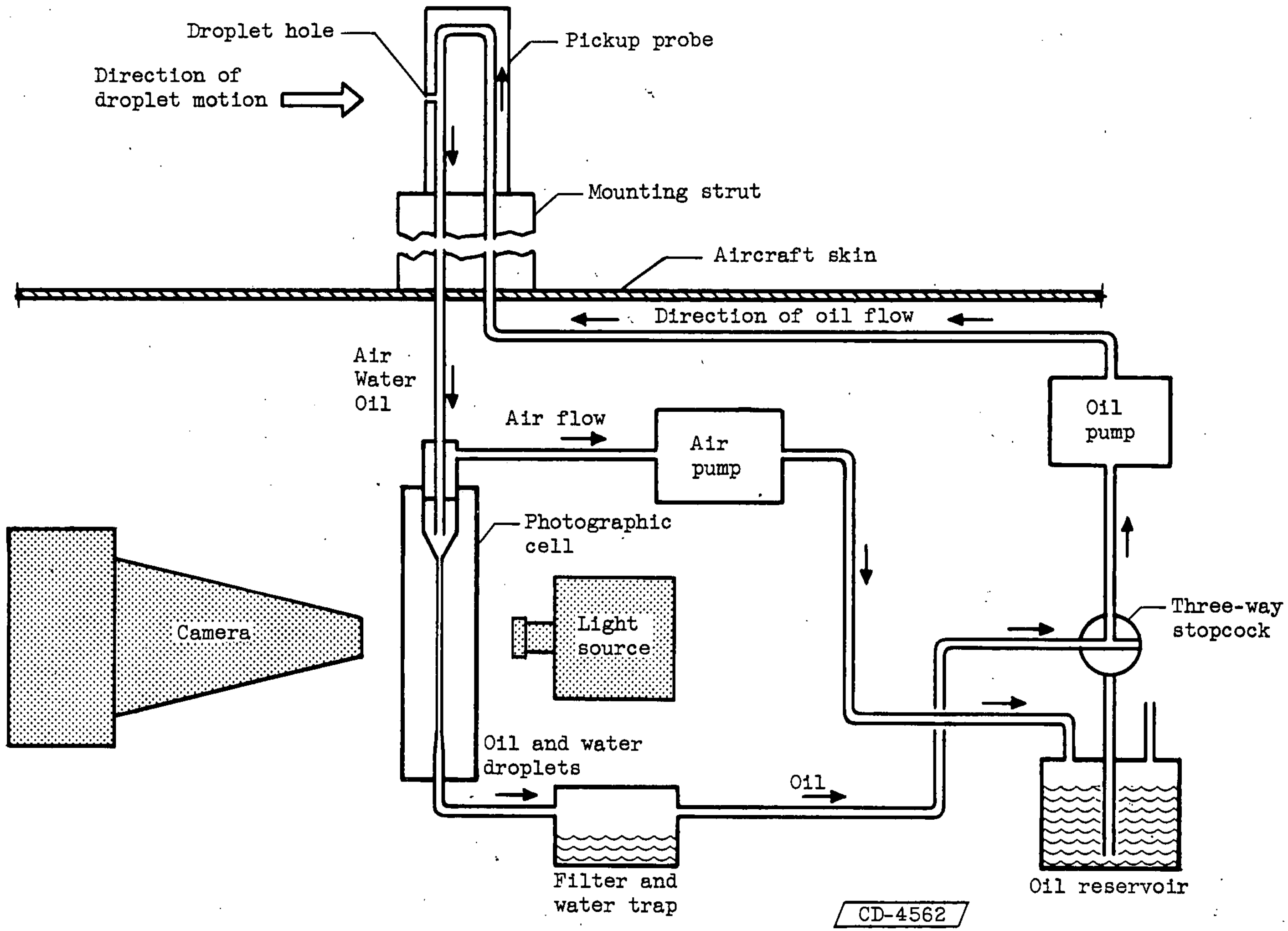


Figure 1. - Schematic diagram of aeroscope.

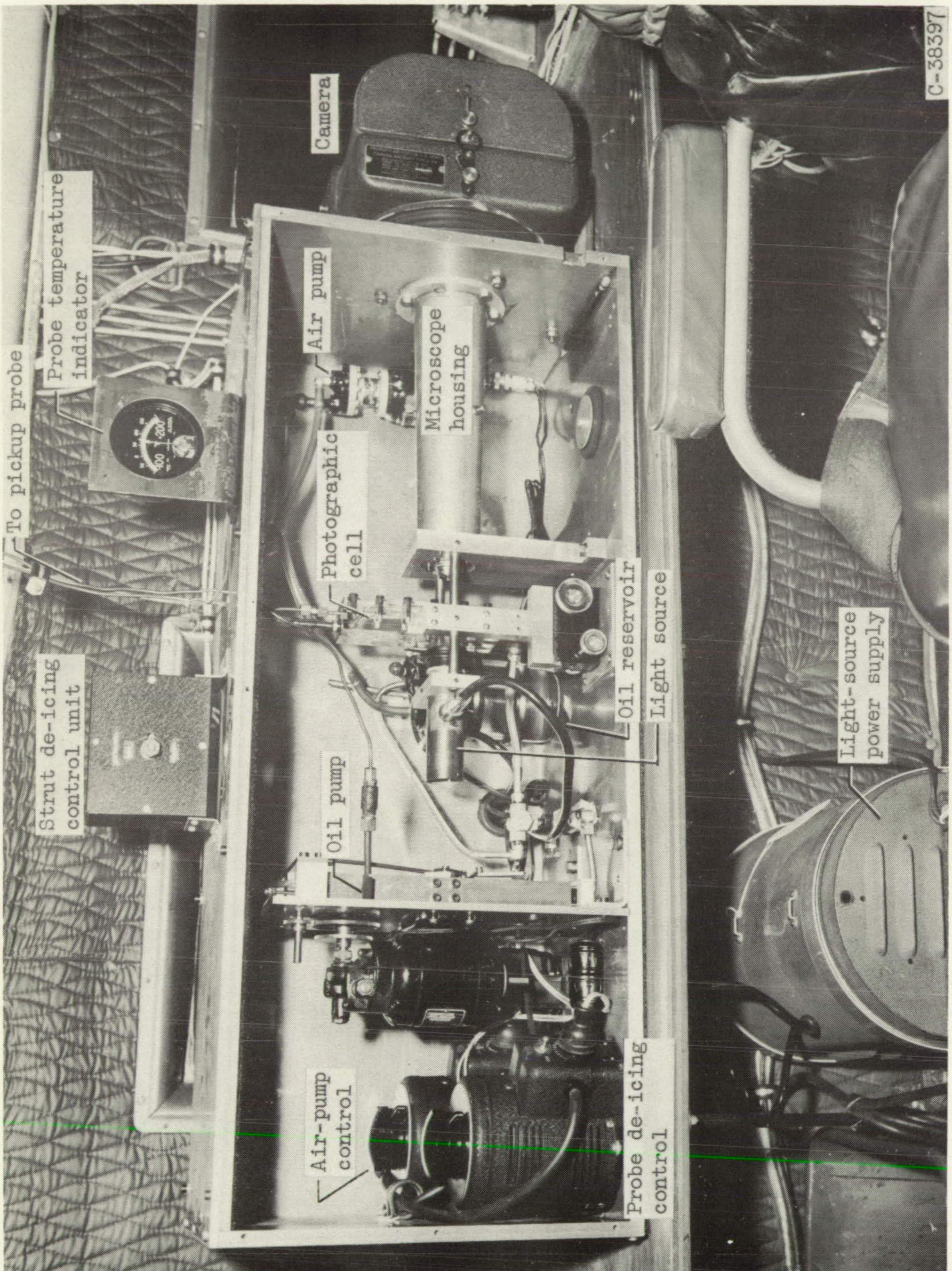


Figure 2. - Aeroscope mounted in airplane.

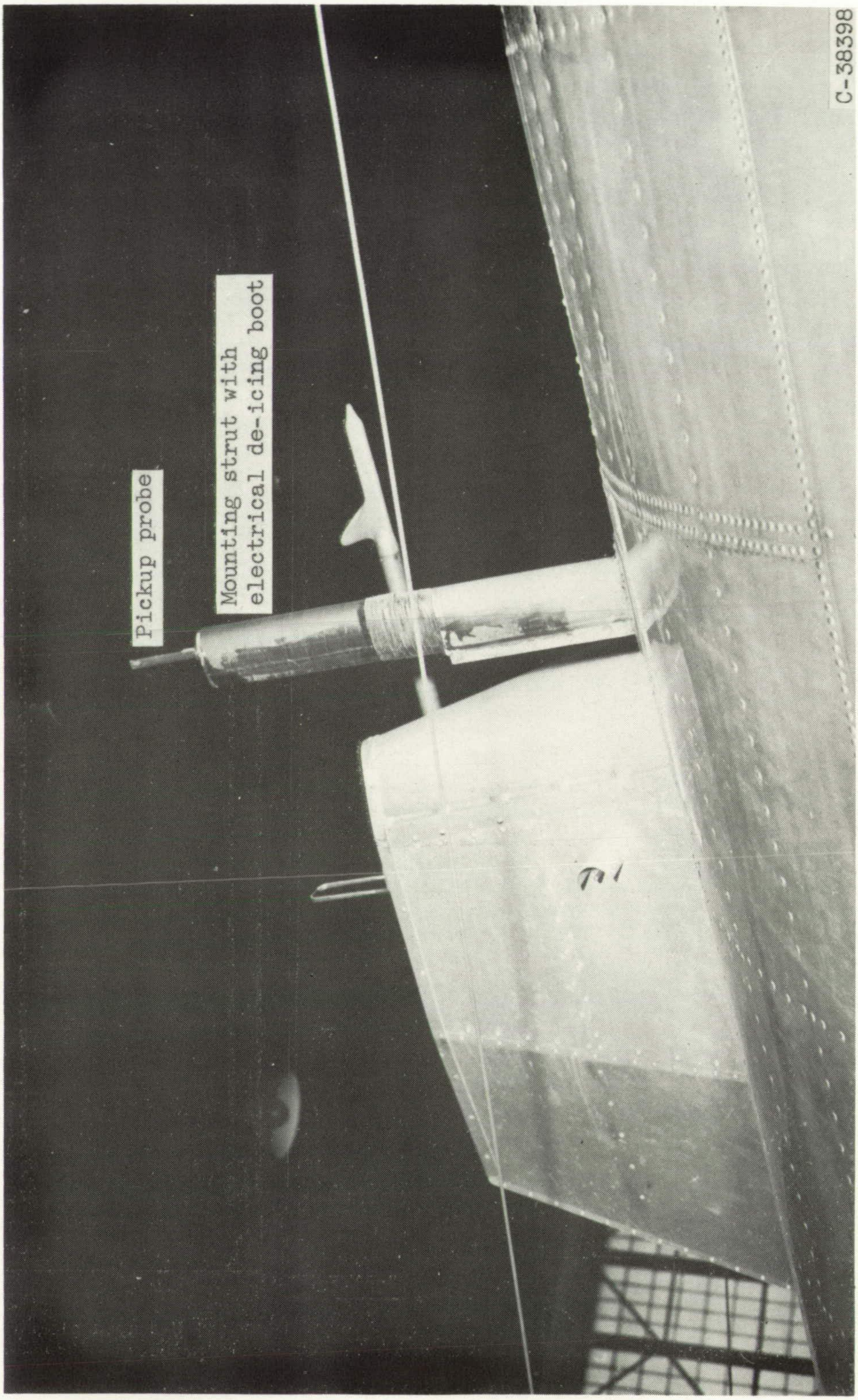
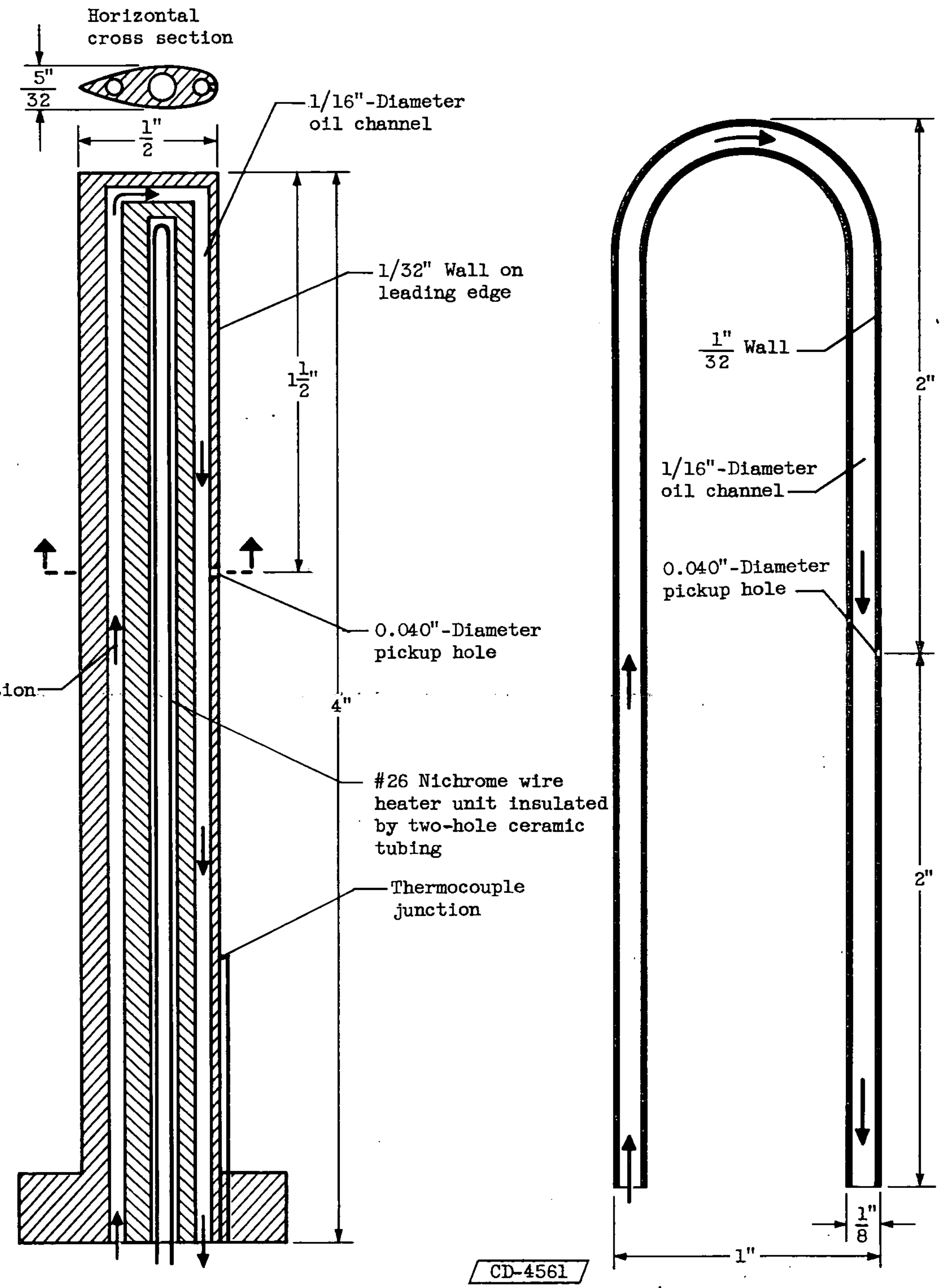


Figure 3. - Pickup probe mounted on top of airplane.



(a) Airfoil-shaped pickup probe.

(b) U-shaped pickup probe.

Figure 4. - Cross-sections of pickup probes.

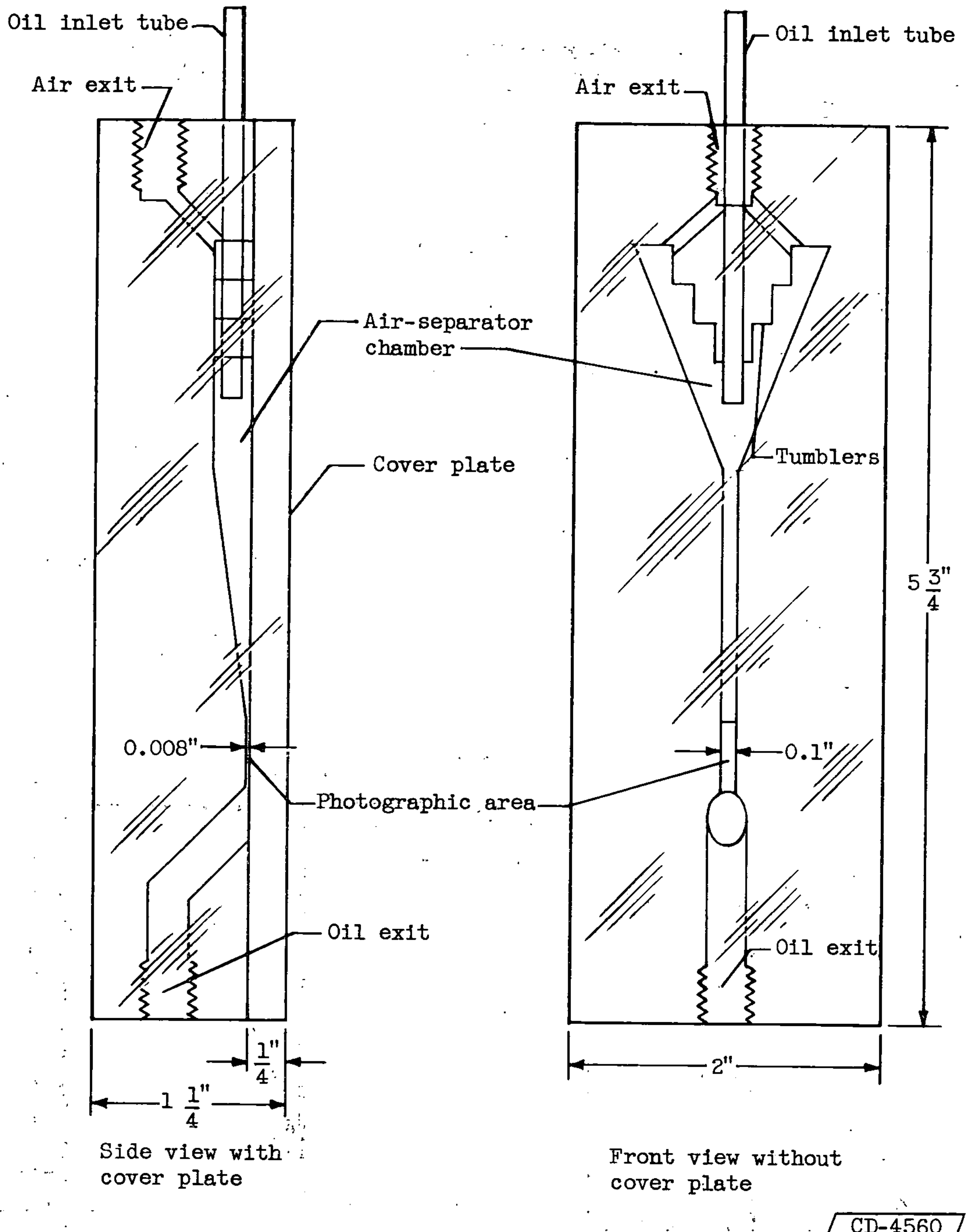


Figure 5. - Sketch of transparent plastic photographic cell.

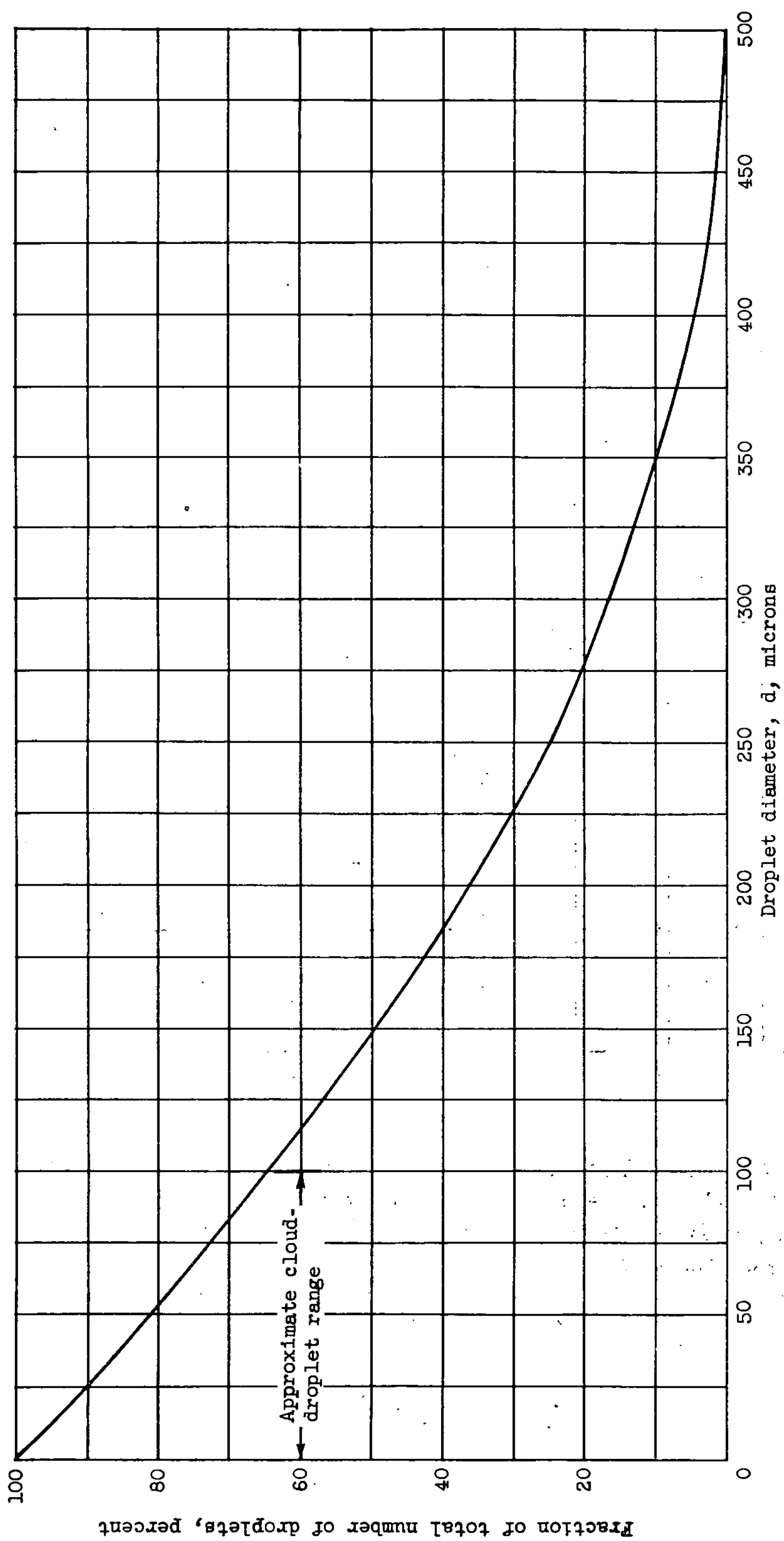


Figure 6. - Fraction of total number of droplets in volume swept out by 0.04-inch-diameter pickup hole that enter without striking edge of hole as function of droplet diameter.

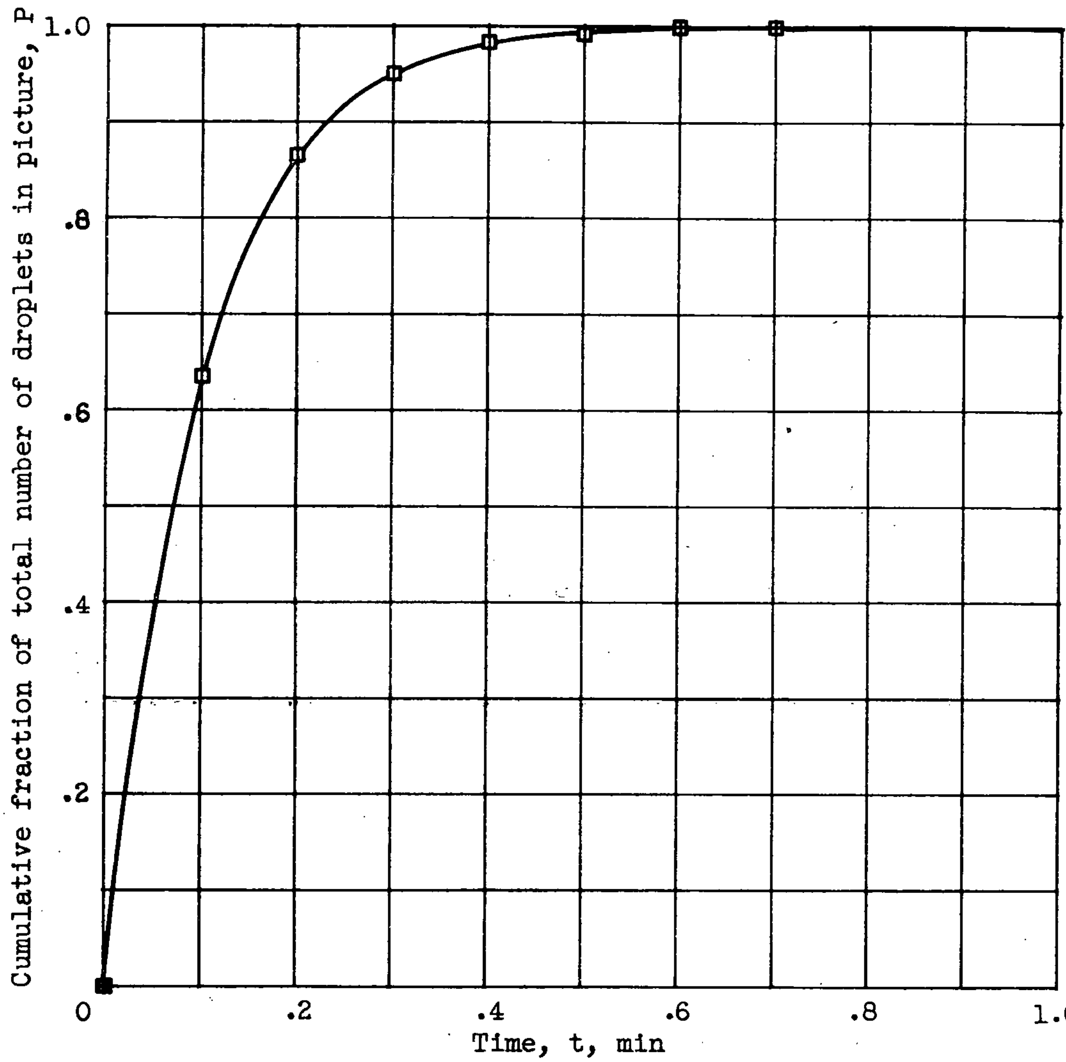
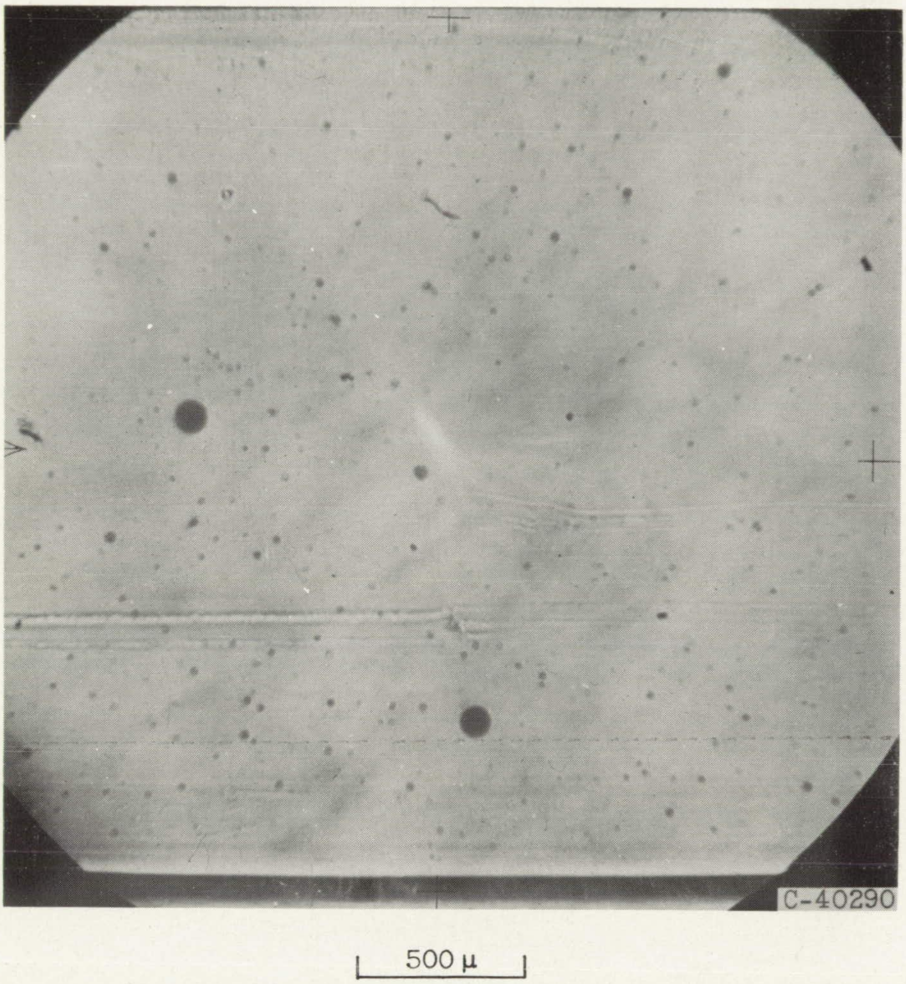
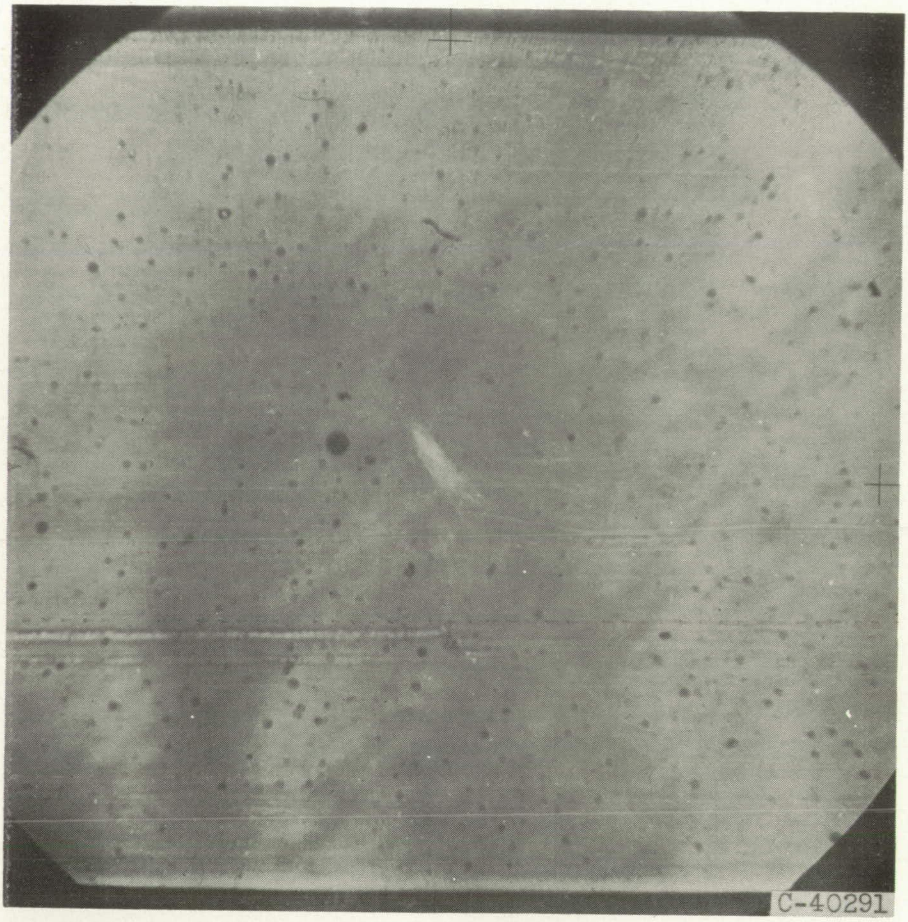


Figure 7. - Cumulative fraction of total number of droplets in a picture that were in air-separator chamber t minutes or less. Mixing volume, 0.03 cubic inch; oil-flow rate, 0.326 cubic inch per minute.



(a) Run 3, picture 2.

Figure 8. - Typical droplet picture. Flight 1 (Oct. 27, 1954).



500 μ

(b) Run 5, picture 4.

Figure 8. - Concluded. Typical droplet picture. Flight 1 (Oct. 27, 1954).

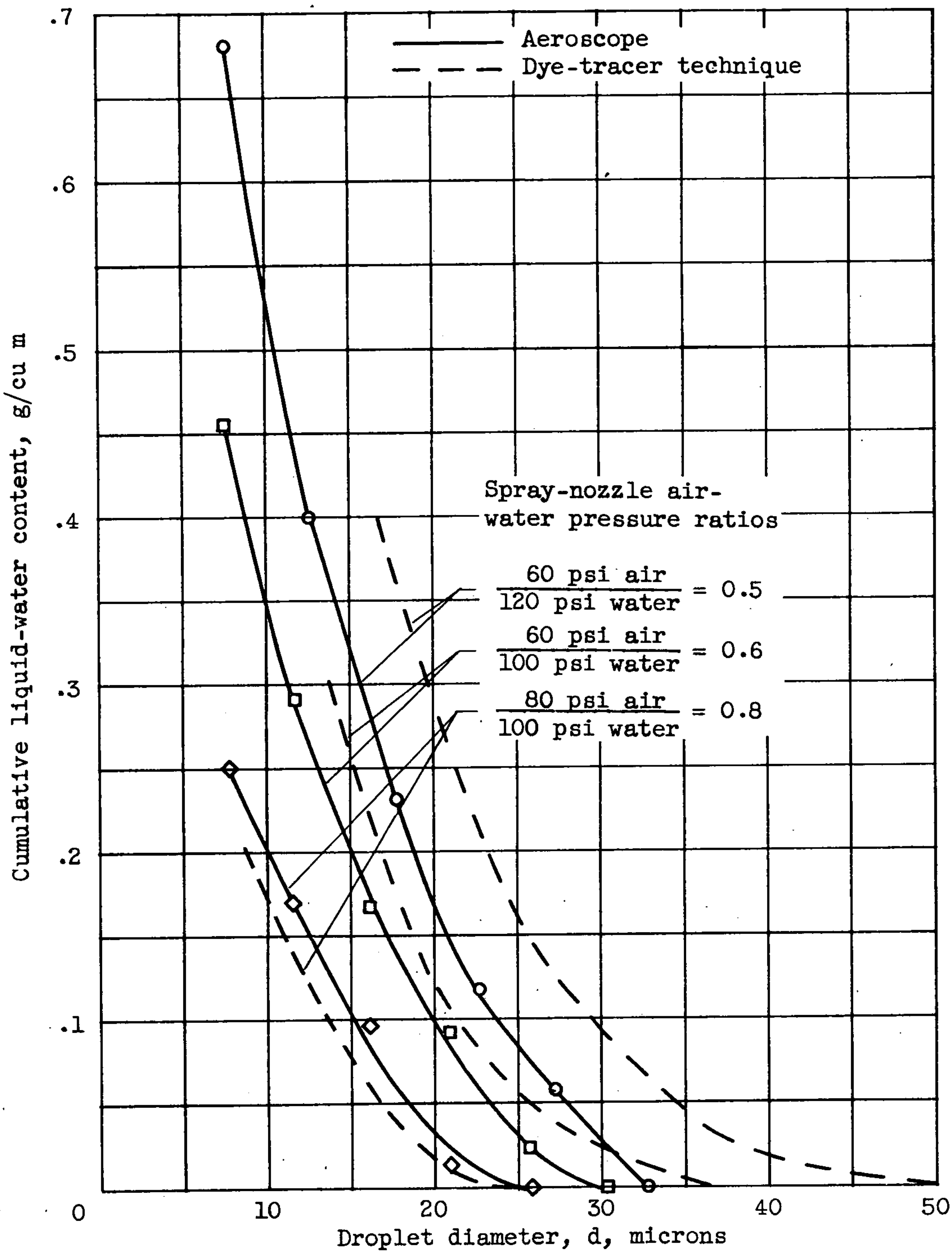
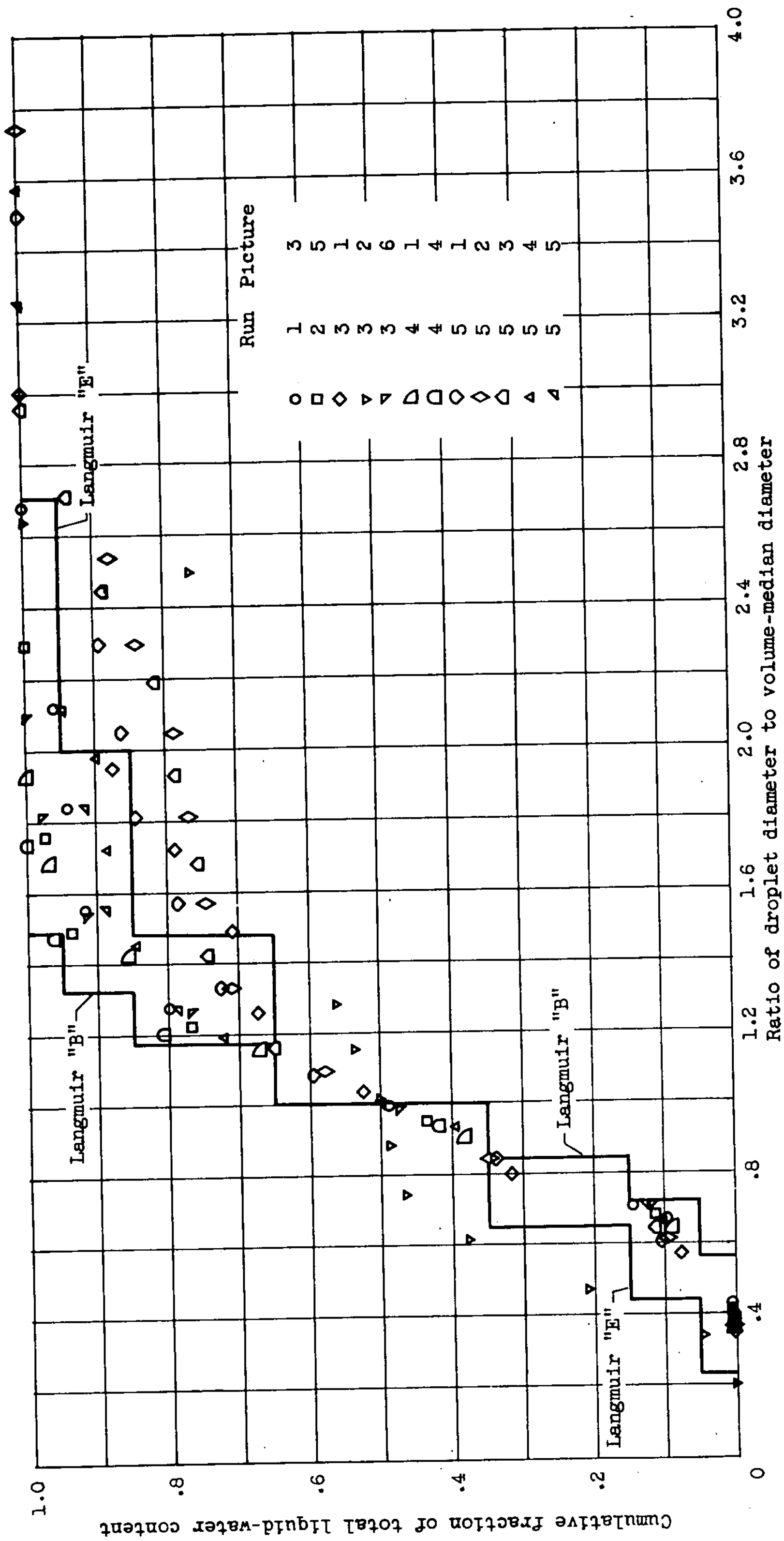
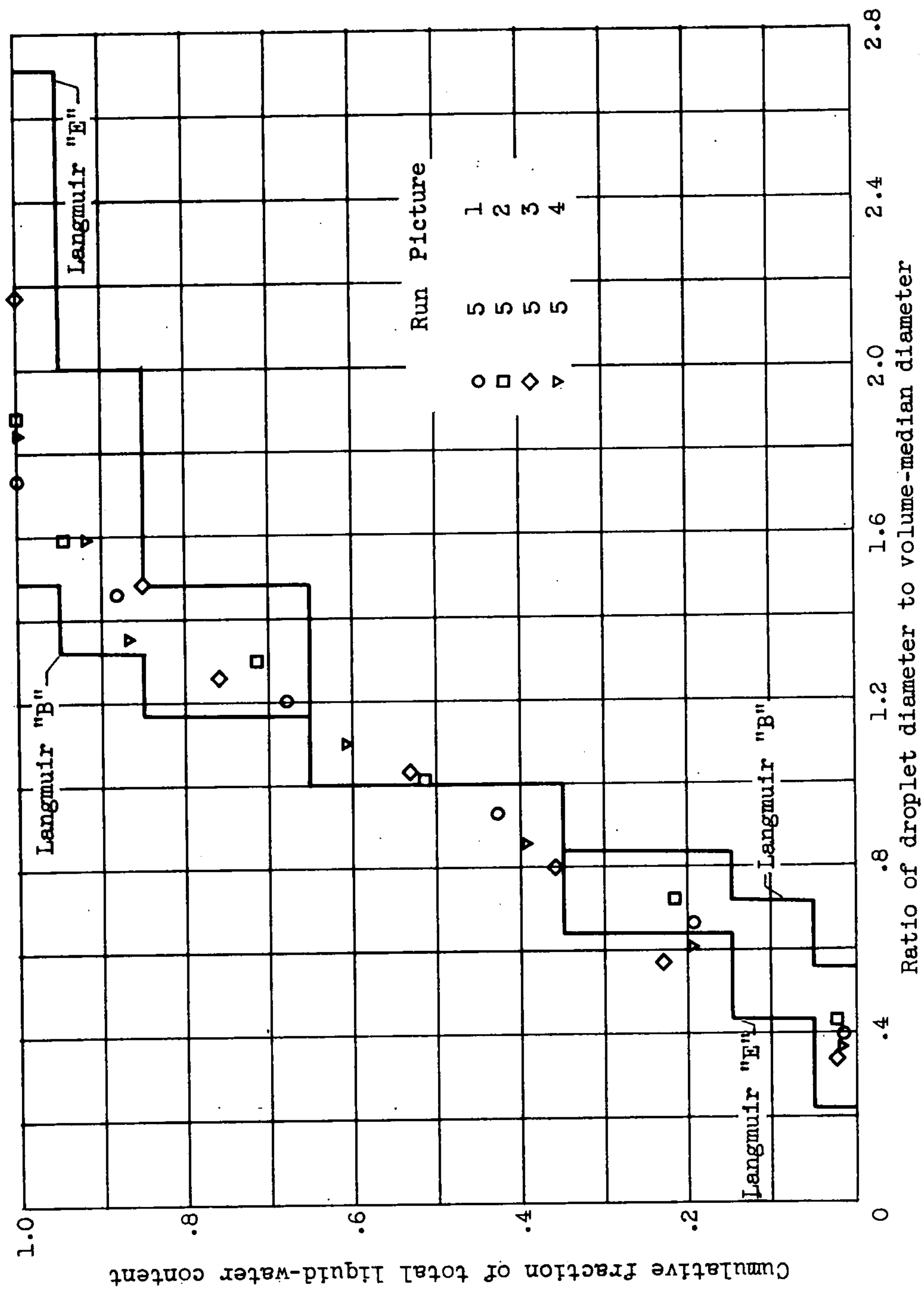


Figure 9. - Droplet size distributions for three spray conditions obtained by aeroscope and dye-tracer technique (ref. 24) in icing research tunnel.



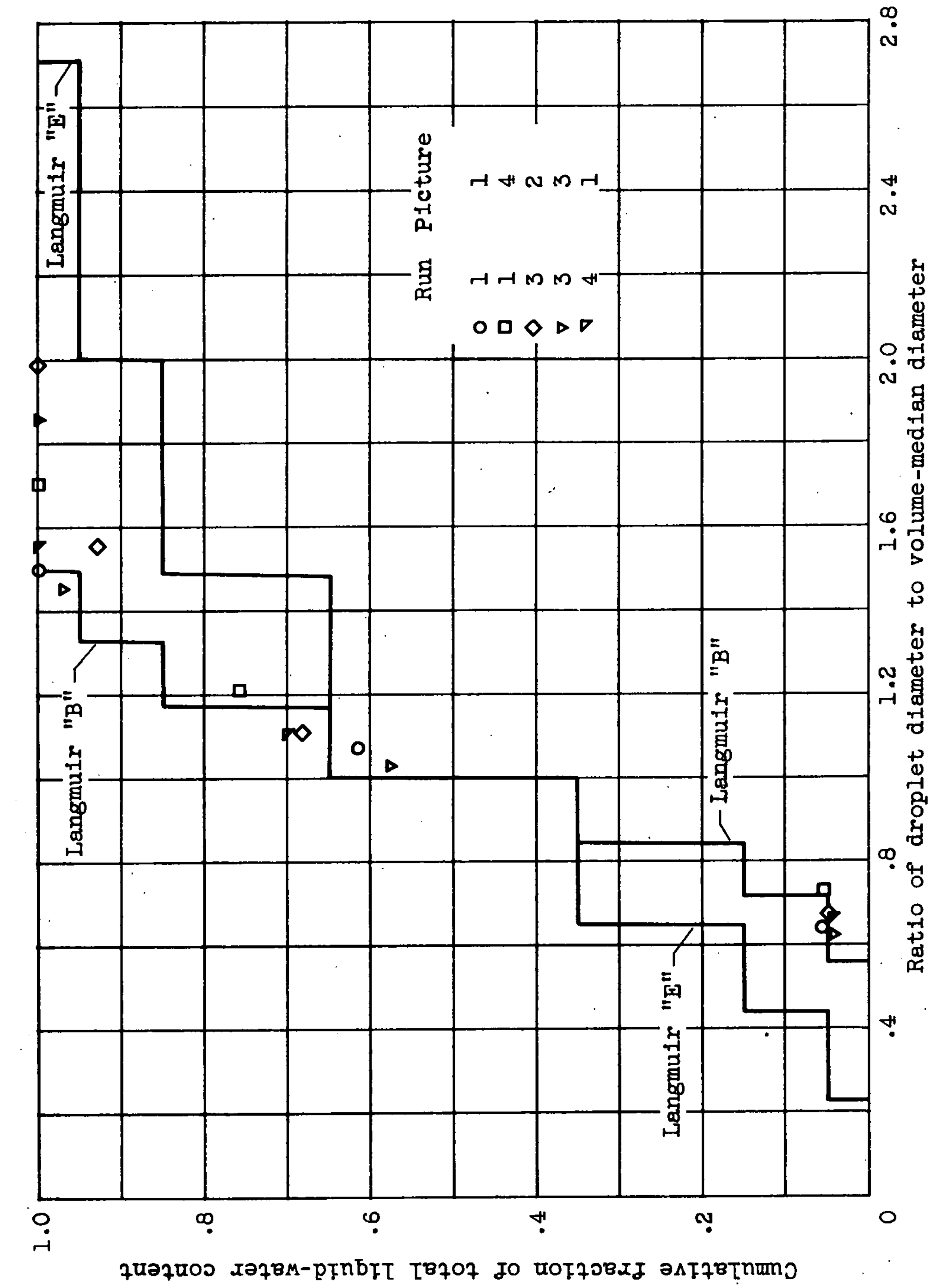
(a) Flight 1, October 27, 1954.

Figure 10. - Dimensionless droplet size distributions.



(b) Flight 2, December 1, 1954.

Figure 10. - Continued. Dimensionless droplet size distributions.



(c) Flight 3, January 19, 1955.

Figure 10. - Concluded. Dimensionless droplet size distributions.