Cloud Particle Replication in Stormfury Tropical Cumulus

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ABSTRACT

An aircraft instrument which provides continuous replication of water droplets and ice particles as an aircraft traverses a cloud is described. The instrument makes use of a continuously moving 16-mm film on which a Formvar varnish is applied just before exposure to the cloud particles at a sampling port. The film then passes through an appropriate drying process, thus producing replicas of the cloud particles in the hardened Formvar coating.

The considerations which enter into the interpretation of the replicas are discussed. Two of the problems which greatly limit the amount of quantitative data which can be obtained are 1) shattering of cloud particles (ice or water) either at the film or at the edges of the entry port, and 2) coalescence of water droplets after impaction on the film.

Examples are shown of the kind of replicas which were obtained in field use of the instrument.

1. Introduction

For several years the Naval Research Laboratory (N.R.L.) and Meteorological Research, Inc. (M.R.I.), Altadena, Calif., have conducted cooperative projects directed toward developing a satisfactory aircraft instrument which would provide continuous replication of cloud water and ice particles in a reproducible manner[1] (MacCready and Todd, 1964). This instrument is based on a suggestion by Dr. Vincent Schaefer whereby replicas are produced in a Formvar varnish coating applied on a continuously moving film. To date most measurements made with the instrument are not quantitative, particularly in high-water-content clouds; however, the instrument can provide some kinds of information which are unobtainable by other methods. Using various instruments with the same basic replicating method, investigations of ice in clouds have been reported by Todd (1965) and Braham (1964). In the accompanying article by Ruskin (1967) a series of aircraft measurements in large tropical cumuli is discussed; several new instruments were used in making these measurements including a cloud particle replicator.

2. The Formvar-film replicator

One of the N.R.L. designs of the replicator is shown in Fig. 1. In this instrument, cloud particles enter through the port shown at the lower left and are impacted in the Formvar coating applied on blank 16-mm movie film stock[2] which moves past the entry port at 25 cm sec^{-1}. The liquid Formvar coating is applied from a 7 mm wide "fountain pen" applicator which is fed by a metering pump geared to the film drive. The applicator is positioned about 1 cm (or 40 msec) before the film is exposed to the cloud particles at the sampling port. For operation above -10C and using the 40-msec delay time, the liquid coating is composed of 8 per cent by weight of Formvar[3] dissolved in chloroform.[4] By using a dye[5] in the Formvar the replicas are improved in contrast and the larger ones show third dimension contours by their gradations in color, as may be seen in the black-and-white reproductions of photomicrographs in Figs. 2–7.

In order to prevent melting of the ice when replicating mixed water and ice at temperatures only slightly below freezing, the film is dried for 5 sec at near-ambient temperature in the lower compartment shown in Fig. 1. This drying partially hardens the Formvar before the ice is melted by the higher temperature employed to complete the drying process. After 5 sec in the ambient temperature compartment the film passes through a 400-W heater and continues at an elevated temperature for a total of 5 sec before passing over a drive sprocket onto the take-up reel. The cloud particle sample and the drying air enter the instrument through separate entry ports. The sample impinges on the film through the lower one. The drying air enters the lower compartment of Fig. 1 through the upper entry shown extending forward (to the left in Fig. 1). This entry incorporates baffles to separate the larger ice and water

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[1] Development sponsored by the Bureau of Naval Weapons with partial support by Advanced Research Projects Agency.

[2] The 16-mm film base is Kronar leader stock P40A, 0.004 inch thick, transparent, DuPont, Wilmington, Del.

[3] The Formvar 15–95E is in flake form, Shawinigan Resins Corporation, Springfield, Mass.

[4] The chloroform can be any anesthetic grade or the J. T. Baker Chemical Company reagent grade containing 0.45 per cent ethanol for reducing toxicity and 0.0002 per cent residue by the maker's analysis.

[5] Oil Red dye 0.05 per cent by weight, DuPont, Wilmington, Del.

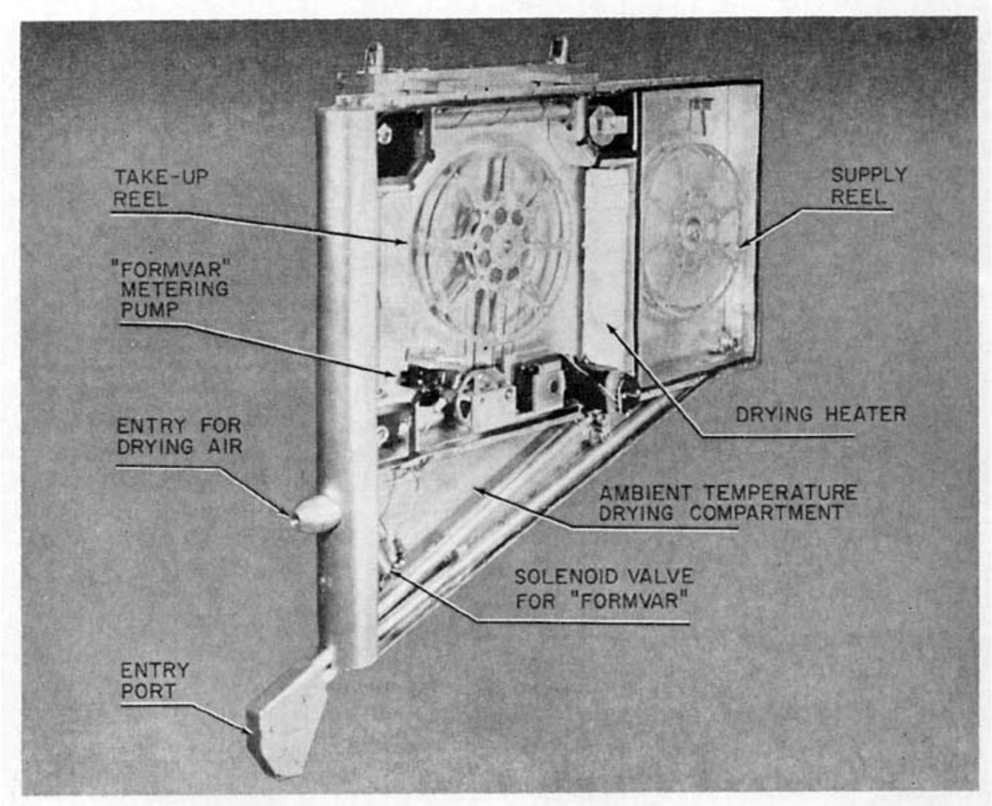

FIG. 1. N.R.L. design of the Formvar film cloud particle replicator flown on a bomb rack on a Super-constellation aircraft in the 1965 Project Stormfury tropical cumulus experiments.

drops from the drying air. Most of the drying air from the bottom compartment passes upward through the heater and then along the heated film; a small amount of the air in the bottom compartment is made to flow downward through the film-guide tube in a direction opposite to the film movement and is discharged near the sample entry port in order to prevent cloud droplets from drifting along the film with unknown numbers settling onto the still-wet Formvar.

Viscosity effects. The temperature and the concentration of Formvar in the coating affect the viscosity of the coating, for a given time delay and ventilation

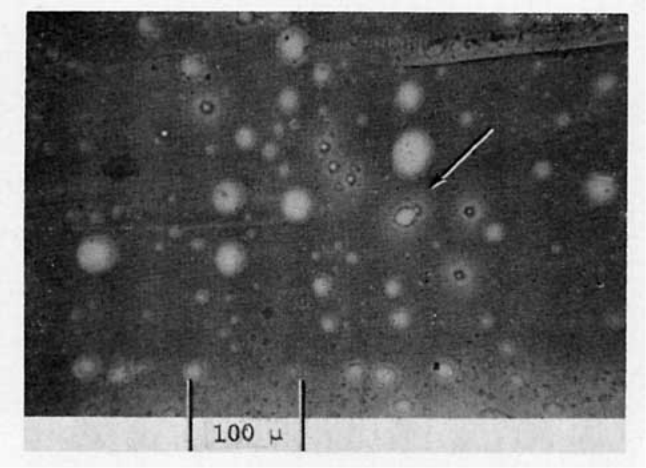

FIG. 2. Replicas of mixed supercooled droplets and 5- to 6-μ ice spheres from unseeded cloud at −5C. Darker areas are "blush." A small amount of spurious growth of ice is visible on the ice spheres in the "blush" free area surrounding each. The arrow indicates a 15-μ frozen image which probably resulted from a water drop being "seeded" by a 5-μ ice sphere.

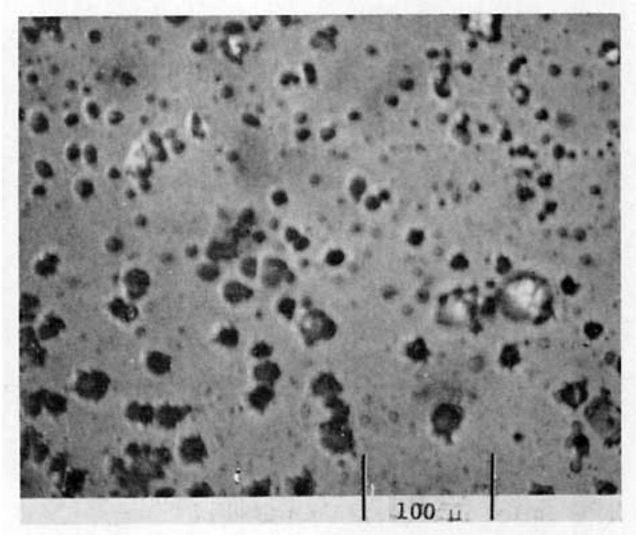

FIG. 3. Ice fragments and possibly 5-μ supercooled droplets (probably 5-μ ice spheres totally encapsulated) replicated in an unsaturated cloud region. Only traces of "blush" or spurious crystal growth are present. Lack of "blush" prevents reliable determination of ice or liquid for the small replicas.

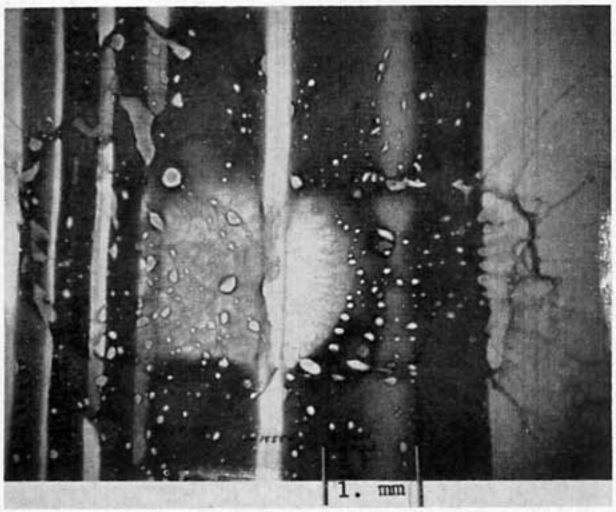

FIG. 4. Large "splatter" image from graupel probably slightly "mushy." Most of the 25- to 200-μ images appear to be from liquid, but some appear as ice fragments.

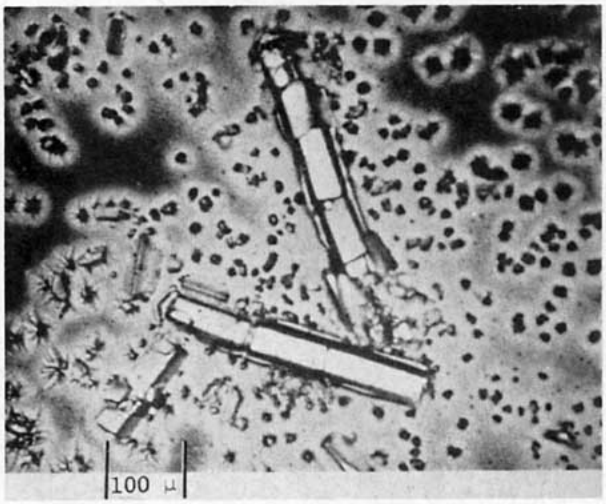

FIG. 5. Images typical of many 40- to 60-μ hexagonal columns. Dark areas are "blush." Spurious crystal growth is distinguishable from the original small shatter fragments.

rate, between the points of coating application and droplet impaction. The viscosity is about doubled by a 15C lowering of the temperature or a 2 per cent increase in the concentration (at 8 per cent). The viscosity of the liquid coating at the time of impaction affects the character of the resultant images in several respects, including the amount of "cushioning" (hence, break-up on impact), the amount of droplet flattening [hence, the size of image for a given droplet size (MacCready and Todd, 1964)], the relative number of droplets replicated (collection efficiency), coalescence of the drops on the film during the period of impaction but prior to encapsulation, and the range of droplet sizes which are encapsulated as compared to those forming open replicas. In the case of ice crystals the viscosity also affects the preservation of the replica shapes during the time when the ice is melting upon entering the heater.

Thickness of coating. The coating thickness also affects all of the above, as well as the drying time, the density of color (if dye is used), and the amount of "blush" (discussed later) formed for a given humidity of the drying air and the time at each temperature used in the drying process. The present design of applicator which uses the pressure-coating method provides a coating thickness that is nearly independent of the viscosity and fluid pumping rate. With this design, viscosity and pumping rate mainly affect the width of the coating on the film and whether or not excess fluid drains away. In order to obtain usable replication over a range of conditions the coating is applied with gradations of thickness across the film as can be seen in Fig. 4.

Coating applicator. The Formvar solution is pumped onto the film through a "fountain pen" which is designed so that hardened Formvar from a previous run is

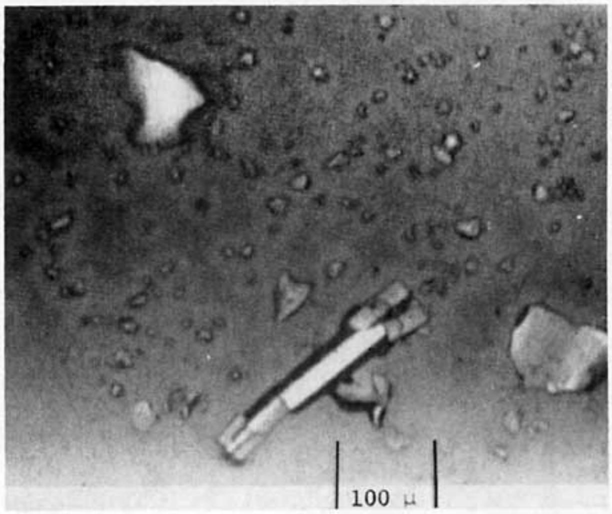

FIG. 6. Hexagonal column 50 μ across and fragments apparently from 150-μ thin-wall hexagonal column.

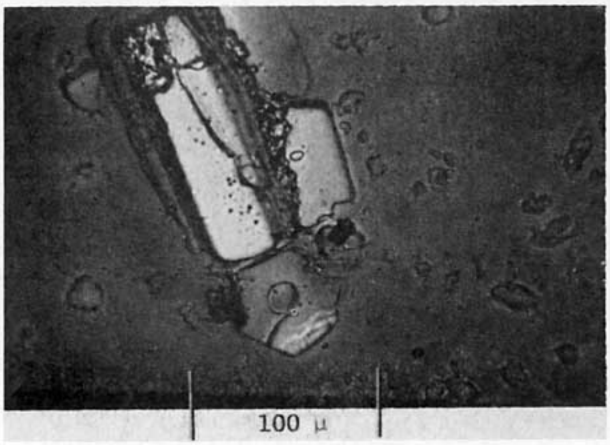

FIG. 7. Hexagonal column 60 μ across showing replica of hollow cross section.

bypassed by expansion of the "pen" under the pressure built up by the metering pump. The solvent gradually softens the hard portion, permitting the expansion to decrease. The point of the "pen" incorporates a 7 mm wide scraper plate which has various depth notches. The Formvar is thereby spread across the film in various thicknesses, any excess forming an extra ridge beyond the edges of the scraper.

Entry port configuration. The entry port configuration limits the minimum distance along the film from the applicator to the sample air entry port. The proximity of the applicator to the sampling point influences the amount of evaporation, hence the thickness and viscosity of the Formvar surface. The applicator can be located as close as 1 cm to the sampling point if the film is passed around a cylindrical roller at the entry port.

1) Collection efficiency.

The efficiency of collection of various sizes of droplets by different aerodynamic shapes moving at various air speeds is discussed by Langmuir and Blodgett (1945). With an aerodynamically leading surface in the form of a flat plate, the collection efficiency for small droplets on that surface is lower than it is for a cylinder of equal size.

Collection efficiency calculations for simple cylinders and flat plates, as presented by Langmuir and Blodgett (1945), are not applicable when the surface contains a sampling entry or slot, since the back pressure and the trajectories of droplets are changed by the presence of the slot. The collection efficiency at the film may be either higher or lower than that calculated for a continuous flat plate or cylinder. With the film located behind the slot, the slot acts as an orifice so that the air and droplet velocity at the film surface is lower than the velocities used in the collection efficiency calculations of Langmuir and Blodgett. Simple proof that the air velocity is lower with a narrower entry slot was found when attempts were made to fly a unit with a larger entry (reducing the diffusing effect of the slot). In that flight experiment, even with aircraft speeds as low as 120 mph, much of the Formvar coating was blown off the film.

2) Coalescence and drop shattering.

At airspeeds as high as the 265 mph of the Super-constellation (at 17,000 ft) with a 2-mm slot and a flat-plate type of leading surface, one of the limitations of the instrument is the excessive number of replicas overlapping each other, leading to difficulty in obtaining meaningful photomicrographs. The less dense regions of the clouds were used for all of Figs. 2–7 in order to improve clarity in identification of the various types of cloud particles. The replicas from more dense (and hence more representative) portions of the clouds were included in the data reduction for other types of analysis.

Several types of particle entry ports have been used in attempts to reduce shattering and excessively high concentrations of droplets reaching the film. The high concentration can result in coalescence of the droplets to produce large images when actually no large drops are present (particularly in high-water-content clouds). On the flights discussed in the accompanying article (Ruskin, 1967), the sampling time of about 0.01 sec was sufficient to cause coalescence on the film. In an attempt to reduce the uncertainties caused by this problem the sampling port was tapered from 3 mm wide at one edge of the film to zero width at the other edge. The wide part of the sampling port permitted large droplets and ice crystals to enter with relatively few being shattered or spattered by the edges of the port. The narrow edge provided a shorter exposure time. Although the density of replicas is not entirely proportional to port width at various locations across the film, comparison of the sizes and concentrations near the opposite edges of the film gives a clue as to the amount of shattering and coalescence. Fig. 8 shows the probability of various drop sizes hitting the edges of the sampling port for the cases of a 1-, 2-, and 3-mm width of the port. Fig. 8 is based on the assumptions 1) that all drops overlapping an edge are shattered and 2) that no fragments enter when shattered drops are entirely outside of the port. Because of departures from 1) the values of probabilities shown on the curves are probably somewhat too high for radii below about 50 μ. Departures from 2) probably cause the values to be underestimated for large drops.

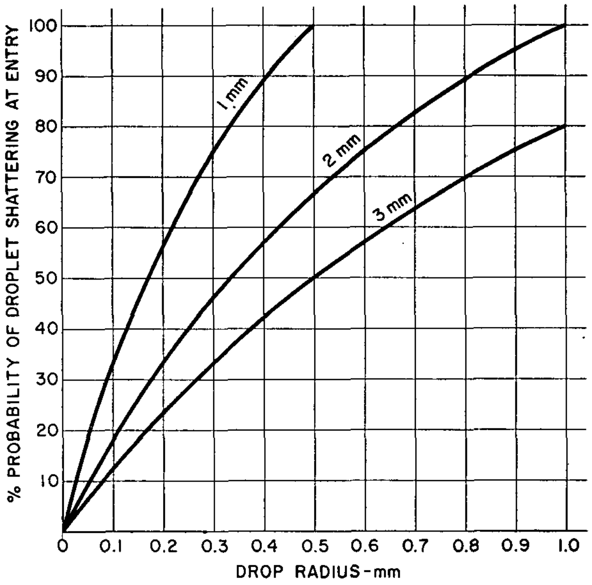

FIG. 8. Probability of various radii drops overlapping the edges of 1, 2, and 3 mm wide entry ports, computed on geometrical basis without corrections for spattering from drops entirely outside entry or for small droplets not shattering when touching entry edge.

Other entry configurations are under study with the aim of reducing the uncertainties in image interpretation.

Drying temperature. Obtaining replicas of intermixed ice and supercooled droplets in the temperature range of 0 to −5C requires that precautions be taken to avoid melting the ice. During the 1965 Project Stormfury experiments in the seeding of tropical cumuli, the altitude having this temperature range was chosen for the N.R.L. measurements in order that information could be obtained on the effectiveness of AgI seeding for producing freezing before it would have occurred naturally. For the flight conditions in the clouds discussed in the accompanying paper by Ruskin (1967) and with an indicated air speed of 170 kt (corresponding to a true air speed of 265 mph at 17,000 ft) the "ambient-temperature" compartment would have a temperature about 6C warmer than the outside free-stream temperature; this warming resulting from the dynamic heating (assuming the usual aircraft skin temperature recovery factor of 0.85). The drying air enters this compartment through a baffled entry which removes the large water drops and i e. Evaporation of as much as 0.5 gm m^{-3} of liquid water in the droplets which are not removed by the baffle would cool the entering air only about 2C, resulting in a net drying air temperature of 4C above ambient. At a cloud temperature of −4C, then, the compartment air temperature would be 0C (assuming negligible heat transfer to or from the walls or film surface). The temperature at the film surface is lowered a few more degrees by evaporation of the chloroform from the Formvar. The temperature of small particles while being replicated is largely controlled by the film temperature, hence should not melt with ambient temperatures up to 0C. Large ice particles provide some thermal restriction between the film and the air, thereby permitting the side toward the film to replicate as ice, even though the surface toward the air may start melting before the Formvar is hardened. Only a small amount, if any, of heat can be supplied at this stage of drying without a likelihood of melting the ice when operating near 0C.

Formation of "blush." When the air entering the first drying compartment is saturated in a cloud, the evaporation of entering droplets, while lowering the air temperature, would also raise the dew point above the original temperature of the air. Evaporation of 0.75 gm m^{-3} of liquid water would result in 100 per cent relative humidity (assuming 6C of dynamic heating). Under most cloud conditions, therefore, water condenses on the evaporatively cooled Formvar coating to form "dew replicas" or "blush." During the 5 sec while the film is in the ambient-temperature drying compartment, this condensation can cause spurious growth of those ice particles which are large enough not to be encapsulated by the Formvar; this growth is usually in a form which appears to be small dendrites which are distinguishable from the original particle, and which are too fragile to have survived impact.

3. Image interpretation

There are several kinds of information that are desired from the replicas on the film, such as the number, size, total quantity, and the nature of the cloud particles. The interpretation of the images to give this information must take into account a number of considerations which are discussed in the following paragraphs in an attempt to indicate those areas in which ambiguities in image interpretation can lead to completely erroneous conclusions.

Number and size of cloud particles. In the previous discussion relating to the configuration of the cloud particle entry port it was pointed out that there are two major problems which lead to difficulty in determining number and size of cloud particles. These problems are 1) shattering of cloud particles (ice or water) either at the film or at the edges of the entry port, and 2) coalescence of water droplets after impaction on the film.

In the case of ice, the shattering problem essentially precludes any number estimates; however, there are frequently numerous fragments still large enough to determine something about the size of the particle, as shown in Figs. 5 through 7.

In the case of liquid drops, the greatest uncertainty in determining the number lies in those images from about 50 to 500 μ in diameter, which may have resulted from large drops which have been partially shattered at the window edge or at the Formvar surface or which may have resulted from small drops coalescing on the film. The number concentrations deduced from this instrument are often a factor of ten times higher than found by calculation from optical extinction vs. liquid water content or from the number of cloud condensation nuclei measured on the same flight below the cloud bases (Squires and Twomey, 1966), whereas these latter agree quite well with data as measured in similar clouds by investigators using other methods of measuring droplet size and concentration (Squires, 1956).

In the replicating of liquid cloud droplets where precipitation is not present, the images in high-water-content clouds are usually quite close together unless the sampling port is reduced in size; but this leads to an increase in the fraction of droplets shattered at the entry. Bursts of higher water content along the film often appear to be accompanied by increases in droplet size and a spread in the droplet size spectrum. It was determined that this appearance was misleading and that possibly the spectrum was even narrower in the regions of higher water content. By using a tapered window and variations of coating thickness it was determined that high droplet concentrations increased the fraction of droplets coalescing, this fraction increasing in regions of higher water content and on areas of the film having a thinner coating.

A similar ambiguity is present in areas of the film having increased numbers of small ice replicas and a decrease in large ones. This appearance may result from cloud regions in which all of the ice crystals were larger, but thinner-walled, and hence had shattered into more and smaller fragments.

An increase in the number of images which one might interpret as having come from small size raindrops may actually result from conditions in which no small drops are present, but a few large drops present overlap the edges of the entry, and thus shatter more than is the case when smaller drops are actually present.

Nature of cloud particles. There is often a need to determine whether the cloud particles which are being sampled are supercooled water or ice. During the seeded cloud monitoring penetrations described by Ruskin (1967), much of the ice of the cloud appeared to be spherical, such as the 5- to 20-μ replicas shown in Fig. 3 (replicated in an unsaturated cloud) and the 5- to 6-μ ones shown in Fig. 2 intermixed with 3- to 30-μ images of apparently supercooled droplets. The only ice particle which is larger than about 6 μ is at the arrow in Fig. 2, a 15-μ image which appears to be a liquid droplet which froze on the film after being "seeded" by a 5-μ ice sphere at its edge.

Judgment must often be made as to which of the smooth round images were frozen before impact. However, the condensation "blush," when present, serves a useful purpose as an aid in distinguishing between ice and liquid particles because the "blush" is continuous up to the replicas of liquid drops, whereas there is a clear area around ice particles. This latter pattern results from the fact that the vapor pressure is lower over ice than over liquid water, thus causing a diffusion of close-by water vapor so that condensation is on the ice rather than forming "blush" adjacent to the ice. Both cases are shown in Fig. 2, the "blush" being the darker areas. This criterion cannot be used in the occasional instances where part of a cloud is unsaturated, as in Fig. 3, such that little "blush" is formed. Another case wherein this criterion cannot be used is that of distinguishing between cloud drops which froze before impact as compared to those freezing upon impact. Since many (and in some cases all) droplet images indicate liquid droplets even at several degrees below −5C, the (admittedly shaky) assumption is made that most ice images result from ice which was frozen before impact. This uncertainty does not prevent obtaining a reasonably reliable upper limit for the quantity of ice.

Many ice images as small as 5 to 50 μ are very irregular in shape as shown in Fig. 3. An uncertainty remains in this case as to whether some of these particles may have been rime or frost around the window and showered off when impacted by a large particle. In some cases some such mechanism must have been responsible for excessively high number concentrations of small ice particles (400 cm^{-3} in some unseeded clouds). Heating the window can prevent icing, but such heating introduces the likelihood that drops of melted ice will appear as large liquid precipitation when none was present in the cloud.

The other form of ice which contributed appreciably to the total ice content at the 17,000-ft altitude in some parts of the cloud was a partially frozen mixture with various amounts of liquid water in "mushy" graupel spheres about 0.3 to 2 mm in diameter. An example of a largely unfrozen graupel is shown in Fig. 4.

Still other forms of ice are those which produced many replicas of needles 5 to 20 μ in diameter and hundreds of hexagonal columns of ice 40 to 60 μ across. Many hexagonal columns in this size range appear to be solid; however, in Fig. 7 the shattering process apparently produced one clear cross section of such a column, showing a round hollow center core. Determination of numbers of ice crystals per unit volume is impossible because of the uncertainty as to which particles are scattered fragments of an originally larger crystal. In some cloud regions, replicas, which are apparently parts of the 40- to 60-μ hexagonal columns, number 500 liter^{-1}, with a total of all types of ice replicas (probably mainly shatter fragments) as high as 600 cm^{-3}. Fig. 6 shows an example of a 40-μ hexagonal column, irregular fragments (500 cm^{-3}), and two larger pieces which appear to be faces of 150-μ hexagonal columns with walls perhaps only 10 to 20 μ in thickness. The walls being this thin could explain why such large numbers of fragments are present and why no intact hexagonal columns of this size were found. One or both of these two classes of hollow hexagonal columns is probably that found by Hallett (1965) to grow at −4 to −6C. If they fell from higher altitudes, the presence of these hexagonal columns could also be explained by the experiments at low supersaturations by Kobayashi (1958) in which he found solid columns throughout the region below freezing, hollow columns below −6C, and needles at −4 to −6C.

Quantity of ice and water. Because the shattering of cloud particles and coalescence of water droplets after impaction present such a problem in determining size or number, it was decided, in the case of the Stormfury penetrations discussed by Ruskin (1967), that the data be analyzed primarily in terms of comparisons of total image areas or ice column lengths rather than numbers. This type of analysis provided a measure of the changes in ratio of masses of water to ice, even though absolute quantities were not considered to be reliable for either mass, size, or number of particles of either water or ice. This information on ratios and on the nature of the ice fills an important gap in the cloud data from more absolute instruments.

Comparisons of water content between this instrument and the hot-wire Johnson-Williams instrument have been possible only in regions of clouds having small droplets and low water concentrations (tenths of a gm m^{-3}). One such comparison at an aircraft speed of 120 kt gave a collection efficiency of roughly 45 per cent and another at 250 kt of 75 per cent. At higher water contents with these aircraft speeds the images were too crowded and coalesced to permit quantitative interpretation. So many factors affect the collection efficiency that before a large effort is expended in calibrations all of the other variables should be optimized and then not changed.

4. Conclusions

In the use of this instrument care must be taken to avoid conclusions drawn from ambiguities in the replicas produced, the uncertainties increasing at higher aircraft speeds. The instrument can provide data which are essentially unobtainable by other means, namely, profiles through clouds giving information as to whether the cloud particles are ice or water, the changes in their ratios, and information about the nature of the ice particles.

The instrument was used in tropical cumulus at −3 to −5C leading to the following results:

1) Replicas were obtained at −3 to −5C of hexagonal column ice crystals, 40 to 60 μ across, some of which had hollow centers.
2) Evidence was found that thin-walled hexagonal columns 150 μ across were prevalent, although all were shattered upon impact at 260 mph. Much ice was present at −5C in spheres as small as 5 μ.
3) Some needles 5 μ across appeared to have grown from one side of 7-μ spheres.

Evidence was found that some hexagonal columns terminated on both ends in points which were extensions of corners of the hexagon. Column length before impact appeared to have been about 300 μ.

Development is continuing toward providing a geometry of sampling entry which is satisfactory at speeds above 50–80 m sec^{-1}.

Acknowledgments. In the N.R.L. phases of the development of the cloud particle replicator, Messrs. R. M. Schecter and R. G. Russ performed most of the flight testing.

The enthusiasm and cooperation of Mr. Clem Todd over a number of years has been a large factor in the instrument having reached its present state of development.

REFERENCES

Braham, R. R., Jr., 1964: What is the role of ice in summer rainshowers? *J. Atmos. Sci.*, **21**, 640–645.

Hallett, J., 1965: Field and laboratory observations of ice crystal growth from the vapor. *J. Atmos. Sci.*, **22**, 64–89.

Kobayashi, T., 1958: On the habit of snow crystals artificially produced at low pressures. *J. Meteor. Soc. Japan*, Series 2, **36**, 193.

Langmuir, I., and K. B. Blodgett, 1945: Mathematical investigation of water droplet trajectories. General Electric Report No. RL-225, Final Report Army Contract W-33-038-ac-9151, 46 pp.

MacCready, P. B., Jr., and C. J. Todd, 1964: Continuous particle sampler. *J. Appl. Meteor.*, **3**, 450–460.

Ruskin, R. E., 1967: Measurements of water-ice budget changes at −5C in AgI-seeded tropical cumulus. *J. Appl. Meteor.*, **6**, 72–81.

Squires, P., 1956: The micro-structure of cumuli in maritime and continental air. *Tellus*, **8**, 443.

——, and S. Twomey, 1966: A comparison of cloud nucleus measurements over Central North America and the Caribbean Sea. *J. Atmos. Sci.*, **23**, 401–404.

Todd, C. J., 1965: Ice crystal development in a seeded cumulus cloud. *J. Atmos. Sci.*, **22**, 70–78.