Interpretation of Foil Impactor Impressions of Water and Ice Particles

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ABSTRACT

Impacts of hydrometeors on aluminum foil over a grooved backing, as in standard airborne foil impactors, have been produced in the laboratory using a modified crossbow to achieve aircraft speeds. The purpose of the work was to test the ability to distinguish the phase of the hydrometeors from the nature of the imprints. Solid, spherical ice pellets (frozen drops) and drops of slush leave impressions that are often indistinguishable from those left by liquid drops, at sizes below about 3 mm diameter.

1. Introduction

Foil impactors, devices by which thin metal foil is exposed on aircraft to impacts of hydrometeors, have been in use for several years (e.g., Bigg *et al.*, 1956; Brown, 1958; Duncan, 1966; Cornford, 1966). Several determinations of the functional relation between raindrop size and imprint size have been made, of which the latest is by Schecter and Russ (1970). The use of the foil impactor in the past has been largely limited to clouds containing rain, snow and small graupel, and investigators have stated, with varying degrees of qualification, that these forms of precipitation can be distinguished by the nature of the impressions produced on the foil (e.g., Miller *et al.*, 1967; Church *et al.*, 1975).

The use of a foil impactor on the South Dakota School of Mines and Technology T-28, an aircraft armored to enable penetration through hailstorms (Sand and Schleusener, 1974), has extended the range of use of the instrument. The T-28 has been used in the National Hail Research Experiment (NHRE). One early objective of this experiment was to evaluate the Soviet accumulation zone model of hail formation (Sulakvelidze *et al.*, 1967). In this model, hail is thought to grow within zones of high concentrations of large, supercooled water drops balanced in fairly strong updrafts. It was therefore very important to make unequivocal determination of the phase of precipitation within hailstorms, and interpretation of impressions on foil was almost the only means available during the early stages of NHRE. Reported data on the T-28 penetrations (May, 1974; Musil *et al.*, 1976) include the results of these interpretations. Liquid water drops several millimeters in size were reported to exist at −10 to −15°C within the storms, though not in the large concentrations that would seem to be required for accumulation zones.

Because of the very great importance of firmly establishing the presence of large, supercooled water drops (their presence or absence might have a large impact upon the possibilities of hail suppression by seeding with ice nuclei), an attempt to "calibrate" the interpretation of foil impressions has been made using a modified, commercially available crossbow to achieve realistic impact velocities.

It might also be worth remarking that, while foil impactors may seem old-fashioned when compared to more recent optical array and photographic devices, they still have competitive features, in particular, low cost, ease of operation and large sample volume.

2. Test equipment

A crossbow manufactured by Dave Benedict Crossbows, Chatsworth, Calif., was used, with a special, 200 lb. pull bow, an extra 4.3 cm spacer between the bow and the stock, and a specially made, light-weight arrow (11.5 g) to achieve a velocity between 90 and 100 m s^{-1}. Without the spacer and with a 30 g arrow, speeds of 60 to 65 m s^{-1} were attained. The arrow is fitted with attachments so that it travels down a "track" consisting of two, tightly strung piano wires (Fig. 1). A serious problem was stopping the arrow in a reasonable distance without destroying it. This was accomplished by mounting fairly stiff brushes beneath the track and placing riders on the track itself in the path of the arrow.

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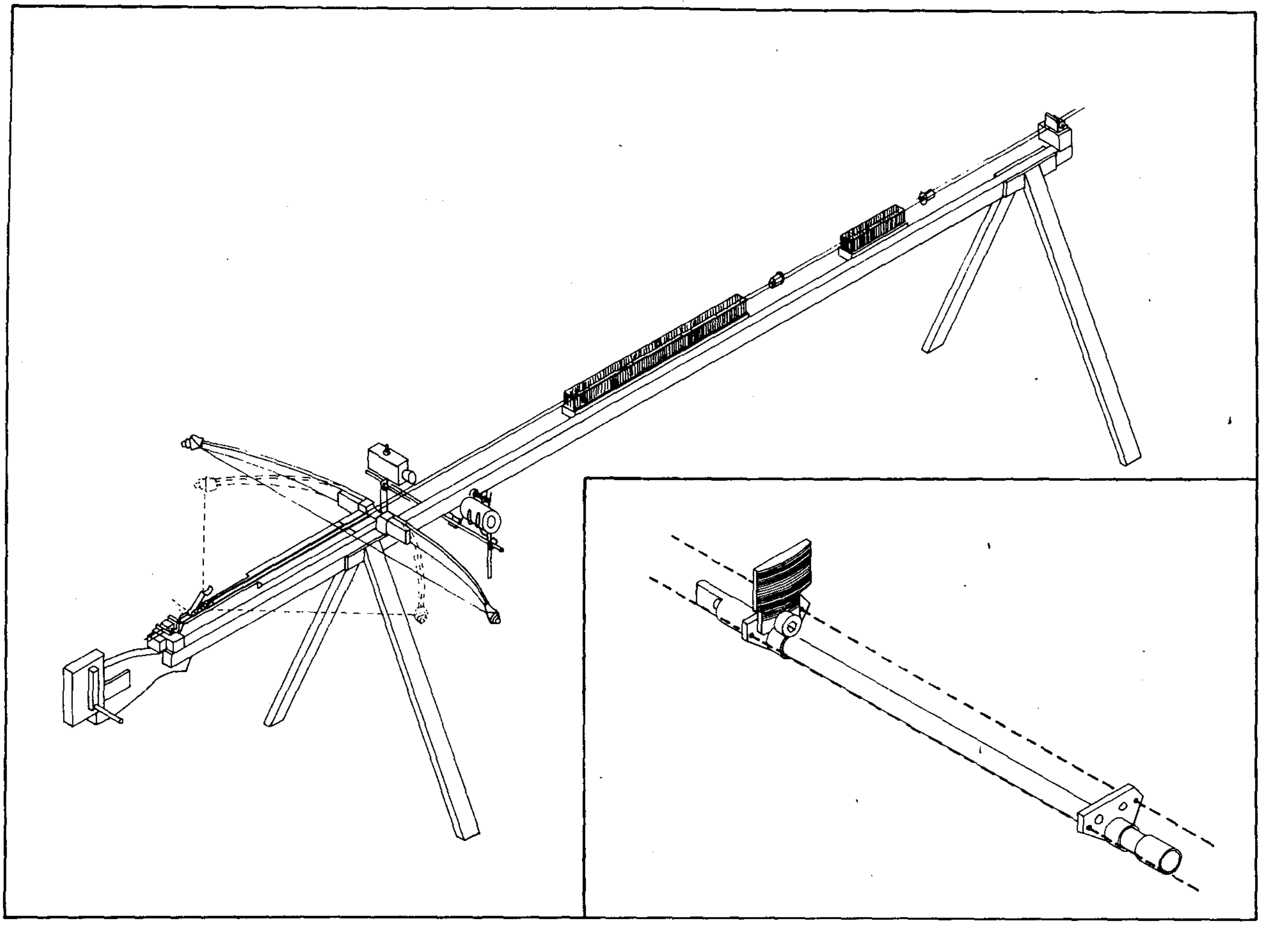

FIG. 1. Schematic diagram of the device for accelerating a small foil impactor to speeds up to 100 m s^{-1} using a commercial crossbow bolted to an aluminum beam. The whole apparatus is 4.06 m long and is drawn to scale. The crank at left was installed for ease in cocking the 200 lb pull bow. Two piano wires are tightly strung above the beam, and the arrow (inset) is fitted to ride along the wires. The stiff brushes and aluminum "riders" on the wires help to stop the arrow fairly gradually. The light and photocell just to the right of the bow are used to trigger the strobe lights that fire in sequence, enabling a photographic record of velocity to be made. The target—a water drop or ice crystal—is hung just ahead of the bow and in line with the impactor, by a fine thread or fiber hung from a horizontal rod. The 16.4 cm long arrow, a hollow fiberglass tube with metal fittings, has a section of the grooved foil impactor surface mounted above it as shown in the inset. The section has a radius of curvature of 3.8 cm, which is the same as that on the airborne foil impactor, and face dimensions of 14 × 20 mm, and grooves 250 μm apart. The standard 1 mil aluminum foil (see Church *et al.*, 1975) is folded over this surface and taped in back. To control looseness, the foil can be put on over several layers of paper that are then removed.

A small section of the curved, grooved backing having the same 38 mm radius of curvature and 250 μm groove spacing as airborne foil impactors, but only 14 mm × 20 mm in area, is attached toward the back end of the arrow, extending upward (insert, Fig. 1). The foil was wrapped over the grooved face and taped in back. The foil used was the same as that used on the T-28, and data on it and its source can be found in Church *et al.* (1975) [aluminum 1100 alloy, 0 temper, 1 mil (0.00254 cm) thickness, with a tensile yield strength of 11.0 lb $inch^{-2}$ (0.773 kg c^{-2}) at 0°C]. The target—a water drop or ice particle—is suspended on a fine thread in such a position that the small section of foil impactor hits it while traveling at its maximum velocity. The largest liquid drops are allowed to fall freely into the path of the impactor section. The arrow velocity is measured by a stroboscopic technique. Fig. 1 is a simplified diagram of the apparatus.

3. Methods

As noted above, liquid drops and ice particles were suspended on threads or fibers in the path of the foil section mounted above the arrow. The ice particles were usually frozen drops, cooled and kept frozen by a gentle stream of nitrogen gas at −10 to −20°C. In a technique suggested by Z. Levin (personal communication) a Dewar of liquid nitrogen was fitted with a cork and a tube, and with a resistor suspended in the liquid. The current through the resistor was adjusted with a variable transformer, and the heating gives a remarkably sensitive control over the velocity and temperature of the cold gas stream coming from the tube.

Medium-sized drops could be hung on the end of a thread or fiber with a hypodermic syringe. It was found most convenient to form submillimeter drops by holding the fiber in the spray from a nebulizer until the proper sized drop had grown on the end, and then to clean other drops from the fiber with a razor blade. The largest drop impacts were obtained by firing the arrow through a uniform drop stream from a burette until a usable collision occurred. The smaller ice particles were frozen, single drops. The larger ice particles were built up from smaller, frozen drops and were sometimes distinctly nonspherical. Natural graupel, pieces of compacted snow and similar particles are easily hung on a slightly dampened thread.

In all cases except the falling drops, the liquid or frozen drop was photographed for size determination just before firing the crossbow.

4. Results

While the main purpose of this work is the qualitative interpretation of the foil impressions in terms of the phase of the impacting particles, measurements were made of the diameters of the drops, the ice particles and the impressions produced by them. These measurements are shown in Fig. 2, along with the relevant calibration points from Schecter and Russ (1970). Previous investigations of the relation between imprint diameter and real diameter (Bigg *et al.*, 1956; Brown, 1958; Bethwaite *et al.*, 1966; Schecter and Russ, 1970) yielded surprisingly disparate results. The imprint diameter always exceeded the real diameter, normally by factors of 1.3 to 1.5, but even up to as large as 2.5. The different conditions of previous results make these numbers difficult to compare. Different foil materials and different geometries of the impacting device were used.

Schecter and Russ (1970) duplicated the geometry of the common airborne foil impactor in their experiments, and obtained values of 1.0 to 1.3 for the ratio of the imprint diameter to the real diameter of water drops. They suggested that this ratio was considerably below that obtained by previous workers because the airborne foil impactor exposed a curved surface to the airflow rather than a flat one. Presumably this would result in less deformation of the drops within the boundary layer of the impactor, and consequently more realistic imprint sizes. The present results, shown in Fig. 2, scatter widely about a ratio of 1 for all sizes, clearly showing no significant deviation from 1. This is intuitively consistent with Schecter and Russ' explanation, since in the present work the moving impactor section (Fig. 1) was both curved and very small, and should have caused even less distortion than Schecter and Russ' apparatus. Their calibrations are still to be preferred for reduction of data from airborne foil impactors, as was done by May (1974).

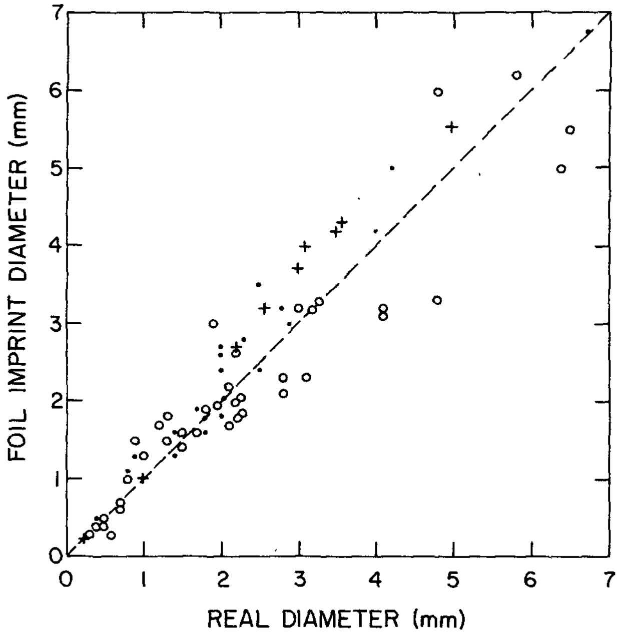

FIG. 2. Foil impact diameters versus the diameters of drops and ice particles for all of the good data runs. Ice (always solid) is shown by dots, liquid water by circles. The data scatter about the 45° line, indicating a 1:1 calibration, within the errors. The very large water drops were freely falling. See the text for a discussion of some of the uncertainties. The crosses show the calibration points at 230 kt (118 m s^{-1}) taken from Schecter and Russ (1970).

The large spread in the present results is due to several factors. The very large, liquid drops are undoubtedly oscillating, and their real diameter is therefore very uncertain. The large ice particles usually did not have a uniform horizontal diameter, and there was no assurance that the measured real diameter was that dimension that was parallel to the foil surface upon impact. A similar problem was present to some degree for all of the drops and ice particles suspended upon threads. Finally, the boundary of a foil imprint was never defined better than the 250 μm groove spacing and often was quite arbitrary within a distance of twice that, especially for the largest drops. In general, our experience is that attempts to measure imprint diameters to within less than 250 μm are unrealistic.

Two sets of experiments have been carried out. One, with the early version of the apparatus capable of 60–65 m s^{-1}, was done at the Elk Mountain Laboratory of the University of Wyoming. Because of poor photography of the original particles, the sizes are not well recorded, and these data are not included in Fig. 2. The other, at 85–100 m s^{-1}, was done at NCAR. The results are as follows:

1) An impact with a particle tends to mold the foil locally into the grooves in the backing plate. Another feature that is sometimes present and sometimes not is a ridge in the foil surrounding the imprinted portion.

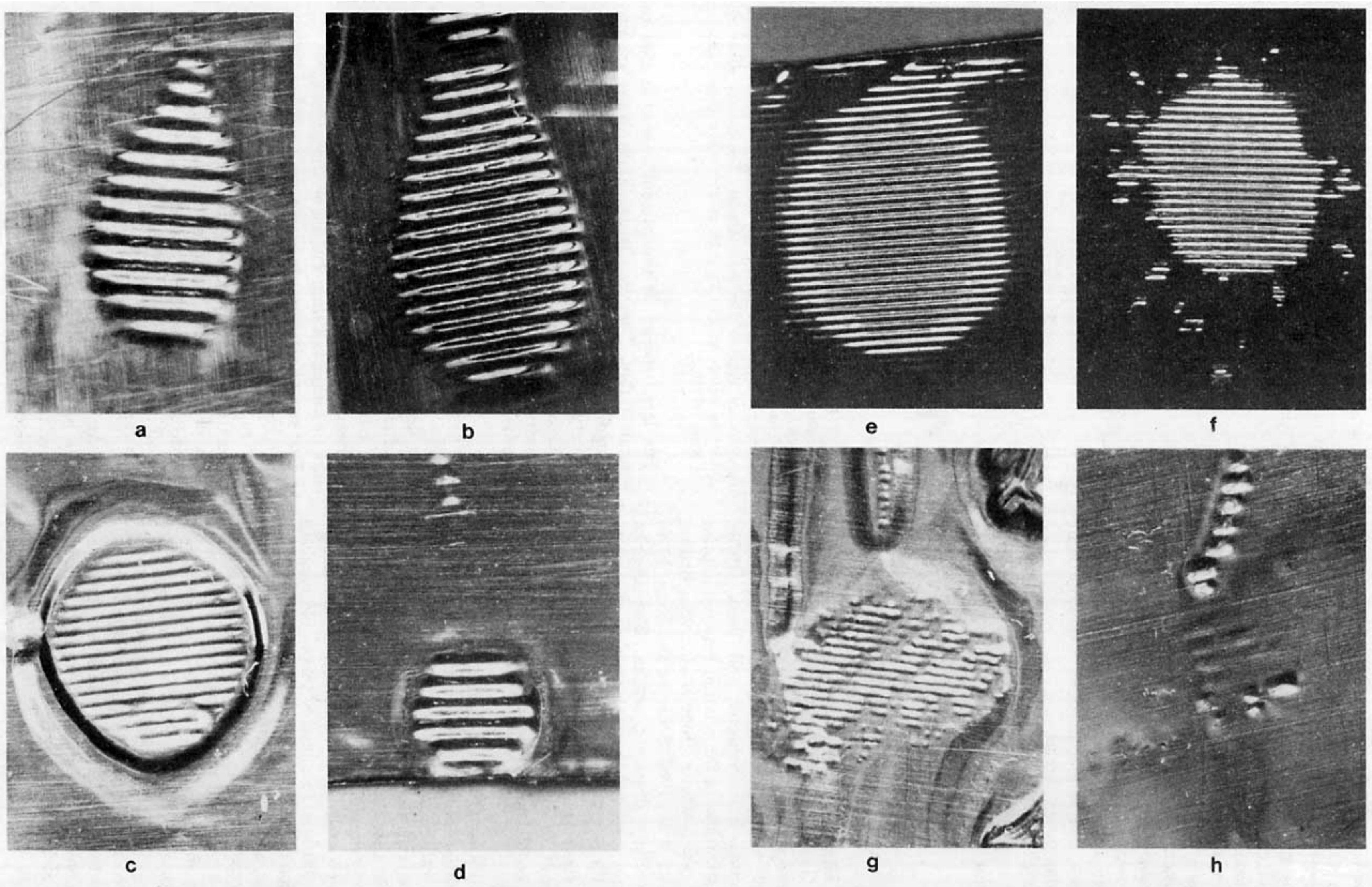

FIG. 3. Examples of foil imprints of ice and liquid at impact speeds between 85 and 100 s^{-1}, except where otherwise noted, with scale given by the groove spacing of 250 μm. The appearance of such imprints on shiny foil is very dependent upon lighting: we used a diffuse source just off the line of sight. (a) and (b) are, respectively, the imprints of a frozen and a liquid drop on a thread with tight foil. (c) is a liquid drop impacted on very loose foil, showing an exceptionally marked, raised rim, and (d) is the imprint of a frozen drop at the loose edge of the foil, showing a more normal raised rim. (e) is the imprint of a very large, freely falling water drop, illustrating the very poorly defined edge to the imprint. (f) is the impression from a large, solid ice particle, showing the satellite imprints. (g) and (h) are a piece of hard rime and a wintertime graupel, suspended on threads, impacted at 60–65 m s^{-1}.

The presence of such a raised rim has been used as partial evidence of phase, the idea being that liquid spreads out upon impact, pushing up this rim, whereas ice does not. A first result of the present work is to establish that the rim reflects the looseness of the foil over the backing, not the nature of the impacting particle. In the experiment, such rims never form when the foil is tight, and always form when it is loose (see Fig. 3). In the experiments the looseness was nearly impossible to control accurately, since it was influenced by aerodynamic and other factors; in fact, it often varied over the foil area, giving partial rims. Our impression is that the same is true on the airborne foil impactor, and no significance should be attached to the presence or absence of these rims.[2]

2) The types of particles used in the experiments were liquid drops, frozen drops, partially frozen drops, dry rime and compacted snow, soaked rime and compacted snow (slush), and a few natural, small graupel. Types of imprints are shown in Fig. 3. It is concluded that distinction between liquid drops, solidly frozen drops, and spherical, very slushy particles (as one gets immediately upon nucleating a drop supercooled to $-10°$C) is difficult and often impossible at diameters $\lesssim 3$ mm. The ice impressions sometimes had a somewhat more ragged edge, but sometimes did not. The molding of the foil into the grooves was uniform and even in all of these cases, evidently because the impact energy is sufficient to crush the solid ice completely. It might be speculated that at lower impact velocities, less than perhaps 30 m s^{-1}, the ice might not crush completely, and the impressions might always have ragged edges.

The larger ice particles, $\geqslant 3$ mm diameter, left a central imprint surrounded by smaller, satellite dents, probably from the initial shattering of the ice (Fig. 3f). The largest water drops, again >3 mm diameter, formed imprints with a quite gradual transition from sharply molded grooves to no grooves at the edges of the imprints, as seen in Fig. 3e, that made the measurement of the imprint diameters somewhat arbitrary.

Distinction between rime, including slushy rime, and solid ice or liquid particles *is* unequivocal, both by imprint shape and by uneven borders and uneven molding of the grooves (Figs. 3g and 3h).

3) A few natural graupel of 1–2 mm size were fastened on the thread and impacted against the foil at 60–65 m s^{-1}. Their density was not measured, but they were the very light graupel commonly found in winter snowstorms. They left virtually no imprint on the foil, though the thread itself made a clear impression. The same result was obtained using very light rime produced in the laboratory.

4) The lower limit for liquid drop detection and sizing with any consistency is 0.4–0.5 mm diameter at 90 m s^{-1}. Drops with diameters of about 0.3–0.4 leave a dent but do not mold the grooves sharply unless they happen to hit directly on a ridge. Such dents are not trustworthy on a foil that has been exposed and then rerolled, as in an aircraft foil impactor, because similar dents can easily arise accidentally. Drops smaller than about 0.2 mm diameter leave no imprint at all.

5. Foil impactor flight tests

During the 1976 NHRE summer field season the foil impactor used on the armored T-28 aircraft on occasion produced images with a distinct periodicity of about 1.6 inches. It was discovered that a small amount of water would become frozen on one of the 0.5 inch diameter idler rollers and as the foil was pulled through the system, distinct imprints would be made on the foil. Flight tests were then conducted to verify this condition by operating the system in cloud and exiting the cloud with the foil impactor still operating. Upon examining the foil produced out of cloud the periodic imprints of realistic shapes and sizes were present. It was concluded by the field personnel involved with the T-28 project that all imprints should be checked for this periodicity and, of course, rejected when the periodicity is found.

6. Conclusion

We conclude that rime particles may be distinguished from water drops by the irregular shape and uneven molding of the impressions left on the foil, but that solid ice particles may not be distinguished with certainty from liguid drops at diameters $\lesssim 3$ mm, unless they have distinctly nonspherical shapes. Interpretations of foil data within hailstorms are subject to this amount of uncertainty. It is also possible that small, very light graupel may leave no recognizable imprints.

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[2] While the authors have no doubt about this experimental result, one field test does need to be mentioned. This test was made and communicated by W. Sand of the University of Wyoming. On one T-28 flight in 1976, the foil impactor was purposely operated in a rain shower below the freezing level. All of the drop imprints had rims, whereas ice impressions of the same mission did not. On the other hand, the photos of drop imprints shown by Schecter and Russ (1970) clearly show the absence of rims, and Fig. 15 of Church *et al.* (1975) appears to show some raindrop impressions with rims and some without. The present results show that the tightness of the foil is the important factor, not the phase of the particle, and we feel that the T-28 result must be caused by an unexplained vagary of the instrument on that flight at that time.

been made at the suggestion of D. Veal and W. Sand (Section 5 and the footnote in Section 4) and P. Smith.

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