THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING
Department of Civil Engineering

Final Report

TASK 1: THE ROLE OF ATMOSPHERIC TURBULENCE IN THE AGGLOMERATION OF CLOUD PARTICLES

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TASK 2: WEATHER RADAR OBSERVATIONS UNDER PROJECT HI CUE AT FLAGSTAFF, ARIZONA, DURING JULY AND AUGUST, 1959

Floyd C. Elder

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FOREWORD

Research Contract No. AF 19(604)-2176 has been in force with this laboratory since February, 1957. The work undertaken under this contract is logically divided into two separate, but related, tasks. Task 1 is the investigation of the role of atmospheric turbulence in the agglomeration of cloud particles and is basically a research program based upon laboratory experimentation. Task 2 is the field observation experimental program, identified as Project Hi Cue, in which personnel and equipment of this Laboratory participated in the Summer of 1959. This final report on the work of the project is accordingly presented in two sections, one for each of these tasks.

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ABSTRACT

A literature review of materials pertaining to the coalescence of cloud droplets in forming rain and to the prominent factors that influence this process is presented. Laboratory work in evolving a method for producing individual vortices reproducibly is discussed, and an airfoil modeled for use in a cloud chamber is described. The development of a 24-ft^3-capacity continuous cloud chamber is described, and the results of tests and analyses of its performance are reported. Satisfactory means of monitoring the cloud-chamber contents throughout experiments without disturbing the chamber and the cloud equilibrium are under study.

A program of measurements of rain under Project Hi Cue was conducted at Flagstaff, Arizona, during July and August, 1959, using the van-mounted APQ-40 radar unit. Data were recorded photographically. The data remain to be analyzed.

I. TASK 1: THE ROLE OF ATMOSPHERIC TURBULENCE IN THE AGGLOMERATION OF CLOUD PARTICLES

by
A. Nelson Dingle

A. REVIEW OF LITERATURE

Two card files have been compiled during the life of the project. The first contains summaries (on 5- x 8-in. cards) of references pertaining directly to the project problems: coalescence processes in clouds, turbulence, laboratory methods of producing turbulence, and the relation of turbulence to coalescence. The second file contains summaries in similar form of references pertaining somewhat less directly to these problems, being papers of a more general nature in the field of precipitation physics. This compilation was given an early impetus by the loan of a card index previously assembled by Professor Richard M. Schotland of New York University. Most of the references have been examined in the original and abstracted for the particular purposes of this research.

1. Review Papers and Sources

A number of publications have reviewed the entire problem of converting clouds to precipitation. Obviously, the principal source for references on the subject, and for abstracts of these is _Meteorological Abstracts and Bibliography_. Several pertinent annotated bibliographies have been assembled in past issues of this publication as follows:

Radar meteorology, _9_, no. 8, 1958.
Radar cloud physics, _6_, no. 7, 1955.
Cloud physics, _6_, no. 6, 1955.
Cloud physics, _1_, no. 3, 1950.

An additional comprehensive bibliography has been compiled and published as Appendix D, Volume II, Final Report of the Advisory Committee on Weather Control, 1957. This list, entitled "Bibliography on Weather Modification and Cloud Physics" includes 2259 references.

The evolution of knowledge and understanding of the processes involved in cloud and precipitation physics is perhaps most readily grasped by reference to a few books and papers such as Humphreys (1940, 1946); Houghton (1950, 1951); Mason and Ludlam (1951); Mason (1953); Browne, Palmer, and Wormell (1954); Johnson (1954); Weickmann and Smith (1957); and Mason (1957).

2. Coalescence of Cloud Droplets

That coalescence of cloud droplets is a process necessary for the production of rain is well established. Defant (1905), in his study of the sizes of raindrops, found a "mass grouping" of raindrops about the mass ratios 1:2:4:8:... and judged that this was attributable to the coalescence of drops of nearly equal size. Although more recent work indicates that there is little justification for this assumption, Niederdorfer (1932) and Horton (1948) have revived the basic idea. All these efforts are based primarily upon the interpretation of raindrop-size distributions as observed at the ground.

a. Observations of Cloud-Droplet Sizes.—Observations of the sizes and relative distributions of cloud droplets have been compiled by Köhler (1925) by means of corona measurements in mountain fog, stratus, stratocumulus, and altocumulus. Köhler attempted to show agreement with Defant's hypothesis of "mass grouping," but his argument remains unconvincing. Hagemann (1936) obtained drop-size distributions in land fog. Houghton and Radford (1938) made drop-size measurements in sea fog and found the sizes to average considerably larger than Hagemann's. Lewis, et al. (1947a, 1947b, 1949) made an extensive series of measurements of drop-size distributions in subcooled water-clouds from aircraft. The volume-median diameters obtained for cumuliform clouds ranged from 3 to 56μ and averaged 20.5μ, whereas for stratiform clouds the range was 3 to 50μ and the average 14.7μ, but the authors felt that the data were not reliable because of difficulty in the use of the multicylinder as an airborne instrument.

Diem (1948) also made extensive measurements of cloud-drop sizes from aircraft. He used a coated slide impingement technique which probably discriminated against the smallest droplets. His observations show generally broader size distributions for precipitating than for nonprecipitating clouds.

A substantial set of cloud-drop-size data were collected on Mt. Washington, New Hampshire (USAF, Air Materiel Command, 1948), in 1946-1947. Most of these data were obtained using the rotating multicylinder which indicates the breadth of the drop-size distribution. The form of the distribution must be assumed. These are generally narrower than the distributions obtained by Diem, but this is reasonable in view of the great difference of physical character of the mountain cloud-cap situation from that of the free air clouds.

The data of Weickmann and aufm Kampe (1953), procured in all types of cumulus clouds using aircraft sampling technique, constitute one of the best sets of data available with which to illustrate the significance of coalescence processes in the development of rain. These data show clearly the evolution of the drop-size spectra from narrow and small (6 to 66μ diameter) in cumulus humilis to somewhat broader and larger (6 to 170μ diameter) in cumulus congestus to the most broad and largest (6 to 200μ diameter) in cumulonimbus clouds. In addition, these data provide vertical profiles of the drop-size spectra from which profiles of mean drop size, water content and droplet number are constructed. The decrease of droplet number together with the increase of water content with height above the base that is observed in these cumulus type clouds is attributable to a coalescence process superposed upon the condensation process.

A large collection of data has been assembled in the course of "Project Shower," a cooperative project involving researchers from the United States, Australia, and Sweden, under sponsorship by the Office of Naval Research. Types of cloud represented are the orographic clouds of Hawaii and trade wind cumulus. Data on drop sizes are reported by Squires and Warner (1957), and analyses are offered elsewhere.

b. Observations of Raindrop Sizes.—The early study of raindrop sizes dating from Lowe (1892), Wiesner (1895), and Lenard (1904) to Laws and Parsons (1943) is largely of historical interest at this point. Interest in raindrop-size spectra was greatly stimulated by the development of precipitation physics and the advent of weather radar during World War II. Numerous principles have been invoked and devices tried since the war in an equal number of efforts to obtain raindrop sizes routinely in detail and in quantity (Blanchard, 1949a, 1949b; Howell, Boucher, and Braun, 1951; Cooper, 1951; Katz, 1952; Jones and Dean, 1953; Mason and Ramanadham, 1953; Mikirov, 1957; and Dingle, 1957), however, relatively few of these efforts have produced major contributions to knowledge of raindrop sizes.

c. Direct Observations of Rain.—Blanchard's sustained interest in this problem has culminated in substantial data procured in the rains of Hawaii (Blanchard, 1953; Blanchard and Spencer, 1957). These have a special interest as regards the artificial stimulation of precipitation because of the predominant orographic effect which has been found favorable for the artificial increase of rainfall (Advisory Committee on Weather Control, Final Report, 1957).

A large mass of data collected by the photographic method of Jones and Dean have been reduced primarily in terms of (a) radar reflectivities and attenuation values (Jones, 1956; Mueller, 1957), and (b) the shapes assumed by freely falling raindrops (Jones, 1959). To date most of the direct measurements of raindrop sizes that have been used in studies of cloud processes appear to have been collected by the dyed filter-paper method (Blanchard). Warm process rains have been analyzed by Ogiwara and Sato (1951) and by Mordy and Eber (1954), among others.

Preliminary data obtained by Mason and Ramanadham have to date not been augmented, and Mikirov offers only token size spectra. Dingle's instrument is currently collecting data, preliminary analyses of which indicate considerable potential. Second-by-second totals of drops 200µ in radius and larger are available from these observations; minute-by-minute raindrop-size spectra are being constructed. Some observations, recorded by means of an oscillograph at a chart speed of 10 in./sec in heavy showers, indicate a pronounced tendency of raindrops to cluster, the number densities per 0.1 sec (870 cm^3) ranging from 0 to 13. Results and preliminary studies of these data will shortly be offered for publication.

A considerable amount of data on raindrop sizes has been collected in connection with radar observations of rain (Marshall, Langille, and Palmer, 1947; Imai, Fujiwara, Ichimura, and Yoshihara, 1955; Kodaira, 1955; Jones, 1956; Mueller, 1957). These research efforts are experimental evaluations of the relationship of rain at the ground to the associated radar echo intensities, and hence they mainly present the radar reflectivity values derived from the observed raindrop-size distributions. Their relationship to the rain-generating processes is not stressed.

d. Radar Observations of Rain.—Considerable effort has been made by radar meteorologists to deduce the rain-generating processes observed by radar. Bowen (1951) infers that the columnar type echoes observed in convective clouds at Sydney, N.S.W., are attributable to the coalescence of cloud droplets without ice particles. Battan (1953) supported by Atlas (1954) finds that 60% of the tops of echoes observed over Ohio first appeared at temperatures above 0°C, and that therefore middle latitude precipitation is frequently initiated without benefit of the ice-crystal process. The inference is that coalescence of liquid droplets is the necessary and important process which converts the initial cloud droplets to raindrops. The observations of Feteris and Mason (1956) are similarly interpreted. Harper (1957) notes that, in sustained steady rains in England, very little increase of drop size is found below 2000 ft, and concludes that in this type of rainfall, the radar measurement at 2000 ft provides a good estimation of the rain at the ground.

e. Comprehensive Observations of Rain.—A few research endeavors have combined several observing techniques to make comprehensive observations of storms and precipitating clouds. Cunningham (1952) concluded from his observations of the 3 April 1951 storm that most of the drop growth in the "steady" rain part of the storm was the product of snow agglomeration at moderately high levels, whereas in the southern, more showery portions, only about one-fifth of the growth was attributable to ice accretion, the remaining four-fifths resulting from coalescence in the low-level dense water-droplet clouds.

On the basis of extensive observations over Puerto Rico, Ohio, Illinois, and New Mexico, Byers, Battan, and Braham (1954) noted that warm process rains occurred both in the maritime subtropics and in middle latitude continental areas, but not over New Mexico. They suggest that whereas the warm process rains of Puerto Rico may be attributed to the presence of giant sea-salt nuclei capable of growing large enough by diffusion to initiate gravitational coalescence, this cannot be the case in the Ohio-Illinois area because such nuclei are not present there. Hence the coalescence process proceeds in the latter area by some other means.

Cunningham and Atlas (1954) on the basis of aircraft, radar, and ground-based observations of five cyclonic storms over New England, report that most of the water for drop growth of rain was derived from low levels in the central and rear parts of the subject storms. Again it is inferred that coalescence of liquid droplets is an important process in rain generation for these parts of the storms.

Ludlam and Mason (1957) report studies in which visual and synoptic data have been used to complement radar observations of rain. In these they find strong evidence that the coalescence process is essential to the release of summertime showers as well as to the production of precipitation in cold front situations. The techniques used are described and the fibrillation zone is discussed. A complete description of the fibrillation zone in decaying cumulus appears in an earlier paper by Ludlam and Saunders (1956). It is concluded that substantial coalescence is required to produce the observed showers (in Sweden) even though the temperature may be as low as -20°C at the tops of the incipient shower clouds.

3. Theoretical Studies of Coalescence

The analysis of collection efficiencies of large drops falling through a field of smaller drops presented by Langmuir (1948) is apparently the beginning of a quantification of this process. Langmuir found that for each droplet size there is a minimum size of the larger impinging drop below which no collision will occur (e.g., no drop smaller than 45-μ diameter will collide with a 12-μ-diameter droplet). In general, the assumption is made that "collision" is always followed by "collection" in accord with the early observations of Findeisen (1932). The computations are not clearly meant to apply to the case of equally or nearly equally sized drops.

Calculations of the rate of growth of raindrops by coalescence in the gravitational field are made also by Ogiwara (1949). Disregarding air turbulence, Ogiwara concludes that the conditions required for warm process rain to occur are frequently present. He disputes the Bergeron (1933) ice-crystal nuclei theory. Dask (1950) calculates collection efficiencies comparable in specification to those of Langmuir (1948), but he obtains higher values. Calculation of the time necessary for a drop of radius r_1 to grow to radius r_2 is carried out by Kriestanov (1950) accounting for air resistance by the use of a constant drag coefficient, C.

The warm process of the formation of rain is analyzed by Bowen (1950). Calculating the rates of growth of droplets by condensation and coalescence on the basis of Langmuir's collection efficiencies and considering their probable trajectories through the clouds, he shows that none can grow large enough without coalescence to fall as rain. The maximum heights reached and the final diameters of the raindrops emerging from the clouds are nearly linear functions of the vertical air speed. The final size of a raindrop turns out to be more dependent upon vertical air speed than upon supersaturation or cloud water content, and the time for rain to form is calculated to be inversely proportional to the vertical air speed.

Houghton (1950) treats the gravitational accretion process for the growth of raindrops and discusses a method for calculating the rate of growth. Shishkin (1951) analyzes the mechanism of coalescence under gravity and under sudden changes of air flow, thus opening the question of the effect of turbulence.

Ludlam (1951), using a model cumulus cloud convection situation, computes the numbers and sizes of cloud droplets formed in the updraft. Growth by coalescence of 20- to 40-μ radius drops is calculated using an efficiency of catch depending upon radius and height.

Numerical evaluations of equations representing the rate of change of drop number were done by Best (1952) under various assumptions. These lead to the conclusion that, except for large drops, the increase in number within a given diameter range due to condensation is much larger than that due to coalescence. It is pointed out that coalescence may result in a decrease of drop number in some categories of size.

The classical theory of von Smoluchowski (1917) is considered by Inn (1952). Effects of surface tension, of electric charges, and of attractive and repulsive forces due to evaporation or condensation are examined. Reference is made to experimental evidence that not every collision between particles results in coalescence (La Mer, Inn, and Wilson, 1950).

Considering the production of rain and drizzle in stratiform clouds, Mason (1952) constructs a theoretical model of droplets grown on salt nuclei by condensation and combined by coalescence. It is found that a uniform updraft up to 10 cm/sec cannot produce drizzle at the ground. It is therefore inferred that turbulence plays an important role in the process, not so much by directly producing collisions as by causing a few drops to traverse a long enough path in the cloud to grow to the requisite size during their residence in the cloud.

Melzak and Hitschfeld (1953) analyzed the coalescence of particles moving randomly and coalescing upon collision with some probability less than one. The analysis is based upon assumed mass distributions because of the additive character of mass in the process.

Changes in the raindrop-size distribution of shower rain due to coalescences in and outside of cloud masses are computed by Rigby and Marshall (1953). Evaporation is neglected. The changes of size distribution produce changes in the intensity of precipitation and in the radar reflectivity. Comparison of the computed changes with radar observations suggests that the observed increases of radar echo intensity can be accounted for by a coalescence mechanism. This problem was studied further using numerical methods by Rigby, Gunn, and Hitschfeld (1954). Two cases, that of continuous rain and that of showery rain, are treated by a discrete collision-capture approach.

Telford (1955) also examines coalescence growth as the product of a discrete accretion process rather than a continuous process. Random fluctuations of the time required for different drops to effect captures lead to a complete raindrop spectrum. The total time required is less than that required for continuous growth of a particle to raindrop size. Specifically, he finds that under typical conditions, drops of 23-μ radius can form from a cloud of 10-μ-radius droplets in about 5 minutes.

Collection efficiencies of small droplets are estimated theoretically by Pearcey and Hill (1957) using Oseen's approximation for the solution of the equations of fluid motion around spheres. A substantial enhancement of the collision cross section of droplets larger than 10μ in radius for the capture of smaller droplets is found. This enhancement is attributed to the wake effect. In addition, the theory suggests that collision will occur only for nearly equal droplets at sizes of 10-μ radius and smaller. It is therefore concluded that such small droplets are unimportant in the formation of raindrops. The authors point out that for the case of equally sized droplets the relative velocities are small and the time required to approach contact is long. They infer that turbulence is likely to affect collection rates strongly and negatively.

In discussion of the paper by Pearcey and Hill, Mason (1957) raises objections to their use of Oseen's approximation for the case of closely spaced (just before collision) spheres.

Browne and Hudson (1957), in considering Swinbank's (1947) statement of the problem of coalescence of drops, point out that there exists a possibility that equally sized drops may join, decreasing their total surface energy steadily in the process. Swinbank had argued that two drops in joining changed their collective surface free energy first upward and then downward, placing an energy barrier in the path of the coalescence process.

Solving the Stokes equations of motion, Hocking (1959) has determined the forces acting upon two spheres moving in a fluid medium. Allowing for mutual interference of the flow around the spheres and for the relative trajectories of fall under gravity, he has calculated the collision efficiency for drops up to 30-μ radius colliding with smaller droplets. Drops of 18-μ or smaller radius are found to have no collection potential, i.e., they must be collected by larger drops. The calculations are meant to fill a void left by Langmuir (1948) and by Mason (1957) in the zone in which the collecting and collected drops are nearly the same size. Mason's (1957) collection efficiencies were computed for the case of the drop much larger than the droplet, but they overlap Hocking's range somewhat. Where comparable as to conditions, Mason's collection efficiencies are high compared to Hocking's. The results are widely different from those of Pearcey and Hill (1957) because of the different approaches used. It is emphasized that the Oseen approximation used by Pearcey and Hill is probably not valid when the drops get quite close together. The Stokes solution used by Hocking is more appropriate for this region.

To this point, only a few of the works cited have been concerned with the specific means of producing or preventing coalescence. Swinbank (1947) and Browne and Hudson (1957) point to surface free energy as an important consideration. Inn (1952) is concerned with several specific phenomena which might have something to do with the question, namely, surface tension, electric charges, and forces due to the phase changes at the drop surface. Mason (1952) suggests that turbulence may sometimes be an important factor.

Of the factors noted, the consensus is that the effects of electric charges and of turbulence are probably the most important. A number of papers treating these specifically have appeared.

4. The Study of Electrical Effects

a. Theoretical.—One of the older pertinent observations is that of Lord Rayleigh (1879) to the effect that drops in impacting jets rebound from one another when they are not electrified, but that when they are slightly electrified, the drops unite upon collision. There is no discussion of the forces involved in producing collision, of surface tension, or of surface free energy.

Later authors' observations in cloud and fog attribute the opposite effect to electric charges. Wigand and Frankenberger (1931a, b) explain the stability of fogs and clouds by invoking the electrostatic forces of repulsion that would be present between droplets carrying charges of the same sign. They found that drop charges measured in natural fogs were of the right magnitude to stabilize the fogs on this basis. Houghton (1938) tends to agree with this view, commenting that electric charge might serve to inhibit collision of droplets.

Pauthenier (1948, 1950) experimented with the seeding of fogs using charged drops on the one hand and neutral drops on the other. The electrified drops were far more effective in improving visibility in the fogs than the neutral ones were, and his inference is that the electrification of the seed drops improved their collection efficiency. This effect was discussed earlier by Houghton and Radford (1938) and by Humphreys (1926).

Cochet (1951) considers the collection efficiencies for charged droplets in a manner similar to Langmuir's (1948) treatment for uncharged droplets. Under otherwise similar conditions, a charged drop of 30-μ diameter grows to 140-μ diameter in 520 sec while falling 116 m, whereas for the same growth the uncharged drop requires 2500 sec and a fall of 300 m. Thus charged drops are much more efficient in collecting cloud water than uncharged drops.

Shishkin's (1951) results indicate that, in a polydisperse cloud with an ascending current, development of cloud drops to 20-μ diameter is accomplished primarily by diffusion. Most rapid growth of drop charge occurs in the layer 600-1200 m above the cloud base when the vertical wind speed is 1 m/sec. Charge and size of drops increase rapidly in falling from about 3 km to about 1 km above the cloud base. This layer is therefore considered to be the probable zone of origin of thunderstorm electrical phenomena. The influence of charge upon coagulation and vice versa are not considered as such.

b. Experimental.—Twomey (1956), using the method of Wells and Gerke (1919), measured the charges on drops in natural cloud in relation to their sizes. The experiments were conducted on Mt. Wellington in Tasmania, elevation 4160 ft MSL. Wintertime observations were made in stratus and stratocumulus clouds formed in clean maritime air. Half of the drops observed carried detectable charges. In the absence of the ice phase, at least 80% of the charged droplets carried positive charges. When the ice phase was present, 40 to 100% of the charged particles carried negative charges. In summer, the temperatures ranged from 8 to 17°C; hence no ice phase was present, and no negative charges were observed. About 80% of the drops carried positive charge. No relationships to coalescence processes are mentioned.

Phillips and Kinzer (1958) and Allee and Phillips (1959) have made similar experimental measurements from Clingman's Peak, elevation 6580 ft, near Asheville, N. C. These studies are all in cumuliform clouds, however. The cases studied are divided into "storm" and "nonstorm" situations. In the nonstorm clouds about 12% of the drops were not charged, but the distribution of charge was nearly Gaussian with the mode at zero charge. It was observed that the charge distribution broadens as the drop size increases, and that maxima of charge in the range 20 e to 90 e were found occasionally. A commonly occurring charge magnitude was 10 e.

In the storm clouds (3 storms) many fewer drops were studied. In two of the storms all drops but one were charged negatively. In the third storm, a shift was observed from (1) a mixture of positively and negatively charged drops lasting about 8 min to (2) a positively charged cloud lasting about 5 min to (3) a nonstorm-type distribution of small charges. The negative charge per drop in the first two storms averaged more than 350 e, and the magnitude of charge per drop in the third storm averaged about 200 e. The drop-size distributions were similar to those observed by Diem (1948).

Additional considerations of the conductivities and electric field strengths at the site lead these investigators to conclude that the observed drop charge distributions are very nearly those described by the theory of Gunn (1955, 1956). In general, the findings tend to disagree with Twomey's (1956) results.

5. The Study of Turbulence Effects

Hydrodynamic effects, electrostatic forces, and differences of gravitational fall speed all appear to have characteristics that should promote the coalescence of cloud droplets in the rain-forming process. For the most part, upon analysis it is found that each does have an effect, but the effect required to produce what is observed regularly in clouds and precipitation must be substantially greater.

In 1939, Arenberg attempted to show that air turbulence might be the major factor in the growth of cloud drops. He pointed out that the role of turbulence in bringing together condensation products having varied histories should lead to the broad size distributions necessary to get active coalescence. Further, the alternating vertical excursions of drops under turbulent conditions, he suggested, could lead to a broadening of the size distribution.

Houghton (1951), however, comments that except for evaporation in the downward motions, turbulence tends to narrow the size distribution and to give a small net effect.

The role of turbulence in clouds in producing rain has been studied by East and Marshall (1954). Referring to Langmuir's analysis (1948), and to observations of the droplet sizes characteristic of young cumulus clouds (e.g., Weickmann and aufm Kampe, 1953), they point out that these droplets are too small to grow very rapidly by colliding with each other under gravity alone. However, the nature of the circulation in cumulus cloud is such as to subject the droplets to random accelerations in the turbulent air. A one-dimensional analysis of random accelerations superposed upon gravity indicates that collisions and growth will result if the turbulence is sufficiently violent. Accelerations of the order of 2 g should make growth possible for droplets down to 11.5-μ radius, and any component of turbulence parallel to gravity must add to the coalescence effect.

Saffman and Turner (1956) carry the analysis further on a more realistic basis. Considering that the droplets are very small compared to the smallest turbulent eddies, they assume that the collision rates depend only upon (1) the rate of energy dissipation per unit mass, ϵ, (2) the dimensions of the droplets, and (3) the kinematic viscosity, ν. The collision rate due to spatial changes of turbulent velocity turns out to be $N = 1.30\ (r_1+r_2)^3\ n_1n_2(\epsilon/\nu)^{1/2}$ as long as $1 \leqq r_1/r_2 \leqq 2$. Here n_1 and n_2 are the mean concentrations of two sizes of droplets of radius r_1 and r_2, respectively. The authors conclude that, as long as it is possible to consider irrelevant the low collection efficiencies calculated for uniform streaming and for drops of widely different sizes when one wishes to treat the case of nearly equal droplets, their equations indicate that considerable rates of coalescence will be found in turbulent air even in clouds of uniformly sized droplets.

East (1957a), drawing on the work of Batchelor (1951, 1953) arrives at a different conclusion using his calculation of collision rates. He finds that turbulence would provide an effective precipitation-forming mechanism in cumulus clouds if the root-mean-square turbulent accelerations were about 3 g. Data procured in airplane flights through thunderstorms lead to an estimate of maximum turbulent accelerations in nature of the order of 1/6 g, but admittedly these data are not well suited to the purpose because of the scale differences involved. East concludes, as he must from the evidence of his computations, that turbulence is not an important factor in convective precipitation.

In a subsequent study, East (1957b) analyzes the process of droplet growth in cumulus cloud on the assumption that condensation and coalescence are cooperative, an idea expressed earlier by Weickmann and aufm Kampe (1953). Starting with an 18-μ radius droplet as the largest found in a fair weather cumulus cloud, and assuming condensation and coalescence proceed together, he finds that 50-μ radius drops first appear in heavy cumulus near a liquid water mixing ratio level of 6 g/kg. He notes that in nature (1) liquid water content increases as cumuli grow, and hence condensation must take place; (2) total droplet population decreases as cumuli grow, and hence coalescence must occur; and (3) droplet-size distribution changes from one having maximum droplets near 18-μ radius to one extending to 100-μ or larger radius, and hence a fraction of the droplets grow rapidly. His conclusion is that the important growth process in cumuli involves both condensation and coalescence.

Mason and Ghosh (1957), in examining the model used by East (1957b), point out that nuclei of mass near 10^{-10} g are necessary to supply the assumed 18-μ radius droplets in the cumulus humilis stage (within a few hundred sec). It therefore appears that the conditions for the condensation-coalescence shower to form are frequently not fulfilled.

6. Laboratory Experiments

The fact that rain does occur as it does despite all the theoretical indications that it is not likely to be formed constitutes one of the basic challenges of cloud and precipitation physics. The invariable conclusion is that the collusion of two or more of the feeble effects (electrostatic, turbulent, gravitational) operates with sufficient efficiency to produce what is observed, namely, rain from clouds. Because theory becomes quite complex in this situation, experiment is adopted as the investigational technique.

A highly ingenious experimental arrangement was constructed by Gunn and Hitschfeld (1951) for the study of coalescence between large and small drops. A cloud was generated in a 3-m-tall chamber through which drops of 1.59-mm radius were dropped. The measured collection efficiencies of these drops with respect to three different cloud droplet sizes agreed well with Langmuir's calculations. Thus it is concluded that every drop-droplet collision resulted in coalescence growth of the drop. Charges of the order of 0.2 e.s.u. per drop failed to influence the collection efficiency.

Sartor (1954) attempted, by a modeling technique, to simulate cloud droplets in air by means of liquid drops in a viscous medium. The resulting collision efficiencies and droplet trajectories differ markedly from those obtained theoretically, and the coalescence of water drops falling through mineral oil is found to depend upon the strength of an applied electric field.

Telford, Thorndike, and Bowen (1955) used a vertical wind-tunnel cloud chamber to study the coalescence of cloud droplets of nearly equal size (about 150-μ diameter) in the absence of turbulence, under g, with and without electric charges present. They found extremely high values of collection efficiency which they attributed to the process of "wake capture," and they obtained up to twenty-fold increases of the collection efficiency by placing electric charges on the cloud droplets. They noted, however, that charges of the same sign tended to inhibit coalescence.

Sartor (1956), commenting upon the Telford, Thorndike, and Bowen experiments, suggests that the velocity profile of the tunnel and uncontrolled electric fields in the apparatus may have distorted the experimental observations.

Telford and Thorndike (1956) present additional data obtained using the apparatus reported upon earlier. In particular, collection efficiencies for the size range 100-μ to 200-μ diameter are presented in graphical form. The regression relating drop size to collection efficiency, and indicating a decrease in efficiency as drop size increases, is considered not significant. Experimental error is estimated at 26% on the average, and the overall average collection efficiency is about 13.

Schotland (1957) modeled colliding water droplets by means of steel balls in a sugar solution. He was able to model all necessary dimensionless ratios except the density ratio (density of drop/density of medium) which was about 100-fold too low. He modeled drops in the range 11-μ to 22-μ diameter and found a collision efficiency of 1.7 (1 ± 0.2).

Additional laboratory measurements of the growth and collection efficiency of cloud droplets are reported by Kinzer and Cobb (1958). In these, 2-μ-radius droplets were held stationary in an upward streaming cloud. Growth of the stationary droplet by accretion was observed and the rate of increase was measured from 4-μ to 65-μ radius by means of a telemicroscope. The collection efficiencies observed agree with an intuitive theory which implies the transfer of small droplets by small-scale eddy diffusion to the growing droplet.

Clouds used in these experiments were of two types, one of narrow size spectrum having 80% of its free water contained in droplets of 5.5- to 8.0-μ radius, and the other having a broader distribution of free water among droplets of 3.9- to 10.4-μ radius. The clouds were randomly electrified, but the electrification was capable of producing dynamic effects only 0.1 as great as those of the eddy transfer. It is inferred that coalescence may, however, be promoted by these small electrical forces whenever the droplets are transported by eddy diffusion to within 2 to 3μ of the growing droplet.

These authors conclude that although the electric effect is negligible for growing drops of radius greater than 100μ, it needs to be studied further for smaller drops. It is, however, unlikely that the electric effect can be significant after the growing droplet radius reaches 7 to 8μ. Electric charge image forces may be effective at distances of 2 to 3μ.

Hocking (1959) criticizes the work of Sartor and of Schotland because their models do not completely simulate the cloud droplet collision process, and hence their results must be regarded with some suspicion. The results of the Telford, Thorndike, and Bowen experiments are criticized by most other researchers in this field, and indeed, they are so far different from other results that they are naturally suspect. In any case, the problem of the coalescence of cloud droplets does not involve particles in the 100-μ diameter and larger size categories except as a product. The work of Kinzer and Cobb appears to attack more directly the cloud droplet coalescence problem. Obviously the technical problems are numerous and difficult in making valid experiments of this type. The fact that their "intuitive theory" involving eddy diffusion at least tentatively agrees with their experimental findings suggests that small-scale turbulence deserves further consideration as an effective agent in droplet coalescence.

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B. LABORATORY PHASE

It is clear that experimentation of the sort proposed, namely, that directed toward the determination of the efficacy of turbulence as a droplet coalescence-promoting mechanism, can be useful only to the extent that it can be reproduced. This requirement demands the availability of three separate techniques, each of which must be well developed to assure definitive results:

1) It means that a method for modeling "turbulence" reproducibly must be devised.
2) It means that the test clouds within which observations are to be made must be reproducible.
3) It further requires an adequate technique for obtaining observations, without introducing extraneous disturbances, of the cloud drop spectra and of the dynamics of the cloud droplets under the influence of the "turbulent" motions.

1. The Generation of Reproducible Vortices

From the outset, the requirement of reproducible "turbulence" has emphasized the need for defining turbulence so that it might be modeled reproducibly. For the most part, turbulence has been described in terms of its effects (see Hewson, 1952), but as yet there appears to be no satisfactory definition of turbulence (Sutton, 1953). Nonetheless, the statistical approach to the construction of a theory of turbulence (Taylor, 1921, 1935, 1936; Batchelor, 1953) has led to the description of turbulence in terms of power spectra (Taylor, 1938). Thus turbulence may be envisioned as a complex of eddy-like motions described by the frequency distribution of their periods of rotation or of some other property of the individual eddies (size, vorticity, etc,).

The approach adopted for the present work has been one of reducing this general concept of turbulence to its "lowest common denominator," namely, the individual eddy. Such an eddy can be generated by means of an airfoil as an acceleration or deceleration vortex, or as the product of an abrupt change of the lift coefficient. The analysis follows.

a. Theory of Vortex Generation.—When the aerodynamic lift of an airfoil is changed, the circulation about the airfoil is changed, and in general this results in the generation of a vortex which is shed at the trailing edge of the airfoil. In the case of two-dimensional flow, the conditions may be stated as follows:

$$L = C_L \frac{\rho V^2}{2} c , \qquad (1)$$

where

L is the lift,
ρ is the air density,
V is the speed of the air relative to the airfoil,
C is the chord of the airfoil,
C_L is the lift coefficient, and

$$C_L = m\alpha \quad , \tag{2}$$

where

m is the slope of the lift curve (for angles of attack below stall), and α is the angle of attack.

For a given airfoil, with angles of attack well below the angle of stall, C and m are constant, and ρ can in general be kept constant. Hence a change in lift can be obtained by changing either C_L or V, and in this case, C_L is dependent only upon the angle of attack, α. Hence

$$\Delta L = \frac{\rho C}{2} \Delta(C_L V^2)$$

$$\Delta L = \frac{\rho C m}{2} \Delta(\alpha V^2) \quad , \tag{3}$$

and alteration of either the angle of attack or the speed of the airfoil through the air may change the lift.

For an airfoil to have lift, it is necessary that some net circulation, Γ, exist about the airfoil. For an airfoil to have lift, it is necessary that some net circulation, Γ, exist about the airfoil. The relation of the lift to the circulation is

$$L = \rho V \Gamma \quad , \tag{4}$$

hence from Eq. (1) and Eq. (2),

$$\Gamma = \frac{Cm}{2} \alpha V \quad . \tag{5}$$

For experimental purposes, either α or V should be held constant, and the resulting forms for $\Delta\Gamma$ are:

$$(\Delta\Gamma)_\alpha = \frac{Cm\alpha}{2} \Delta V \tag{6a}$$

for constant angle of attack, α; and

$$(\Delta\Gamma)_V = \frac{CmV}{2}\Delta\alpha \tag{6b}$$

for constant air speed, V.

If the lift, L, is changed abruptly, as by an impulsive acceleration, or by an instantaneous change of α, then the circulation, Γ, must also change abruptly, and it is this change that results in the generation of a vortex. The circulation of the vortex may be written:

$$\Gamma_V = \oint V_i \cos(V_i, ds)ds \quad , \tag{7}$$

where

Γ_V is the circulation of the vortex,

V_i is the instantaneous air speed in the vortex tube considered, and

s is the path length in the vortex tube, and the parenthesis denotes the angle between the direction of V_i and ds.

Initially, the analysis of the artificially generated vortices may be based upon the assumption that, to a first approximation, the change of circulation about the airfoil may be set equal to the vortex circulation; hence

$$\Gamma_V = \frac{Cm}{2}\Delta(\alpha V) \quad . \tag{8}$$

In the present experiments, the angle of attack is held constant and the airfoil is accelerated at a measurable rate. Equation (7) for these conditions is

$$\Gamma_V = \frac{Cm\alpha}{2}\Delta V \tag{8a}$$

b. Description of the Airfoil.—The above analysis was developed under the assumption of two-dimensional flow which does not hold in the case of a three-dimensional airfoil of finite span. With an airfoil of finite span, air tends to flow over the tips, causing the formation of tip vortices and consequent reduction of lift. The addition of tip plates prevents the formation of tip vortices and justifies the two-dimensional assumption.

The airfoil chosen is an NACA 63_4-021 type which is rather thick and symmetrical (Abbott, von Doenhoff, and Stivers, 1945). A rectangular airfoil with a 3-in. chord and a 4-in. span and with large tip plates was built. The accompanying photograph, Fig. 1, shows the airfoil mounted on its car in the test chamber. In this picture, the airfoil is set to have an angle of attack of -9°.

The formulae of the preceding section may be adapted to the actual three-dimensional case by substituting the projected area for the chord. Thus, the lift becomes

$$L = \frac{\rho V^2}{2} Sm\alpha \quad , \tag{1a}$$

where S is the area of the airfoil (chord times the span), and the vortex circulation is

$$\Gamma_V = \frac{Sm\alpha}{2} \Delta V \quad . \tag{8b}$$

The slope of the lift curve, m, cannot be determined from NACA experimental data because those data were obtained under conditions of steady flow with the Reynolds number near 3×10^6. In the present chamber, Re is about 3×10^3. The best approximation for m can be derived from the two-dimensional theory which gives

$$m = 2\pi \quad .$$

This theory also predicts that the drag will be zero but this does not hold in the actual case. Again, the NACA data do not apply directly, but at angles below stall, most of the drag comes from skin friction. This is practically what it would be if the airfoil were a flat plate aligned with the stream (Rauscher, 1953). Therefore, it is reasonable to assume that the drag will be nearly constant for angles of attack below stall.

c. Airfoil Tests and Results.—A smoke chamber was used to test the airfoil model as a vortex generator. The smoke chamber is a cubical box (2 by 2 by 2 ft); three walls are transparent plastic and the other three are plywood. The airfoil was mounted on rails that run through the box.

Impulsive acceleration was provided by pulling the airfoil with a cord tied to the 1/4-in.-diameter shaft of a 1525-rpm electric motor. To allow the motor to gain speed before pulling the airfoil, two inches of slack were left in the line. The speed with this arrangement was 22 in./sec. The starting position was arranged so that the starting (accelerating) vortex would be generated near the middle of the box and the stopping (decelerating) vortex off to one side.

The initial experiments were performed using smoke as an aerosol. It was not possible to photograph the vortices successfully because of the difficulty of obtaining sufficient contrast. As a result, the patterns were recorded by means of sketches (Figs. 2-6). The sketches are labeled to indicate the angle

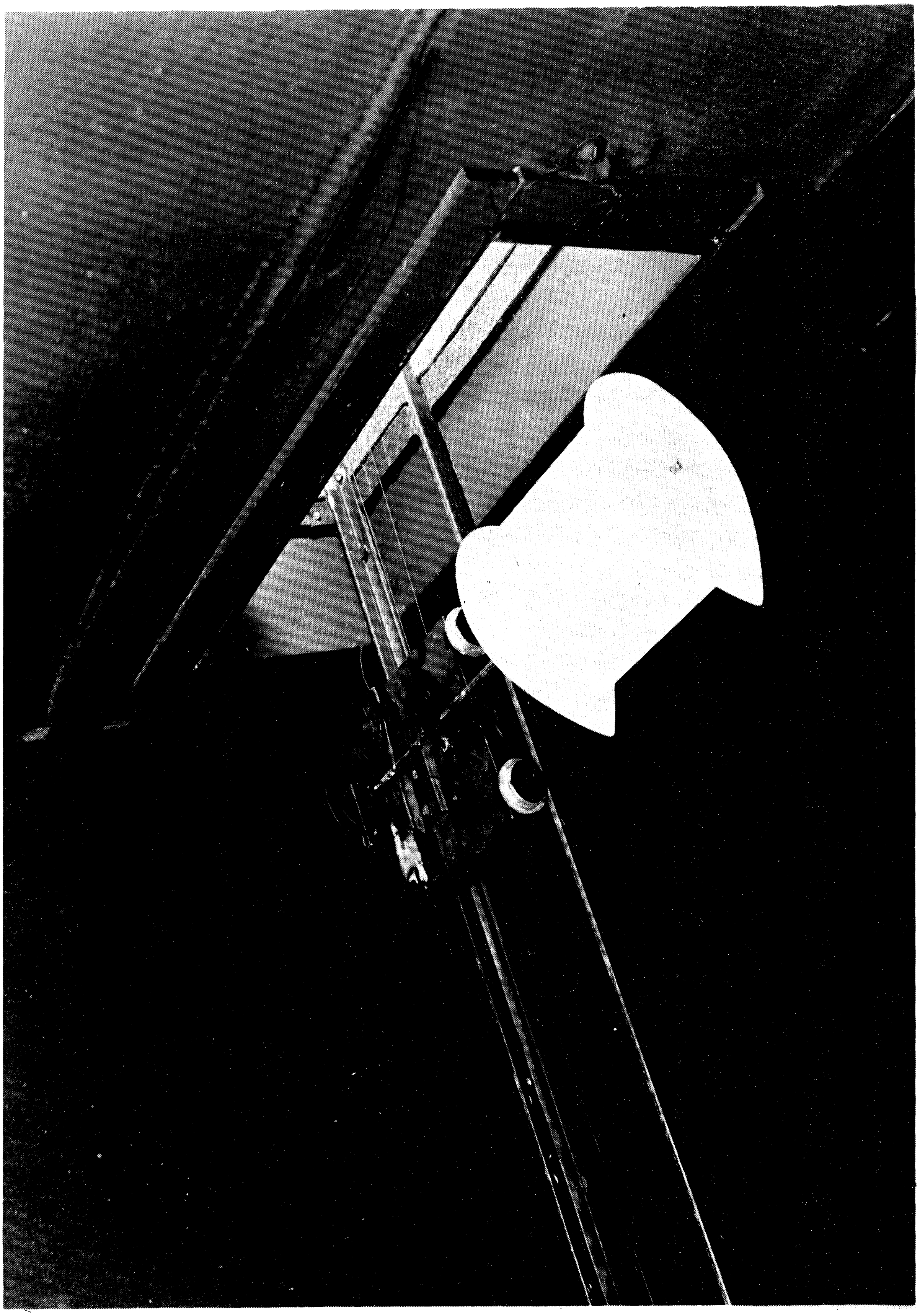

Fig. 1. The airfoil assembly as it appears in the vertical tunnel cloud chamber.

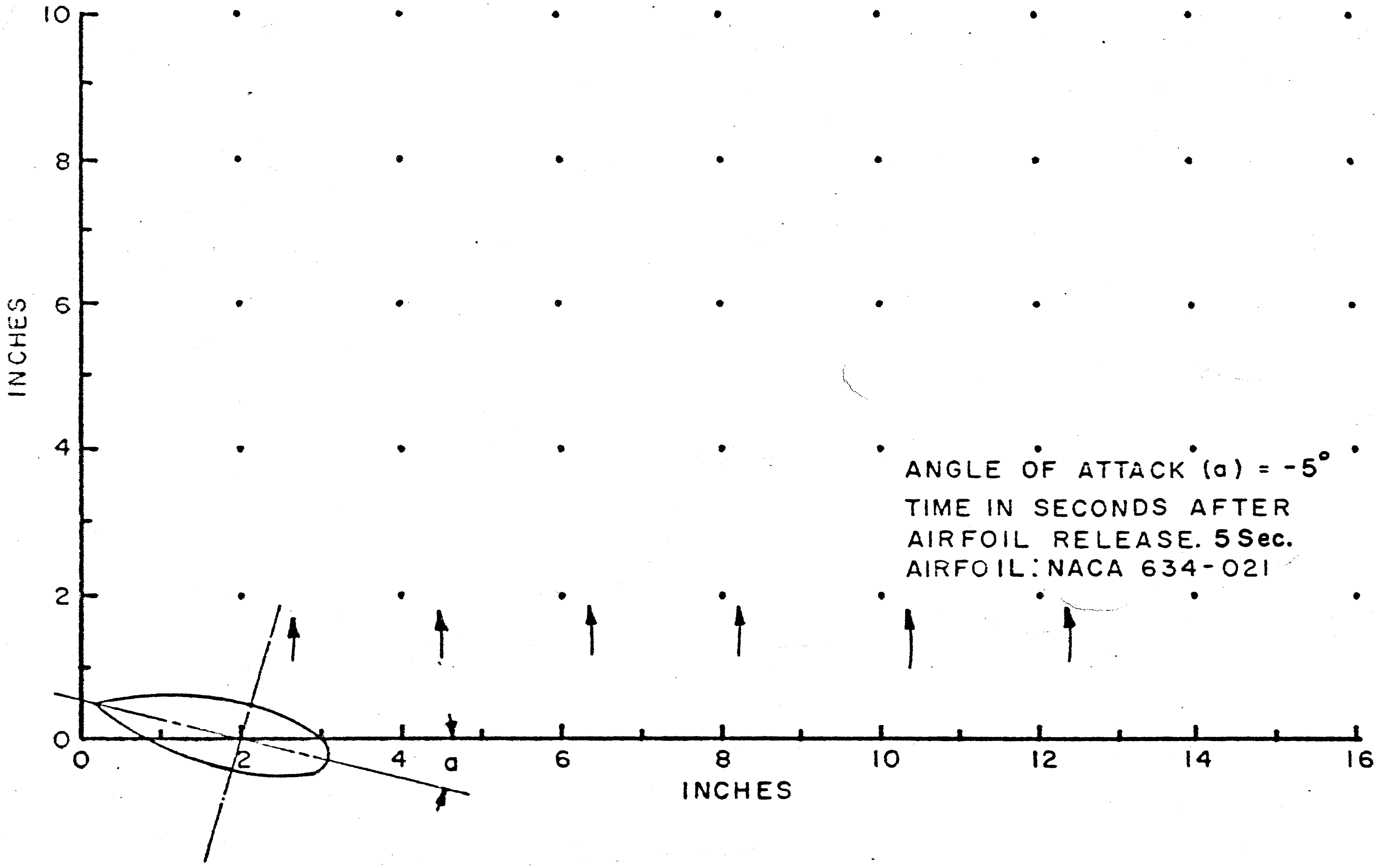

Fig. 2. Sketch of observed vortex generated by use of the airfoil model.

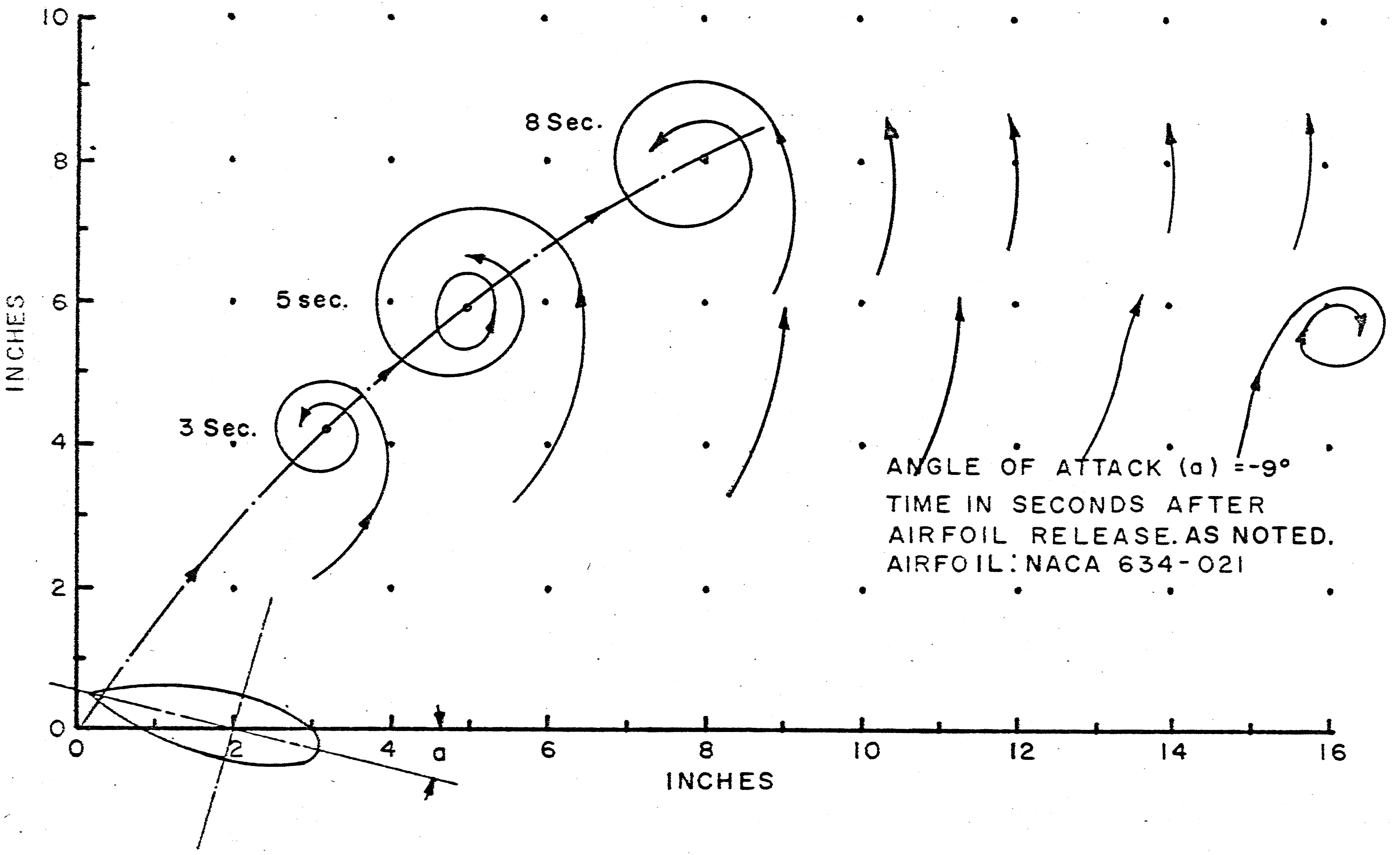

Fig. 3. Sketch of observed vortex generated by use of the airfoil model.

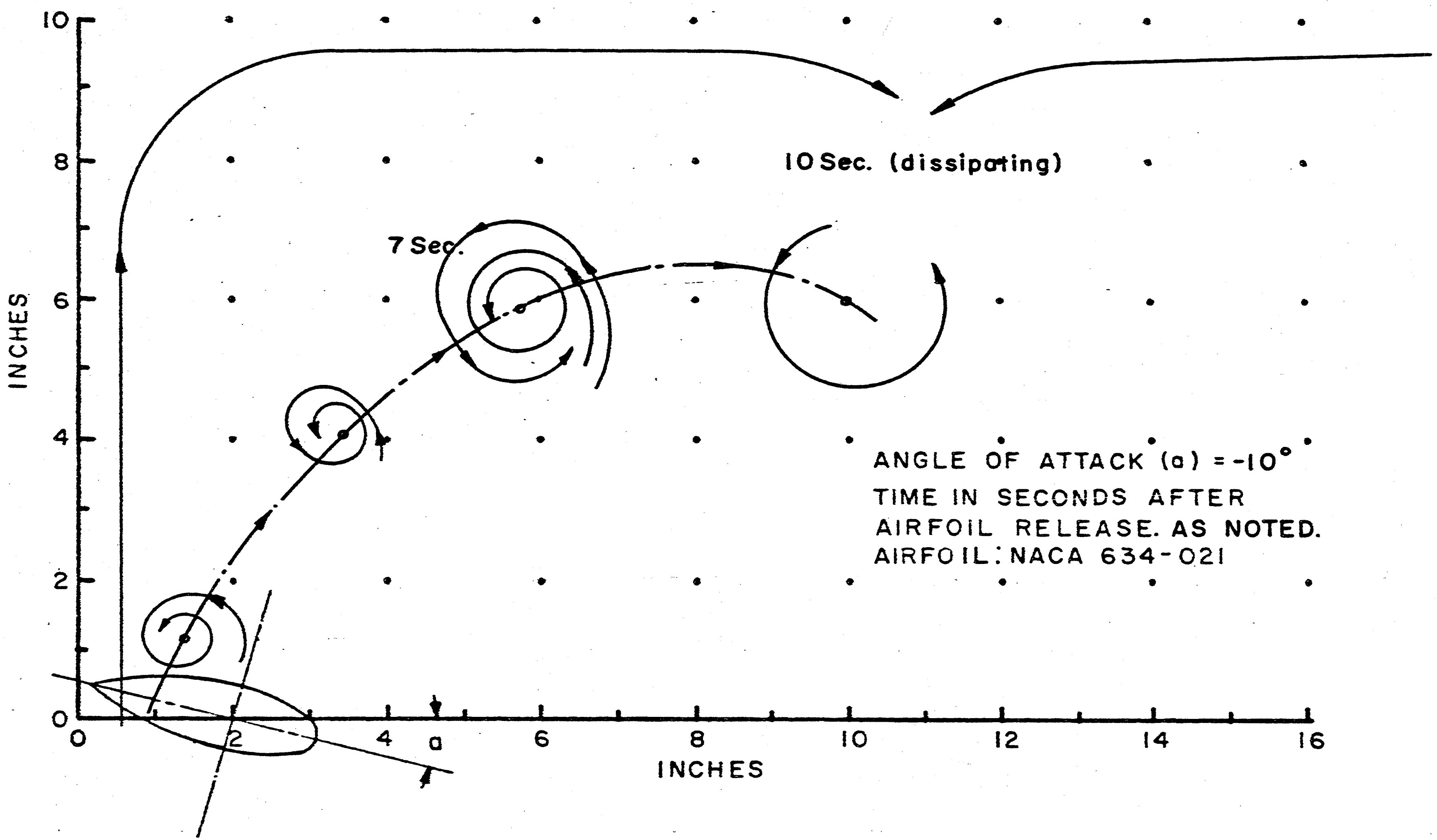

Fig. 4. Sketch of observed vortex generated by use of the airfoil model.

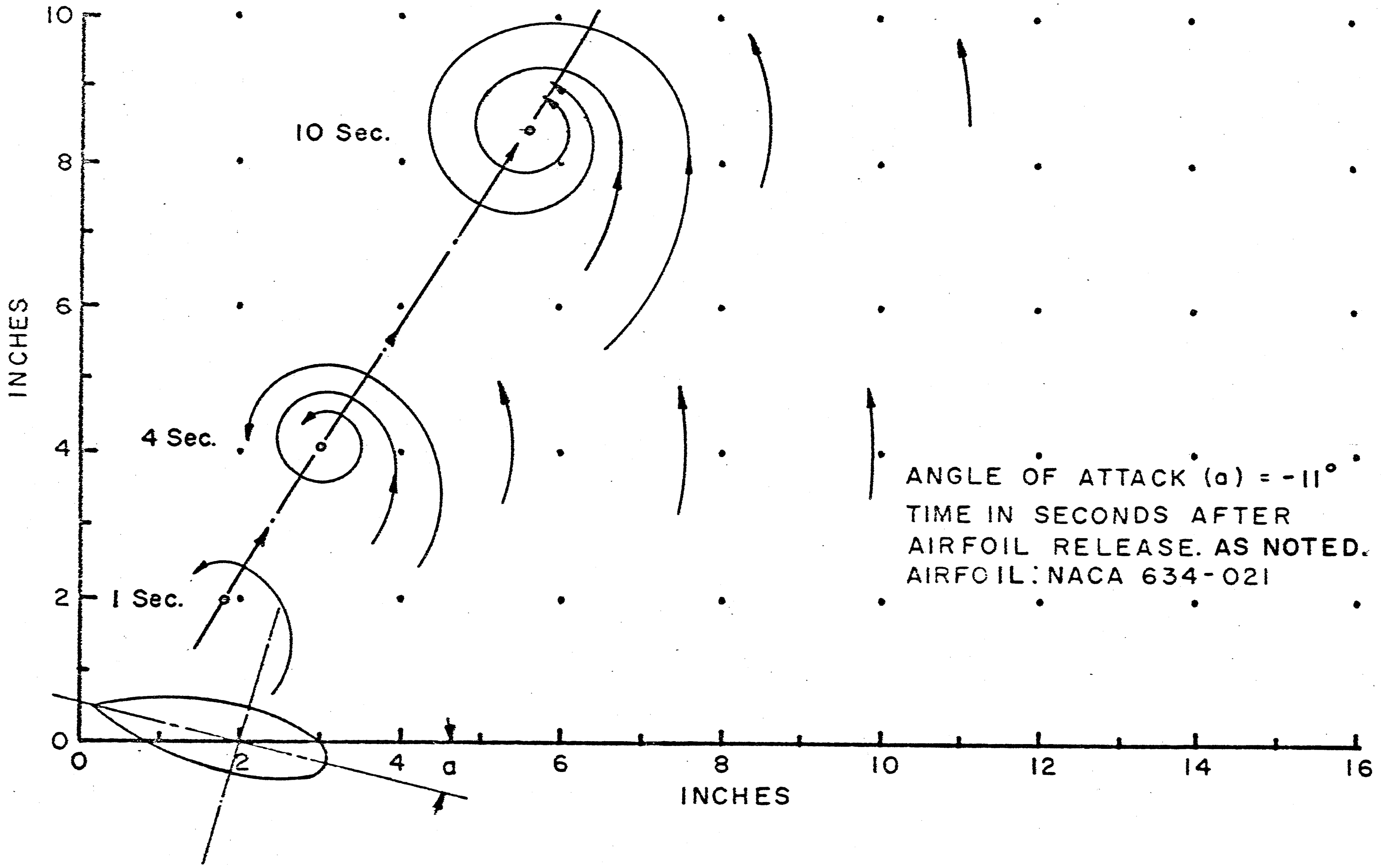

Fig. 5. Sketch of observed vortex generated by use of the airfoil model.

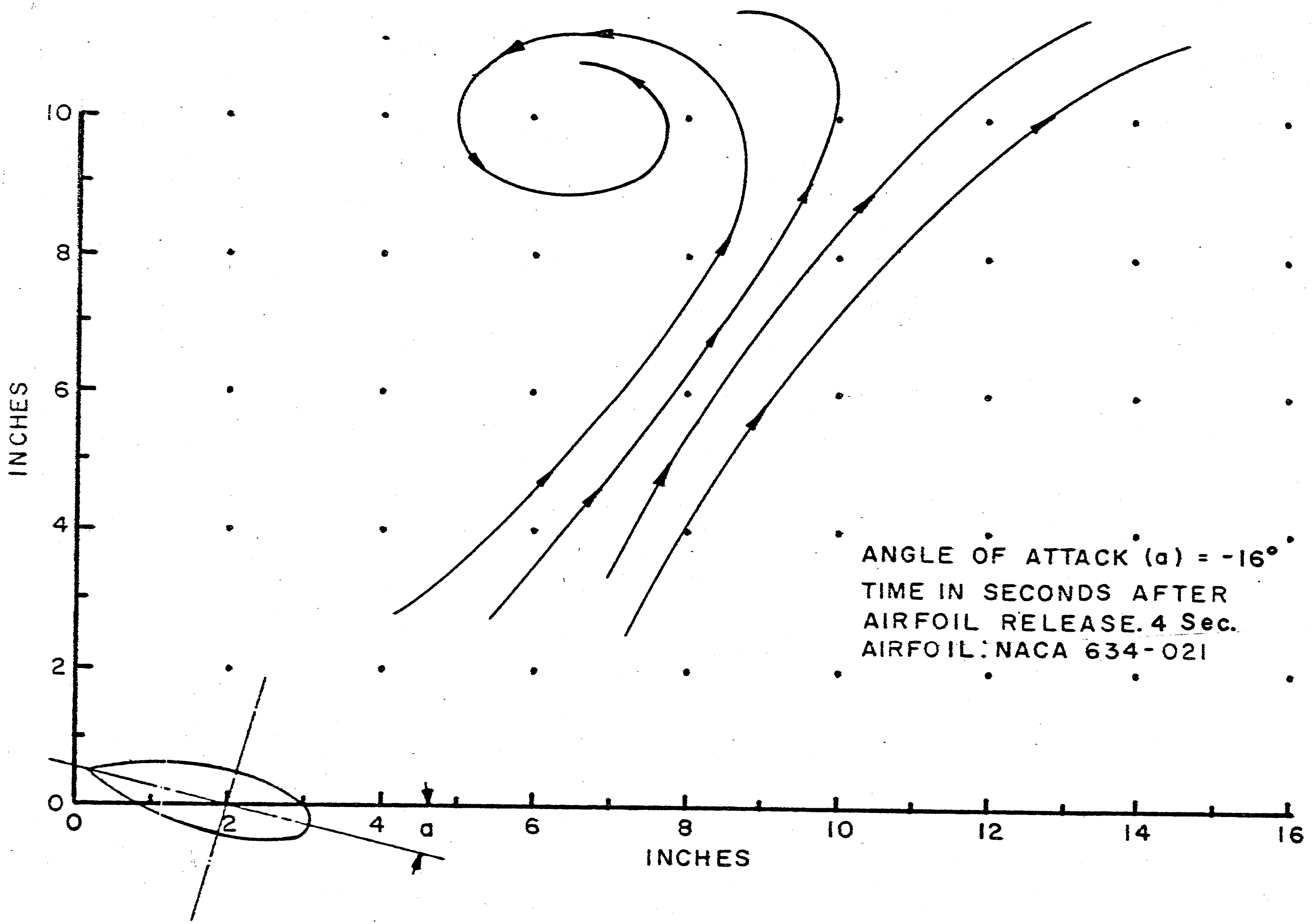

Fig. 6. Sketch of observed vortex generated by use of the airfoil model.

of attack and time after the start of acceleration.

Figure 2 shows the starting position of the airfoil and indicates that a -5° angle of attack does not cause a significant vortex with the acceleration used.

Figure 3 shows the sequence of air flow for a -9° angle of attack. Initially there is an upward impulse attributable to the negative lift; the acceleration vortex rises slowly, expanding at first, and then dissipating.

Figures 4, 5, and 6 show the sequence of development and dissipation of the acceleration vortex for -10, -11, and -16° angles of attack, respectively.

Figure 4 shows interference with the circulation by convection currents arising at the walls because of localized heating by the strong light coming from the left side.

This series of tests shows that, for the magnitude of accelerations employed, an angle of attack of at least -9° is required, but that an angle of attack as large as -16° produces excessive general vertical displacement of air.

The airfoil acceleration technique appeared to function satisfactorily for generating reproducible vortices in the smoke chamber. More refined methods for obtaining identical acceleration rates will be used in the final installation (in the test cloud chamber).

d. Discussion.—Since any complex of eddy motions can be generated by the superposition of vortices of various characteristics, the present approach is considered to hold substantial potential for research involving the evaluation of turbulence effects. Whereas, in the present case, the immediate plans call only for the study of individual vortices, it is entirely conceivable that the case of two reproducible interacting vortices may be substantially more effective, and hence more interesting, in the production of coalescences between cloud droplets. The point should not be overlooked that the basic idea may serve to provide reproducible turbulence for the purpose of evaluating its effects experimentally, and that this of itself represents something of a breakthrough in the study of turbulence.

2. The Generation of Reproducible Clouds

Numerous methods for generating clouds have appeared in the literature. High-pressure spray nozzles are capable of producing fog in large quantity (Layman, 1952). Following the method of Schaefer (1950), aufm Kampe, Weickmann and Kelly (1951) used a pre-cooled room as a chamber and introduced steam directly to form a cloud. The experiments of Aitken (1880, 1881) and of C.T.R. Wilson (1895, 1897) are of course classics based upon the adiabatic expansion cloud chamber later developed more fully for meteorological studies by Findeisen and Schulz (1944), Cwilong (1947), and d'Albe (1949). The development of continuously sensitive (to nuclear events) cloud chambers received impetus from Langsdorf's (1939) work, but did not become a useful technique unitl about ten years later in the laboratories of Cowan (1950) and of Dingle and Nielsen (see Nielsen et al., 1951).

Of these methods, most are quite limited for meteorological work. The high-pressure fire-fighting fogs have not been used in meteorological work, and hence their detailed characteristics are not well known. The principal problems evident in contemplating their use are (1) first cost of the system, which requires pressures up to 900 lb/in.^{2} pressure and (2) high initial energy input, most of which must be dissipated in turbulence. It is anticipated that these fogs would be quite polydisperse, but the drop-size distributions have not been studied from the cloud physics research point of view.

The cold box provides an effective demonstration of the ice nucleation and cloud seeding processes, but has severe limitations for the study of other cloud processes. The intermittency of the Wilson cloud chamber places serious limitations upon its usefulness for meteorological research; and the low rate of transfer of vapor to which the diffusion chambers are limited by the stability requirement prevents their effective simulation of atmospheric clouds particularly in regard to liquid water content and drop-size distributions.

The spinning-disc sprayer of Walton and Prewett (1949) provides a means of obtaining relatively equally sized droplets, but fails to meet the problem of how to concentrate these into a laboratory cloud of reasonable liquid water content.

The mechanism of the advection fog, that is, the mixing of saturated air from sources of widely differing temperatures, has been used by Phillips and Woessner (1952). Although the droplet sizes reported are quite small and broadly distributed, the continuous generation of adequate cloud by controlled procedure renders this technique highly attractive for the present purpose.

a. Performance Requirements.—To serve the purpose envisioned, certain exacting conditions, some of which are mutually conflicting, need ideally to be satisfied.

Because the objective is to study the effect of introduced calibrated "turbulence" upon the cloud droplet-size distribution, it is essential that the experimental cloud chamber operate without turbulence from any other source. This requirement can be met by due attention to the thermal relationship of the cloud chamber contents to the environment, to the vertical stability of the entire chamber contents, and to the characteristics of the chamber which affect the flow of the cloud-laden air.

The experimental cloud should ideally be composed of uniformly sized droplets adjustable in the range of about 10-μ to 40-μ diameter. It should have a liquid water mixing ratio near 3 g/kg (Kinzer and Cobb, 1958). These sizes are typical of those available in clouds prior to the precipitating stage (e.g., see East and Marshall, 1954), and may therefore serve to simulate the hypothesized coalescence process.

The experimental cloud, and hence the chamber, should be large enough so that the introduced vortices act primarily within the cloud volume without interference by the chamber walls. The desirability of being able to attribute the entire energy of the introduced vortex to turbulence within the cloud is apparent when one considers the process of decay of such a vortex. According to East (1957), the rate of dissipation of energy by turbulence is fundamentally related to the rate of production of coalescences within a cloud.

The flow system must be capable of maintaining continuously, in a substantial part of the volume of the chamber, a constant cloud over an extended time of the order of at least minutes, or more ideally hours. Under these circumstances the large droplets resulting from coalescences will fall downward through the flow-supported cloud, providing an easily detected and measured clue to their relative sizes.

The velocity profile within the chamber should be constant at each level.

Additional requirements such as that to provide for monitoring the contents of the chamber without disturbing them tend to complicate the design problem further, but these are developmental problems common to most efforts of this type.

b. <u>Description of the Cloud Chamber</u>.—Once it had been concluded that a continuous flow system similar to that of Phillips and Woessner (1952) might be made to fulfill most of the requirements cited, the design problem was attacked experimentally. A series of pilot cloud chambers of reduced size was accordingly constructed and tested.

These led to important modifications of the basic scheme, resulting in the following system:

1. Cloud is produced by the mixing of live steam with cool air, both under controlled flow, in a mixing chamber at the base of the chamber. Turbulence serves to bring about rapid growth of the cloud elements formed in this chamber, thus eliminating the extended "aging" chamber suggested by Phillips and Woessner, and making possible a higher rate of production of cloud.

2. The cloud is carried past straightening vanes into the base of the observation section of the chamber. As this section flares out to its full dimensions of 24 in. by 24 in., the upward speed of the cloud drops to 2 to 5 ft/min, depending upon the rate of admission of air, which is adjusted so as to float droplets of the size under study.

3. The temperature of the cloud is carefully controlled near that of the chamber environment so as to avoid turbulence due to instability on the one hand and evaporation of the cloud on the other.

Complete control of the three basic variables is accomplished by appropriate valving of (a) the steam input, to control liquid water content, (b) the cold air, to control the temperature, and (c) the room-temperature air to control the rate of flow through the chamber.

(1) The observation section. Figure 7 is a vertical cross section of the vertical tunnel cloud chamber. The observation section, 6 ft high by 2 ft square, is the large upper portion of this diagram.

The walls of this section except for the glass observing panel are lined with black cloth which is normally moistened prior to the start of an experiment. The observing panel is a removable glass window 20 by 47 in. in the "front" of the chamber. Suitable openings in the other walls are provided for illumination purposes and for the insertion of instrumented probes into the tunnel.

The airfoil (see above) is mounted in the left tunnel extension so that it can be accelerated abruptly by means of a spring release mechanism. The tunnel extension on the right side of the chamber is provided to trap the deceleration vortex. The supporting rails are so placed that the vortex generated in this manner will have maximum residence time in the center of the test cloud. Except during the moment of transit of the airfoil across the chamber, the lateral tunnel extensions are isolated from the chamber by sliding plates.

(2) The mixing chamber. The sloping assembly at the base of the structure is a 7-in.-diameter by 18-in.-long mixing chamber into which the steam is introduced for mixing with the cold air. The air flow rate is observed by means of the Pitot tube, pipe-wall piezometer arrangement shown. The flow of steam is controlled by powerstat adjustment of the electric current to the boiler heater. This control is remarkably sensitive when properly used.

(3) The accessories. The flow diagram, Fig. 8, shows the system for processing compressed air from the service line before admitting it to the chamber. This air normally carries a good deal of water and oil, and hence the preliminary water trap is indispensable. Irregular fluctuations in the air pressure are damped through the surge tank, and final deep cooling of a part of the air is accomplished in the cooling coils.

Details of the water trap are shown in Fig. 9. The cooling coil, which is immersed in dry-ice-cooled alcohol, is a simple coil of 3/4-in.-diameter copper tubing.

The steam generator is a 6-liter flask of distilled water, with boiling chips, on a powerstat-controlled hot-plate. In operation, this unit, as well

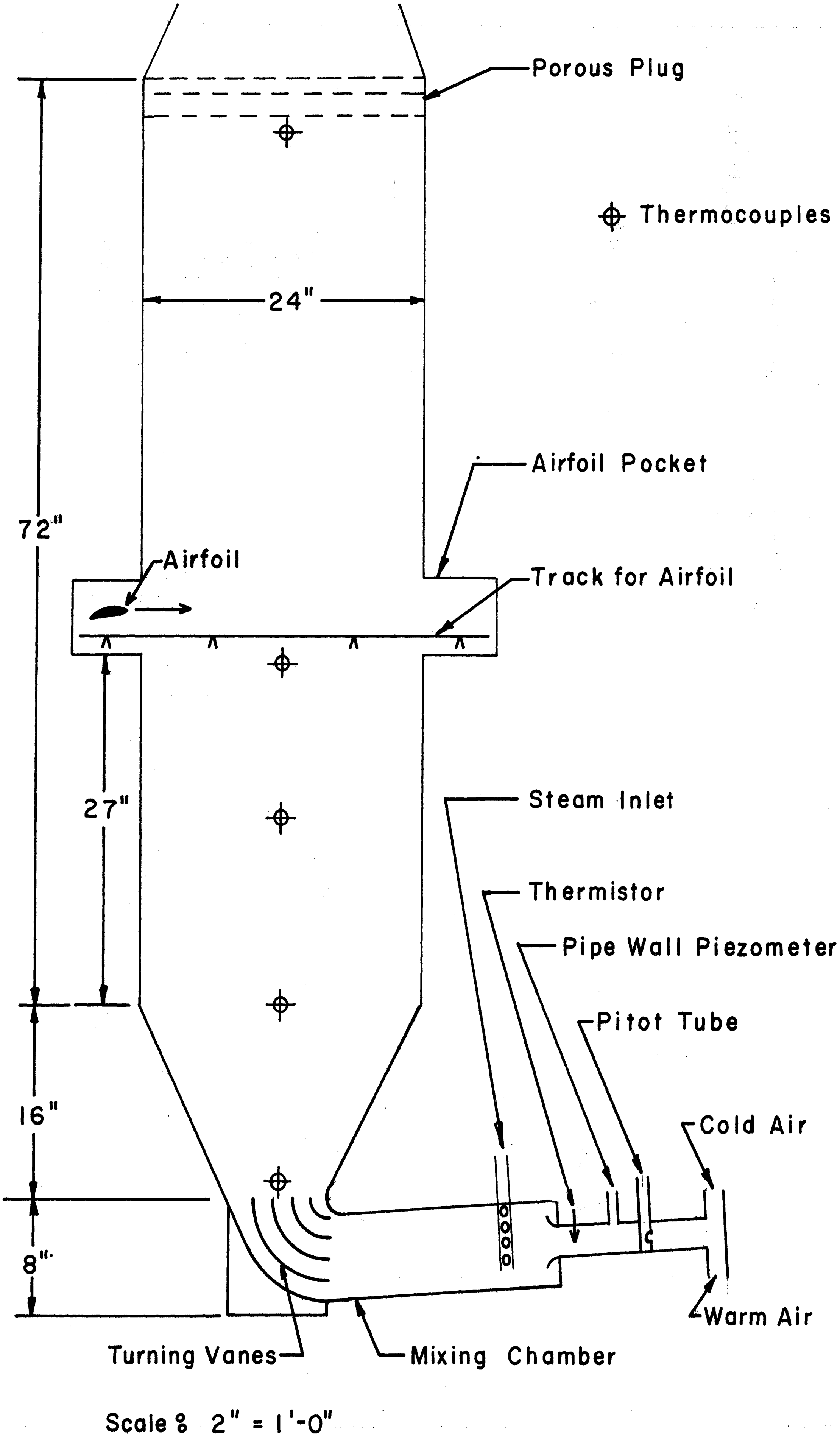

Fig. 7. Cross section of the vertical tunnel cloud chamber.

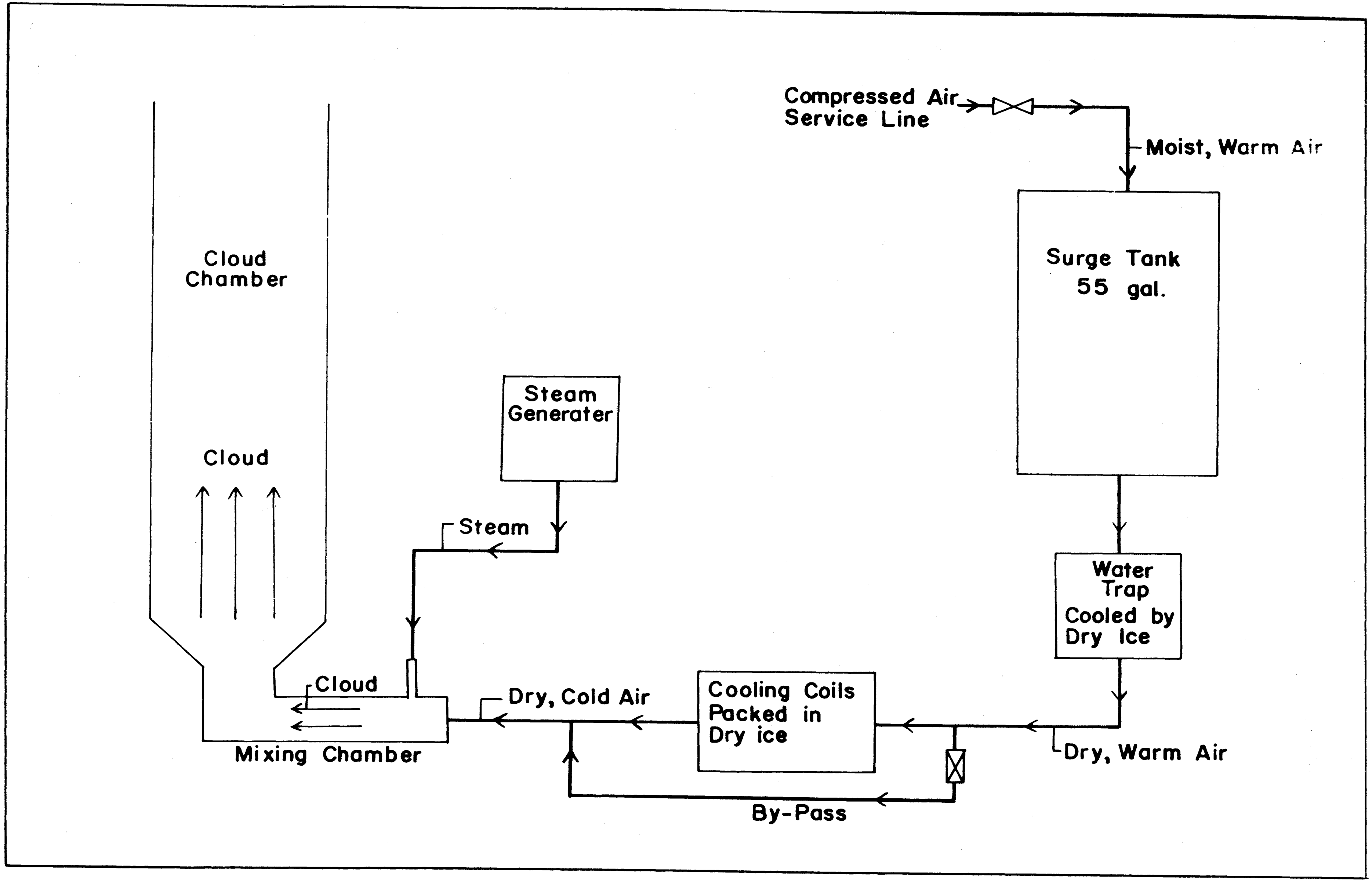

Fig. 8. Flow diagram of the vertical tunnel cloud-chamber system.

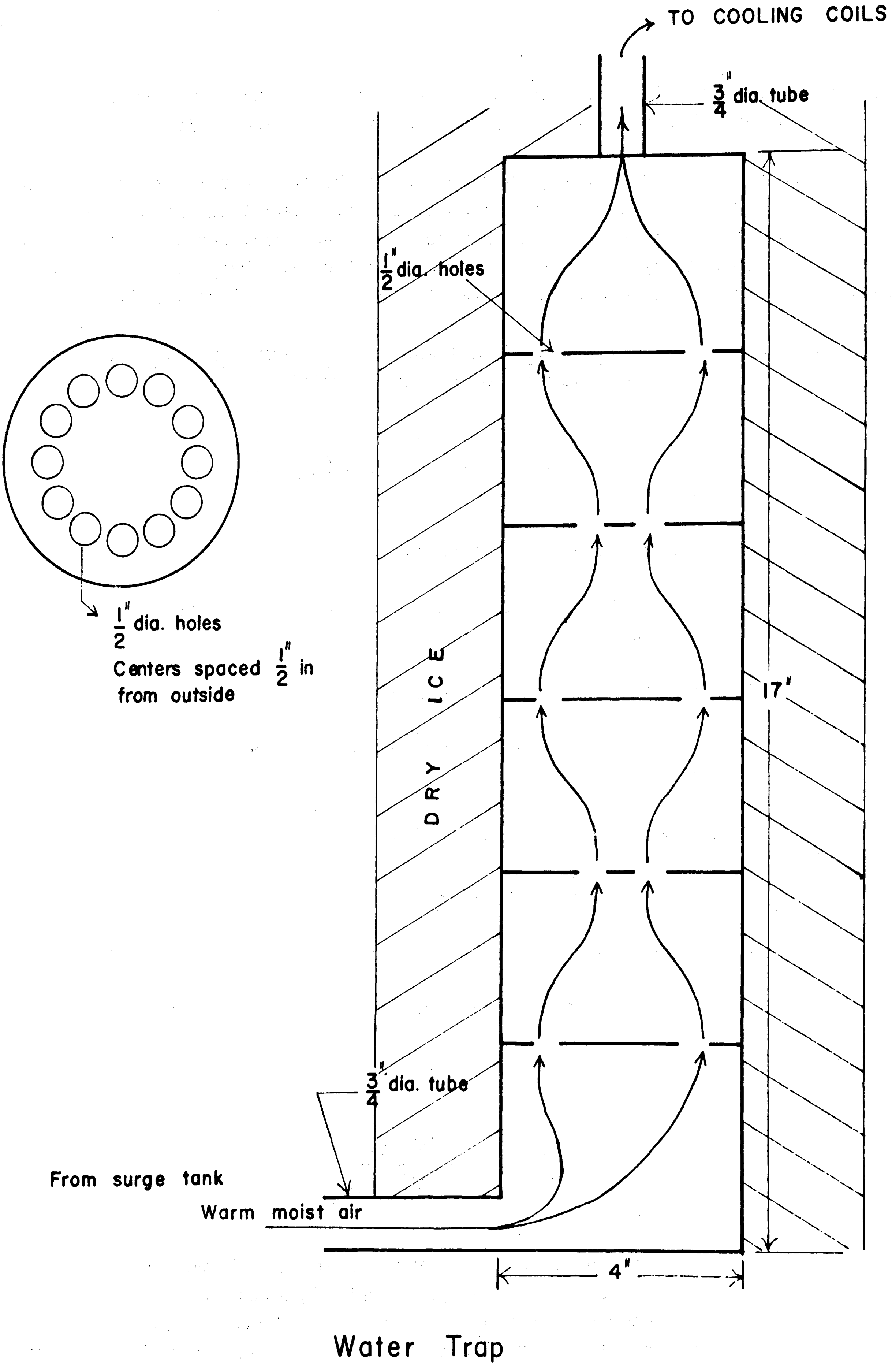

Fig. 9. Details of the water trap.

as the water trap and cooling units, is insulated from the environment so that its rate of heat loss is not subject to change from migrant air currents.

Temperatures at the mixing chamber and at the top of the observation section are monitored by means of thermistor probes. VECO 32A1 glass probes are used because of their very low power dissipation and good response time. They are used in such a way that their power dissipation is always less than 0.1 milliwatt, and the temperatures covered the range from -10 to +40°C.

c. Analysis and Testing of Heat Transfer and Cloud Persistence.—The heat balance for the cloud-generating process may be written

$$m_w \bar{L}_v + m_w C(\bar{T}_w - T_a) = m_c C_p (T_a - T_c) \qquad (9)$$

in which m_w is the mass of water condensed,

$\bar{L}_v$ is the mean latent heat of condensation released during the mixing process,

$\bar{T}_w$ is the mean temperature of condensation of the steam,

T_a is the equilibrium temperature of the mixture (near room temperature),

T_c is the temperature of the cold air,

m_c is the mass of the cold air,

C_p is the isobaric specific heat of air, and

C is the specific heat of water.

The ratio of m_w to m_c is obtained from (9)

$$\frac{m_w}{m_c} = \frac{C_p(T_a - T_c)}{\bar{L}_v + (\bar{T}_w - T_a)C} \qquad (10)$$

Nonturbulent operation of the chamber requires that T_a remain quite constant near room temperature. Thus the principal adjustment available for controlling the liquid water specific humidity is that of T_c. It should be clear, however, that this control is not linear with the value of $(T_a - T_c)$ because there are contingent effects upon both $\bar{T}_w$ and $\bar{L}_v$.

These observations are not inconsistent with the statement made earlier concerning the three basic control quantities, for it is clear that the progressive reduction of the steam flow and of the cold air together with the increase of room-temperature air will produce progressively thinner cloud while the speed of flow in the chamber remains constant. A broad range of values of liquid water content up to 8 g/kg is readily available in the generated clouds.

(1) Thermal isolation of the chamber. Calculations of heat-transfer rates for the various parts of the cloud chamber were made because of the extreme sensitivity of the experiments to minor temperature gradients and fluctuations. The estimated heat-transfer rates are as follows:

Mixing chamber (insulated)	1.42×10^{-4} cal/cm sec deg
Expansion funnel (insulated)	1.27×10^{-4} cal/cm sec deg
Wall (3/4-in. plywood)	7.87×10^{-5} cal/cm sec deg
Window (single pane)	7.87×10^{-3} cal/cm sec deg

Evidently the heat transfer through the window could be reduced effectively by the use of a second pane of glass properly spaced from the first. Observations of the flow in the chamber indicate, however, that the present heat-transfer rate is reasonably satisfactory. By operating the chamber so that its temperature is very nearly that of the laboratory environment, the heat flow directly between the chamber and the environment is kept quite low.

Tests of the adequacy of the chamber, in regard to the heat-transfer problem, were run by generating typical clouds in the chamber and then observing the persistence of the clouds after the flow system had been shut off. When the wetted cloth liner was used, the time of dissipation of the cloud, was of the same order as the time required for the cloud to settle out gravitationally. Visual observation of the descent of the upper limit of the cloud corroborated this evidence. This is not interpreted to mean that no evaporation of cloud droplets was taking place, but rather that the rate of dissipation of the cloud by evaporation was not rapid compared to its rate of settling, and was therefore sufficiently under control.

A photograph (Fig. 10) of the vertical tunnel chamber in operation, with associated equipment, and with the insulation removed from the mixing chamber and expansion funnel so that they can be seen, serves to illustrate the physical relationships among the various components. The lateral tunnels for the airfoil had not yet been added at the time this photograph was made.

d. Cloud Generation.—The process of generating clouds in the present chamber is based in part upon the findings of others (Phillips and Woessner, 1952; Weickmann and aufm Kampe, 1953) that aging of clouds is a prominent factor in the development of broad droplet-size spectra. Narrow-size spectra are desired for the experimental evaluation of turbulence as a coalescence-producing mechanism. Accordingly, the time for growth of the cloud elements is re-

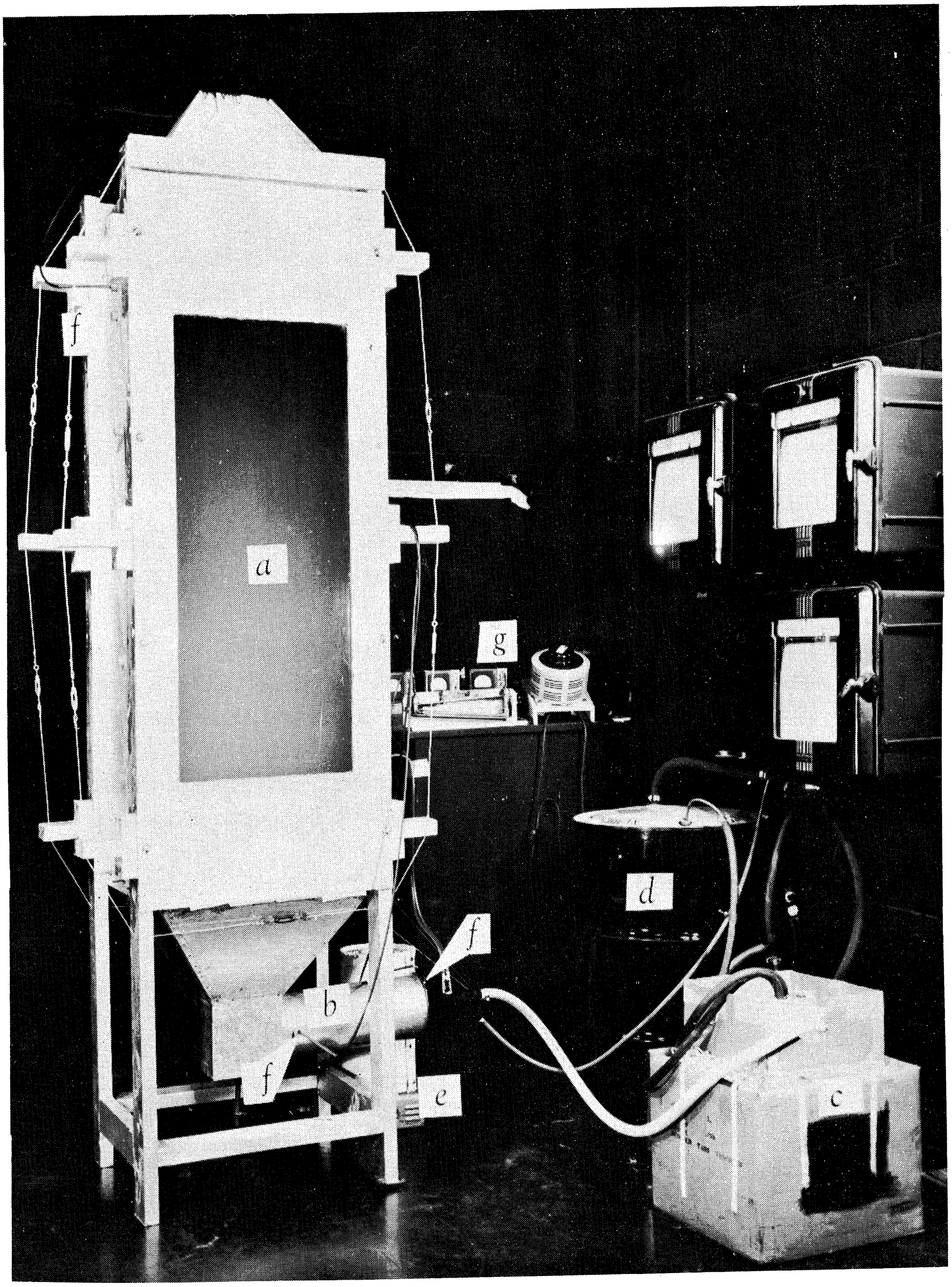

Fig. 10. Photograph of the vertical tunnel cloud chamber in operation, showing associated equipment (a) observation chamber, cloud visible; (b) mixing chamber; (c) insulated container for dry ice pack containing cooling coils and water trap; (d) surge tank; (e) steam generator, hot plate under asbestos-wrapped water flask; (f) three temperature probes; (g) manometer, powerstat, and temperature indicators. The recorders on the wall at right are not part of this setup.

duced to a minimum. Howell (1949) has analyzed the factors that affect the time of growth of cloud elements. The resulting equations indicate, as should be expected, that the time of growth can be reduced by increasing the heat and water diffusion coefficients and by increasing the degree of supersaturation. Howell's analysis is not readily adapted to the present case; however, his findings provide a point of departure. Thus, whereas Howell in no way considers eddy diffusion of heat and water vapor, the present apparatus uses eddy diffusion as a means of increasing many fold the rate at which heat and water can be exchanged in the mixing chamber. Again, whereas Howell is concerned exclusively with modest supersaturations (up to 8.0%), very high supersaturations are used in the present case by mixing steam directly with cold air. This and the turbulence in the mixing chamber should reduce the time required to grow 20-μ-to 40-μ-diameter droplets to a minimum.

Whether these extreme measures actually produce a narrow-spectrum cloud probably depends upon additional factors that should be considered. For example, it should be anticipated that many marginal and submarginal nuclei would be activated under the extreme supersaturations in the mixing chamber. Howell (1949) points out that "...the drop concentration does reach a maximum when the supersaturation is highest and decreases thereafter...approaching a fixed value slightly less than the maximum. It is only when the rate of cooling decreases significantly after the first formation of the cloud that more drops can evaporate and the concentration be materially affected." If this reasoning applies to the present case, one should anticipate that the abrupt cessation of cooling to which the cloud is subjected as it leaves the mixing chamber and enters the expansion funnel should result in the evaporation of many of the small drops. This also will contribute to uniformity of the cloud finally observed in the working section of the chamber.

e. Flow Characteristics.—The turbulence needed to generate large droplets quickly in a narrow-size spectrum must not be transmitted into the observation section of the chamber if the present objectives are to be served. Accordingly the cloud flows through turning vanes into the throat of the expansion funnel, and then is decelerated within the expansion section. The residual turbulence from the mixing chamber damps out quickly in the expansion funnel under suppression of the stable stratification of the cloud chamber.

There is a tendency for the rising air to advance somewhat more rapidly adjacent to the walls than in the center of the chamber. The resulting flow is characterized by a zone of small eddies along the walls to a depth of about two inches. The central working section is not affected by this turbulence, and the velocity profile across the chamber is essentially uniform except for the region at the walls.

3. The Determination of Cloud-Droplet-Size Spectra

Recent efforts have been directed toward the problem of making adequate determinations of the drop-size spectra of the laboratory clouds without destroying the experiment. The Houghton cloud droplet camera (Purdy and Franklin, 1954) was borrowed from the Department of Meteorology, Massachusetts Institute of Technology, to see whether it might be adapted to this end. Because it requires that an impingement sampling technique be used, some attention was given to collection efficiencies of cylinders and square rods and to the impaction speeds required to penetrate oil films. These problems have been studied by Brun and Mergler (1953), Langmuir and Blodgett (1946), and Aldaz-Isanta and Keily (1957).

These studies show that a square rod of 1 mm x 1 mm cross section has a considerably higher collection efficiency than a 1-mm-diameter cylinder for 20-μ-diameter water droplets:

U, m/sec	1.0	2.0	4.0
Rod, %	84	90	95
Cylinder, %	63	79	88

but that the impaction speeds required for smaller droplets to penetrate the oil film (to protect the droplets against evaporation) range quite high:

Drop diameter, microns	4	6	8	15	20	30
Penetration speed, m/sec	3.87	3.18	2.74	2.00	1.73	1.41

Thus, although the impingement sampling technique might be used to determine the character of the generated clouds, its use is incompatible with the experiment because at these speeds any sampling device will introduce uncontrolled turbulence.

It now appears that a telemicrophotographic technique may more adequately fulfill the needs of the project, and this method is under study.

4. Conclusions

A vertical tunnel cloud chamber has been developed for the purpose of studying the role of turbulence in the cloud-droplet coalescence process. The characteristics of the chamber include a 24-ft^3 working section in which the upward flow of air can be adjusted to float droplets of selected size up to 60-μ to 80-μ diameter without turbulence except within 2 in. of the wall surfaces. The cloud-generation technique is devised to minimize the plumbing and to increase the rate of growth of the droplets by means of eddy mixing without transmitting turbulence to the chamber.

A technique of producing vortices reproducibly has been developed and is proposed as a significant experimental approach to the study of the elements of atmospheric turbulence. Single vortices are to be used in the present experiments to determine their effectiveness in producing coalescences of cloud droplets. More complex vortex systems, all reproducible, offer promising potential for more complete studies of turbulence.

A telemicrophotographic technique for monitoring the laboratory clouds without disrupting the chamber conditions is under investigation.

Additional work to be done in attaining the objectives of this research includes an analysis modeled after Howell's (1949) study of natural cloud droplet formation but applied to the processes of the mixing chamber of the vertical tunnel cloud chamber. Such an analysis will be helpful in idealizing the cloud-generation process for the production of nearly monodisperse clouds.

Analytical studies paralleling those of East and Marshall (1954) and Kinzer and Cobb (1958) are also proposed to apply to the working sections of the chamber under the influence of single vortices of various intensities and sizes.

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II. TASK 2: WEATHER RADAR OBSERVATIONS UNDER PROJECT HI CUE AT FLAGSTAFF, ARIZONA, DURING JULY AND AUGUST, 1959

by
Floyd C. Elder

A. GENERAL BACKGROUND

On March 20, 1959, it was proposed that a portion of the funds from Contract No. AF 19(604)-2176 be expended for radar observation of cumulus cloud growth under Project Hi Cue. This action received approval of the contracting agency and on May 20, 1959, the contract was modified to include such a study. On April 20, 1959, Floyd C. Elder met with personnel of the Aerophysics Laboratory, Air Force Cambridge Research Center, to make necessary arrangements for participation in the observation program to be conducted at Flagstaff, Arizona, during July and August, 1959.

The period from May 20 through June 26 was utilized in modification and calibration of the radar. Some small amount of special revision of components was required to provide the type of measurements desired in this program of study. About one week of technician time was required for this work. The radar was packed and shipped to Flagstaff, Arizona, on June 26, 1959.

B. PROGRAM OF MEASUREMENT UNDER PROJECT HI CUE

Personnel of the University arrived at Flagstaff on July 9, 1959, and the mobile radar was placed in operation in conjunction with other phases of Project Hi Cue on July 10. However, final location of the radar at the Flagstaff Airport and operation on a permanent basis was not initiated until July 14. Thereafter, observations were made during all periods of suitable cloud conditions with the exception of short periods when failure of equipment was experienced. A total of 155.3 hours of radar observations was recorded.

The observation of cloud radar echoes may be categorized into five different phases of operation, each designed to gain a specific aspect of knowledge of the cloud echo growth and behavior.

1. Three-Dimensional Mapping of Precipitation Echoes

This phase of observation was designed to provide information giving the three-dimensional distribution of precipitation echo with a maximum of resolution of the temporal changes in echo pattern. Throughout this phase of observation the radar was operated on maximum gain and scope photographs were taken each 360° scan of the antenna. Antenna elevation was increased one degree following each scan commencing with a minimum elevation determined by the ground echo pattern. If precipitation echoes were observed at greater than 20° elevation, the increment of elevation change was increased to 5° or greater.

The beam width of the radar is 1.5° to the half-power points. This procedure of observation thus provided a total volume coverage throughout the volume of primary interest. The range of observations was determined by the location of significant precipitation echoes but was most frequently chosen as 20 miles to provide for greater resolution in space.

2. Precipitation Echo Intensity Mapping

Phase Two was designed to provide measurements of spatial distribution of precipitation echo intensity. This was accomplished by taking successive photographs of the radar scope while reducing the receiver gain by a calibrated increment each scan. The minimum gain at which the echo was detectable then gives a semi-quantitative measure of echo intensity. Comparative analysis can be accomplished directly but absolute measure of cloud reflectivity must await further calibration of the radar antenna system.

3. Echo Area Distribution Mapping (Movies)

Phase Three operation gives only the geographical distribution of precipitation echoes and movement of echoes in time. It is accomplished by taking successive photographs of the radar scope with the radar operating at maximum gain and a fixed elevation angle usually near zero degrees. Such observations result in time-lapse pictures of the precipitation cells.

4. Range-Height Observations

Phase Four consisted of vertical scanning by the radar at fixed or chosen azimuths. The result is an RHI picture giving the vertical development of precipitation echoes as a function of range. Intensity of echo may also be determined through successive scans at different receiver gain settings. Since this type of observation is not economical of time with the APQ-40 radar, only short periods of such observations were accomplished.

5. Cancellation Ratio Measurements

Phase Five of the operations is an experimental application of a unique feature of this mobile APQ-40 radar. It is possible, in a short time interval, to change the polarization of the transmitted wave from horizontal-linear to circular. This change in polarization will theoretically discriminate between spherical and nonspherical scattering particles. Thus, some determination of the presence of significant amounts of ice in clouds should be possible through observation of difference in reflected signal strength from circularly and linearly polarized energy. Several short periods of such observations were conducted.

All data were recorded on photographic film which is now being processed. A tabular summary of the radar observations has been completed and is included below. This table should permit other research groups within the project to determine which of the data may be of value to their analysis. The numbered phases of observation correspond with the description given above.

TABLE I

SUMMARY OF APQ-40 OPERATIONS AT FLAGSTAFF, ARIZONA

July 14 through August 20, 1959 Total hours operated—155.3

Date	Time	Phase of Observation	Range
7/14	1048-1054	1	100
	1100-1107	2	100
	1108-1110	1	100
	1111-1119	2	100
	1122-1125	1	100
	1126-1135	2	100
	1431-1434	1	100
	1442-1457	2	100
	1514-1526	1	100
	1528-1535	2	100
7/15	0808-0833	Ground Return	
	0834-0933	1	20
	0935-0938	2	20
	0939-1041	1	20
	1047-1107	2	20
	1108-1113	1	20
	1113-1126	2	20
	1127-1131	1	20
	1132-	3	20
	1300-1645	Photo Calibration	
7/16	0750-0811	2	20
	0810-0839	Photo Calibration	
	0840-1027	1	20
	1030-1124	2	20
	1127-1134	1	20
	1138-1145	2	20
7/17	0755-0826	2	20
	0907-1043	1	20
7/18	1126-1133	4	20
	1150-1209	1	20
7/20	0930-0932	Ground Pattern	
	0947-1055	1	20
	1058-1106	5	20
	1115-1130	3	100
	1132-1135	1	100
	1152-1214	2	100
	1216-1218	1	100
	1219-1234	3	100
	1235-1238	1	100
	1239-1337	3	100
	1338-1342	1	100
	1344-1427	3	100
	1428-1434	1	100
	1436-1450	3	100
	1503-1517	2	100 and 20
7/21	1016-1130	1	20
	1135-	2	20
	1137-1139	1	20
	1139-1140	2	20
	1141-1145	1	20
	1145-1147	2	20
	1147-1149	1	20
	1149-1152	2	20
	1152-1153	1	20
	1153-1154	2	20
	1154-1155	1	20
	1159-1300	2	20
	1330-1333	1	20
	1335-1356	2	20
	2000-2003	1	100
	2004-2017	2	100
	2018-2020	1	100
	2022-2029	2	100
	2043-2045	1	100
	2052-	3	100
7/22	1004-1029	1	100 and 20
	1032-1143	1	20
	1145-1147	3	100
	1147-1155	1	20
	1155-1157	3	100
	1157-1207	1	20
	1208-1210	3	100
7/22	1210-1254	1	100
	1335-1341	3	100
	1342-1345	1	100
7/23	1048-1059	1	20
	1102-1320	1	100 and 20
	1325-1335	4	20
	1352-1425	5	20
7/24	0904-1015	1	20
7/25	0936-0943	Photo Calibration	
	1108-1129	1	20
	1131-1220	5	20
	1224-1226	1	20
	1230-1242	2	20
7/27	1137-1217	1	100
	1222-1239	2	100
	1241-1300	4	20
	1301-1304	1	100 and 20
	1305-1450	5	20
7/28	0859-1000	3	100
	1016-1101	1	20
	1101-1110	5	20
	1112-1143	1	20
	1144-1305	1	100 and 20
	1315-1541	2	100 and 20
	1545-1550	4	20
7/29	0925-1000	Photo Calibration	
	1009-1147	1	20
	1344-1357	1	100
	1357-1407	2	20
	1411-1424	4	20
	1425-1433	3	100
	1434-1445	1	100 and 20
	1448-1520	3	100
	1521-1525	1	100
	1526-	3	100
7/30	0939-1048	1	20
	1108-1228	3	100
	1231-1237	1	100 and 20
	1238-1254	2	100 and 20
	1315-1326	3	100
	1326-1331	1	100
	1332-1352	2	100 and 20
7/31	0840-	Photo Calibration	
	1003-1014	3	100
	1014-1017	1	20
	1018-1520	2	100 and 20
	1833-1848	2	100
8/3	0836-0847	1	100
	0848-1116	2	100
	1117-1125	3	100
	1126-1200	1	100
	1200-1249	3	100
	1253-1302	5	20
	1307-1314	3	100
	1314-1327	4	20
	1328-1334	3	100 and 20
	1335-1338	2	20
	1340-1355	3	100
	1355-1359	1	100
	1400-1521	3	100
	1522-1527	4	20
	1528-1543	5	100 and 20
8/4	1004-1055	1	20
	1058-1106	2	100 and 20
	1108-1116	3	100
	1116-1129	1	100
	1131-1229	3	100
	1231-1234	1	100
	1235-1250	3	100
	1251-1254	1	100
	1256-1301	2	100 and 20
	1307-1322	2	100 and 20
8/4	1323-1333	3	100
	1333-1339	1	100
	1340-1442	2	100 and 20
	1443-1453	4	20
	1454-	3	100
8/5	1013-1101	1	20
	1105-1123	2	20
	1128-1133	1	100 and 20
	1133-1147	2	20
	1150-1157	1	100 and 20
	1158-1202	2	20
	1208-1255	3	100
	1255-1259	1	100 and 20
	1259-1310	2	20
	1310-1325	4	20
	1410-1618	2	100 and 20
8/6	0826-0932	3	100
	0933-0940	1	100 and 20
	0940-0949	3	100
	0949-0953	1	20
	0953-1005	3	100
	1005-1010	1	100 and 20
	1010-1026	3	100
	1026-1031	1	100 and 20
	1031-1051	3	100
	1051-1130	2	100 and 20
8/8	0939-0942	1	100
	0942-0957	3	100
	0957-1003	1	100
	1011-1022	3	20
	1022-1050	1	100 and 20
	1050-1058	3	20
	1058-1243	1	100 and 20
	1243-1255	3	100
	1255-1302	1	100 and 20
	1302-	3	100
8/10	1003-1052	1	100 and 20
	1052-1109	2	100 and 20
	1257-1628	2	100 and 20
8/11	0915-1016	3	100
	1016-1101	5	20
	1108-1114	4	20
	1115-	3	100
8/12	1017-1248	1	20
	1248-1401	3	100
	1408-1422	1	100
	1422-1544	3	100
	1548-1655	1	100 and 20
8/13	1105-1457	1	100 and 20
8/14	0844-1507	1	100 and 20
8/15	0848-1005	1	20
	1005-1020	3	100
	1020-1359	1	100 and 20
8/16	0954-0958	2	20
	1001-1023	3	100
	1023-1121	1	100 and 20
	1121-1124	2	20
	1304-1308	1	100
	1313-1332	3	100
	1334-1350	1	100
	1350-1353	2	100 and 20
	1355-1534	1	100 and 20
8/17	1020-1050	1	100
	1050-1110	2	100
	1110-1113	1	100
	1120-1129	2	100
	1137-1142	1	100
	1142-1151	2	100 and 20
	1154-1430	3	100
8/19	0826-0940	1	100 and 20
	1523-1552	1	20
8/20	0955-1120	3	100 and 20

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