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Project Cirrus, Final Report on Contract W-36-039-SC-32427,

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GENERAL ELECTRIC

Research Laboratory

FINAL REPORT

PROJECT CIRRUS

Contract No. W-36-039-SC-32427

Report No. RL 140 31 December 1948

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GENERAL ELECTRIC

Research Laboratory

Final Report

PROJECT CIRRUS

RL 140

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Approved by

Victor Frenkel

Schenectady, New York
20 December 1948

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INTRODUCTION

Since February 28, 1947 six members of the Physical Studies Group of the General Electric Research Laboratory have been participating in a research project related to basic problems in cloud physics. This project has had the joint sponsorship of the Army Signal Corps, the Office of Naval Research, and the Air Forces, the Signal Corps having assumed the active contract negotiations which resulted in the establishment of Contract W-36-039-sc-32427.

For more than four years previous to the above date, a considerable amount of research was conducted by some of this group in the field of the production of artificial fogs, precipitation static, and the icing of aircraft. This was done partly under government sponsorship through NDRC, Army Chemical Corps, and Air Forces and partly as a Research Laboratory activity. Various reports and papers were published during the course of these studies(1).

In order to assure a reasonable amount of freedom from delays and other complications in carrying out the research activities under the project, especially with reference to the flight operations, a Technical Steering Committee was created shortly after the formal contract signing to co-ordinate the participation of the three services in the project. This originally included a representative and his alternate from the Signal Corps, the Office of Naval Research, and the General Electric Company. This membership arrangement was subsequently revised to give the Air Forces equal representation on the Committee while the General Electric representatives were removed from formal membership but retained as active consultants.

Shortly after formal sponsorship of the present project was arranged, it was decided by the Steering Committee that work under the project should be divided into two basic activities. These would consist of (1) flight operations and (2) research activities. It was proposed that the flight operations should be under the direction of an Operations Group made up of representatives of the Army, Navy, Air Forces, and the General Electric Group. Subsequently, this group membership was revised to include only the representatives of the three military services. The General Electric representative was retained in a liaison capacity to maintain a close relationship between the Operations and Research Groups.

Experiments in the laboratory and field, excluding flight operations, were considered to be part of the activities of the Research Group. In addition, all results of flight experiments were turned over to the Research Group for analysis as quickly as possible after the completion of flights for assemblage and reduction of the flight results.

Close liaison between the Flight Operations Group and the Research Group is maintained by frequent meetings and by having a laboratory representative included in all Operations planning and activities.

The early flight operations were made using Olmsted Field at Middletown, Pennsylvania as base of operations. It was soon discovered, however, that many delays in carrying out flights could be traced to this geographic separation of the Operations and Research Groups. Accordingly, in the summer of 1947 all of the flight operations were transferred to the Schenectady Airport and facilities established at the General Electric Flight Test Hangar.

These facilities have been steadily expanded until at the present time all requests by the Operations Group for space and operating facilities have been met by General Electric. These consist of the following:

A total of 1830 square feet of office, operations, and storage space is supplied. Within this area are a flight tower, weather office, administration office, dark room, navy cage, Recordak room, operations office, analysis room, and a parachute and stock room.

In addition to this, about 640 square feet of conference room is available whenever required. In the same category is a room in the hangar for aircraft when a heated area is needed for installation work, repairs, or other reasons.

On call are two aircraft mechanics, two shop men, two transcribers, and an instrument man.

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(1) Schaefer, V. J. Final Report on Icing Research, July 1, 1945 to July 1, 1946. ATSC Contract W-33-038-AC-9151.

Schaefer, V. J. The Production of Ice Crystals in a Cloud of Supercooled Water Droplets. Science, 104, 2707, pp. 457-459, (November 15, 1946).

Schaefer, V. J. Heat Requirements for Instruments and Airfoils during Icing Storms on Mt. Washington. Transactions of the A. S. M. E., pp. 843-846, (November, 1947).

Schaefer, V. J. The Natural and Artificial Formation of Snow in the Atmosphere. Transactions, American Geophysical Union, 29, No. 4, pp. 492-498, (August, 1948).

A full-time secretary handles reports, correspondence, telephones, etc.

To facilitate flight operations, the A and C teletype circuits were installed, as well as a Teletalk system connecting all offices. This can also operate a Public Address system in the hangar and the ramp.

At the G. E. hangar, a class A repair station is available. In addition, extra guards have been assigned for the protection of aircraft and equipment, and standard aircraft fire fighting equipment with trained personnel is on hand for emergencies.

In carrying out effective flight operations, the Research Group has emphasized, from the beginning, that there are two things of basic importance for achieving the tvpe of results anticipated.

As in all basic research, it is of prime importance that after each flight the experimental results be carefully analyzed so that mistakes in planning are detected and each successive experiment used to uncover new aspects of the general problem under study. If this is not done, mistakes may pass unnoticed during a number of experiments and result in the amassing of data that may be of little value.

As the result of many different attempts to increase the efficiency of flight operations and analysis of the experimental results, the following procedure is now under trial.

Immediately after a flight, all data is gathered and scheduled for delivery to the Research Group. Within an hour following a flight, the following information is supplied to the Research Group:

- Date
- Flight Number
- Take Off Time
- Area Over Which Flight Was Made
- Objective of Flight
- Type of Clouds Worked On
- Base of Clouds
- Top of Clouds
- Measured or Estimated
- Temperatures as far as known
- Type of Seeding
- Quantity of Agent Used
- Number of Photographs Taken
- Cameras Used
- Number and Type of Aircraft Used
- Altimeter Setting
- Remarks

Subsequently, and as soon as possible, the photopanel data is transcribed from the developed film, the flight photos developed and printed as contact prints, and other instrument readings supplied as raw uncorrected data. This and all other information related to a specific flight is delivered to the Research Group as a packet within a week. Although this goal has never been achieved up to the formal termination of this contract*, there is no apparent reason why it cannot be done, and it is believed that such results will be obtained in the near future.

During the period February 28, 1947 to July 1, 1948, many exploratory laboratory and field studies were instituted by the Research Group to gain a better knowledge of the physical processes governing the genesis, growth, maturity, and dissipation of various types of cloud systems. These were, in general, directed toward achieving a better understanding of the precipitation cycle, especially as related to the growth of cloud particles, supercooling, sublimation and condensation nuclei, and the formation of rain and snow. One of the major purposes of this program was an effort to establish in definitive terms the various physical parameters of such meteorological phenomena.

Eight of these studies had developed sufficiently by July 1, 1948 to warrant the preparation of Occasional Reports. In order to save time and effort, it was agreed by the Steering Committee that these reports should be considered as the major part of the Final Report.

In addition to these eight reports and because it contains a fairly good summary of the developments which led to the present activities of Project CIRRUS, the First Report is also included as part of the Final Report.

The following includes a listing by title and a brief summary of the contents of the Occasional Reports:

Occasional Report No. 1

"The Production of Rain by a Chain Reaction in Cumulus Clouds at Temperatures Above Freezing" by Dr. Irving Langmuir.

This report, which has since been published in the Journal of Meteorology, October, 1948, summarizes the result of theoretical work initiated early in 1942 for the design of the artificial fog smoke generator. The equations developed at that time were found later to be applicable to the growth of droplets in orographic clouds on Mt. Washington and to suggest a mechanism for the growth and development of clouds in the free atmosphere by evaporation-condensation processes. The main part of this paper consists of the equations developed by Langmuir for application to conditions in the free atmosphere. Thirteen tables are presented

* It should be mentioned that under a subsequent contract which will continue until July, 1949, this goal was achieved during the latter part of November.

which delineate the critical conditions obtained for known conditions in natural clouds. Using this information, it is possible to determine the limiting conditions required to institute a chain reaction in a cumulus cloud system by "seeding" with water droplets. It also affords an explanation of the development of the precipitation cycle following the formation of snow by dry ice seeding of cumulus clouds.

Occasional Report No. 2

"A New Plane Model Cloud Meter" by R. E. Falconer and Dr. V. J. Schaefer.

This report described a modification of the G. E. Cloud Meter which was used successfully in studying 39 summer storms on Mt. Washington in 1945(2). The recording device of the new model produces a continuous trace while the instrument traverses a cloud, and the variation in width of the trace represents an instantaneous and continuous record of the liquid water content of the cloud. The present model, as described, still requires development for use at air velocities in excess of 150 mph.

Occasional Report No. 3

"Some Experiments in the Freezing of Water" by Robert Smith-Johannsen.

This report summarizes preliminary studies on the freezing temperature of bulk water. It was so conducted that no air-solid interface below 0°C was in contact with the water, although the surface was exposed to air.

By thus guarding against the "seeding" of the supercooled water by the development of frost at or near the solid-water contact point, it was found that the common freezing point of water is about -20°C. A sample of water which had been exposed to ultrasonic radiation was cooled to -38.5°C before it froze.

Various powders were added to the water as contaminants. A fine dispersion of graphite was found to be the most effective in raising the freezing temperature to a value of -6.9°C. No conditions were found to cause water to freeze at 0°C except seeding with a piece of dry ice held above the water surface. The shower of minute ice crystals generated by the dry ice always caused freezing as the temperature indicator passed 0°C.

Although graphite was found to be the most effective freezing nucleus, it did not serve as a sublimation nucleus when dispersed as a suspension in a cold chamber supersaturated with respect to ice.

Occasional Report No. 4

"Smoke from Smelter Operations As a Possible Source of Silver Iodide Nuclei," by R. E. Falconer and Dr. B. Vonnegut.

This report briefly summarizes a climatological study conducted to determine whether or not any additional precipitation occurs in the general vicinity of silver smelters due to the reaction of silver in the flue gases reacting with iodine in the air to form silver iodide sublimation nuclei.

The study was conducted to determine the validity of statements purporting to show unusual belts of precipitation in the vicinity of large smelters.

The study brought out the interesting fact that approximately one pound of silver is lost to the atmosphere per hour in the United States. If this silver were efficiently converted to silver iodide, enough nuclei might be formed to seed as much as ten to one hundred thousand cubic miles of air per hour with a concentration of one particle per cubic inch.

After making a study of the general climatological data of Utah and the western United States, no significant precipitation trends could be discovered which might be assigned to the variations in silver output.

Occasional Report No. 5

I "Production of Ice Crystals by the Adiabatic Expansion of Gas."

II "Nucleation of Supercooled Water Clouds by Silver Iodide Smokes."

III "Influence of Butyl Alcohol on Shape of Snow Crystals Formed in the Laboratory" by Dr. B. Vonnegut.

This report describes three separate studies conducted by the author as laboratory and field activities.

Part I describes a simple but very effective way of producing large numbers of ice crystals in the laboratory by adiabatic expansion of the gas which momentarily cools the air below the critical temperature of -38.9°C. It infers a similar mechanism as the source of ice crystal vapor trails produced due to adiabatic expansion of moist air by the propellers and wings of airplanes.

The experiments show that about 1.6×10^{10} ice crystals are generated per cc of expanded air. Another important experiment showed that a loud explosion per se had no effect in producing ice crystals in a supercooled cloud.

(2) Schaefer, V. J. The Liquid Water Content of Summer Clouds on the Summit of Mt. Washington. ATSC Contract W-33-038-AC-9151, (April, 1946)

The second part of the report describes the major work of the author in his study of the physical chemistry of silver iodide and the efficient production of large concentrations of such sublimation nuclei by smoke generators.

A study using the electron microscope to determine the size of particles produced with the aspirating hydrogen flame, the most effective generator so far developed, shows the particle size to lie in the range of 30 Å to 1400 Å in diameter. Yields of silver iodide particles as high as 10^{16} per gram of silver iodide were observed. A high temperature coefficient was observed. Thus a smoke which produced an average value of 10^{16} particles per gram of silver iodide at -20°C only produced about 10^{13} particles at -10°C.

A very interesting fact discovered is that silver iodide particles do not react immediately as sublimation nuclei when introduced into a supercooled cloud of water droplets. Even fifty minutes after introducing a smoke sample in the cold chamber, ice crystals could be seen to form at a measurable rate. The general conclusion reached as a result of this study is that the rate of reaction at -13°C is 30 to 40 times faster than at -10°C.

The third part of the report describes a modification of snow crystal forms from hexagonal plates to hexagonal columns which was observed when butyl alcohol vapor was accidentally introduced into the cold chamber. A subsequent study of this phenomenon showed that with a partial pressure of butyl alcohol vapor of the order of 10^{-6} atmospheres or less, no modification was observed. However, at a partial pressure of about 10^{-5} atmospheres, long hexagonal prisms were found to form instead of the normal thin hexagonal plates. As the vapor pressure of the alcohol was increased, however, the crystal habit reverted to the normal platelet form.

Dr. Vonnegut likens the effect of butyl alcohol on the crystal form of ice to a similar effect in solution of sodium chloride which normally crystallizes in a cubic form, but with the addition of urea, shifts its crystal habit to that of an octahedra. This effect is thought to be a blocking action produced by the preferential absorption of the impurity on certain faces of the crystals slowing down the rate of growth in certain directions and permitting the development in others.

Isobutyl and allyl alcohol showed a similar effect, but the shorter chain ethyl alcohol failed to exert any effect.

Occasional Report No. 7

"Observations on the Behavior of Water Drops at Terminal Velocity in Air" by Duncan C. Blanchard.

This report deals with observations and experiments on the behavior of water drops falling at terminal velocity through air. The study included observations on the breakup of drops in turbulent and non-turbulent air and the mechanism of breakup under various conditions.

The report includes a description of the apparatus used for making the study, which consisted of a vertical wind tunnel so designed that the drop remained essentially in a fixed position in space. This was accomplished by producing a vertical air stream having a velocity of 8.2 cm sec^{-1} with a region in the core of the stream having a slightly lower velocity. In this central region, the drop floated in a nearly stationary position, thus permitting observations on breakup, oscillations, etc., to be carried on with ease.

One of the interesting features of the report is the series of ten stroboscopic photographs selected from more than seventy pictures showing the oscillations, gyrations, and pulsations that go on as water drops fall at their terminal velocity.

This study was planned to shed more light on the mechanism of growth and breakup of rain drops in cloud systems and is the first stage of an investigation which is continuing under the new contract.

Occasional Report No. 8

"A Method for Obtaining a Continuous Record of the Type of Clouds in the Sky during the Day" by R. E. Falconer.

The report describes and illustrates a simple method of obtaining continuous records of cloud types during daylight hours. The method not only makes it possible to have a detailed record of cloud cover but seems to provide graphical information which may be "read" by an experienced observer so that the cloud types for a specific day or period in the day may be determined by scanning the record.

It is believed that the method may be useful for a number of practical applications beyond the fundamental studies for which it is being used by the Research Group. A few of these possibilities are mentioned. One of them — the use with an automatic weather station — may have considerable practical importance.

Occasional Report No. 9

"Methods for Detecting Sublimation Nuclei in the Free Atmosphere" by Dr. Vincent J. Schaefer.

This report describes several methods for detecting sublimation nuclei in clear air. It is believed that one or more of the suggested methods may be useful in reaching a better understanding of some of the erratic variations in the occurrance of such particles in the free atmosphere which so often permit the development and persistance of supercooled clouds.

The variations which have been observed are tabulated to illustrate the extremes that have been noted in the preliminary studies.

Three detection methods are described. Two of these employ supercooled water films — one in the form of a free floating bubble or a film mounted on a ring, the other as a water soluble plastic coating placed on a thin plastic membrane. Either of these, after reaching a supercooled state, permits the formation of ice crystals when an active nucleus contacts the film surface. The third method employs a cold chamber in which a supercooled cloud is formed after introducing the air sample to be tested. Any active sublimation nucleus immediately becomes visible in a light beam directed into the chamber and may be counted. A table of early results obtained with such a unit on Mt. Washington, New Hampshire, is presented. A continuing study under the new contract is in progress and will be subsequently described in detail.

Occasional Report No. 10

"Studies of the Effects Produced by Dry Ice Seeding of Stratus Clouds" by Dr. Irving Langmuir

This report is the first full scale analysis of a two plane flight operation carried out by the Operations Group of Project CIRRUS and submitted to the Research Group for study.

More details are included in this report than will normally be given by the Research Group. It is presented in detailed analysis to serve as an example of the methods and techniques which may be used in evaluating the results of a particular flight operation.

Flight 23, which is analyzed, was a two plane mission in co-operation with the M. I. T. Weather Radar Group and was conducted in the general vicinity of Cape Cod, Massachusetts. An L-shaped seeding and six spot drops were made in two phases of the flight operation. The rate at which these regions grew as the dry ice seeding modified the supercooled clouds is shown and quantitative information is supplied to illustrate the effects produced.

In addition to this information, the general conclusions that may be drawn from such activities are given by the author so that intelligent planning for future research experiments is possible.

Vincent J. Schaefer
General Electric Research Laboratory
Schenectady, N. Y.

15 December 1948

First Quarterly Progress Report

METEOROLOGICAL RESEARCH

1 March - 1 June 1947

Work on both laboratory and outdoor experiments which were actively underway before the official signing of the present contract has continued and is now going ahead as a considerably augmented program.

Detailed reports on various phases of the work planned, accomplished, and contemplated are included as sections of this report as shown in the Table of Contents.

GENERAL ELECTRIC PERSONNEL ON THE PROJECT

Those actively engaged in the work at General Electric at present are:

Dr. Irving Langmuir who is engaged in analyzing flight results, setting up procedures for routine analysis of such results, and planning methods and techniques for future programs. He is also developing the mathematical theory of the growth of cloud particles, water droplets, and ice crystals as affected by the air movements within clouds.

Vincent J. Schaefer, who works with Dr. Langmuir in the planning of the project, is carrying out laboratory experiments on some of the fundamental processes involved in changes in clouds; he is following the development of the general program and plane instrumentation and keeps in touch with the development of cloud studies in this and other countries.

Dr. Bernard Vonnegut who is actively working on various methods for producing silver iodide generators producing foreign-particle ice nuclei for both plane and ground installations, and is planning a study of meteorological conditions favorable to the effective operation of ground generators. This will be done by using such a generator in conjunction with a Navy fog generator; subsequent plans call for sampling the air at various altitudes. A number of generators have been made and tested on both the B-25 and the B-17, and their performance under flight conditions is being used in the design of a newer generator.

Raymond E. Falconer who is working on various phases of instrumentation of the flight plane, laboratory studies and other related problems. A cloudmeter, decelerator, accelerometer, icing indicators, and an exposure gun for sampling cloud particles have been constructed or obtained by him, and installations of these and other equipment in the B-17 are nearly completed.

Kiah Maynard who is assigned to participate as the Research Laboratory representative on all flight tests. He is familiar with the mechanism of the various cloud measuring instruments and will be responsible for their operation in flight operations. He is also responsible for gathering the data from the other observers during a flight and assembling the results into as complete a record as possible for each operation.

Robert Smith-Johannsen who is actively working on certain phases of the aircraft icing problem on another contract, but will be available and will probably participate in the cloud studies project whenever additional help is needed.

LABORATORY STUDIES

An active laboratory program is underway involving studies of supercooled clouds under various conditions of temperature and liquid water content. The type of crystals produced by different seeding techniques, the rate of growth of crystals under controlled conditions and the various ways of producing them are among the projects under study in the laboratory. The possibility of having a field kit for detecting ice nuclei in the natural atmosphere is under consideration and several units have been constructed for experimental use. The properties of clouds under high electric fields are also being studied to see what changes occur under different types and degrees of electrification.

PHOTOGRAPHIC STUDIES OF CLOUDS

Lapse-time photographs in color and in black and white are being made to determine the various factors involved in the development of the several types of clouds. Nearly 500 feet of such movies have now been obtained. Most of them are made by taking a picture every 2.5 seconds with a special shutter attachment used with 16 mm movie cameras. The movie is then projected at normal speeds to show the development and growth or dissipation of the clouds.

Stereoscopic pictures are also being obtained to show the three dimensional structure of different types of clouds. Besides using this technique to study ordinary cloud systems, one of the purposes of the project is to have the equipment ready and operating in a satisfactory manner for recording modification operations and the types of clouds under study in the above freezing part of the project.

DETECTION OF SUPERSATURATION IN THE NATURAL ATMOSPHERE

A regular daily observation program has recently been started to explore the possibility of inducing the development of cirrus type clouds under clear sky conditions. It is believed that supersaturation with respect to ice probably occurs fairly frequently at temperatures warmer than -35°C in air devoid of foreign-particle nuclei. Lacking such nuclei, a considerable degree of supersaturation can develop as is often shown by the development of so-called vapor trails behind high flying aircraft. To explore these possibilities, 50 and 100 gram balloons carrying chunks of dry ice in an open mesh bag are being released on a daily schedule from the top of the laboratory and followed by theodolite. If sublimation trails are observed, we hope that the program can be expanded to use high flying aircraft to explore the possibilities of producing ice-crystal clouds on a large scale for studying turbulence, lateral diffusion rates, radar echoes, and other similar meteorological phenomena.

CO-OPERATION WITH PLANE FLIGHTS

Up to June 1st, a plane from the Weather Squadron assigned to the Signal Corps has been at Schenectady a total of six times. During such visits a total of five seeding flights have been made. Of these flights, all have produced visual results; three have produced photographs although on only one flight were the results reasonably complete enough for analysis.

It is expected that, if the present crew is permitted to stay with the project, subsequent results will be much more satisfactory.

During all flights, two or more of the Research Laboratory Group have been in attendance at the radio in the G. E. Flight Test Division control tower and have obtained a record of everything communicated by radio to the tower. All of this information, which was recorded on wire, has been transcribed and records delivered to all concerned with the analysis of the flights. On all seeding flights from 50 - 150 pounds of granulated dry ice have been prepared and delivered by the Research Laboratory to the plane for use in the operations.

The data obtained on April 7 have been worked up quantitatively and are included as an appendix to this report. The method of analyzing this data will be described so that others will be able to follow the same method if desirable. Considerable time has been spent with representatives of the Army, Navy and other governmental agencies discussing the general program going over in detail the flight plans of the project.

CONCLUSIONS

As plans for the summer and winter season progress, it becomes evident that the present arrangement for supplying flight facilities needs to have considerable revision.

It is hoped that a satisfactory method can be devised which will lead to a more efficient use of the crew and the plane whenever proper conditions for cloud studies occur.

II. SUMMARY OF RESULTS THUS FAR OBTAINED IN ARTIFICIAL NUCLEATION OF CLOUDS

Irving Langmuir

HISTORY OF OUR EARLY WORK

Beginning in February 1942, Mr. V. J. Schaefer and I worked on the development of a generator for screening smokes for the Army. We were guided by what I call the evaporation-condensation theory of the growth of small droplets in fogs or clouds. When a small droplet, of dimensions greater than the mean free path of the air molecules (10^{-5} cm), is surrounded by air which has a partial pressure of the volatile material of the drop which differs from the equilibrium pressure of the drop by a small amount Δp, then the rate of gain or loss of weight of the droplet is given by:

$$Q = \frac{4\pi MDr\Delta p}{RT} \qquad (1)$$

where M is the molecular weight of the volatile substance, D is the diffusion coefficient of the vapor through the air, r is the droplet radius, R is the gas constant, 8.3×10^7, and T is the absolute temperature.

Because of the surface tension, the interior of a small droplet is under a hydrostatic pressure. As a result, the droplet has a higher vapor pressure than that of the liquid in bulk. The increase in vapor pressure produced by this surface tension effect is $p_r - p_0$ which is given by:

$$p_r - p_0 = \frac{2M\gamma p_0}{\rho RTr} \qquad (2)$$

where γ is the surface tension of the liquid and ρ is the density of the liquid. This equation is known as Thompson's equation. On the basis of this theory, a small droplet surrounded by air which is in equilibrium with an extended flat surface of the liquid will have only a definite life τ. The value of τ is given by:

$$\tau = \frac{r^3}{6D\gamma p_0}\left(\frac{\rho RT}{M}\right)^2 \qquad (3)$$

This theory can be applied to calculate the rate of growth of particles in a fog or smoke. The small particles, in accord with Eq. (2), tend to evaporate, since they have a higher vapor pressure and give vapor which condenses upon the larger droplets. This rate of transfer naturally depends upon the distribution of the sizes among the droplets. In 1943 I did not know how to calculate this distribution of sizes, but I made the very simple assumption that during the growth of particles within the cloud or smoke the type of distribution remains constant or "invariant." This I could not prove, but it seemed a reasonable assumption. On the basis of this assumption, it was easy to show that the number of particles in the fog would, in general, decrease according to the equation:

$$\frac{d \ln n}{dt} = \frac{1}{\beta\tau} \qquad (4)$$

where τ is given by Eq. (3).

This theory was now applied to the calculation of the rate of growth of smoke particles in a jet of vapor escaping through a nozzle from a boiler in which hydrocarbon oil was boiling to give a pressure of 5 to 15 pounds per square inch on a gage. The jet, by its momentum, dragged in very large quantities of air so that the vapor was chilled within a few milliseconds to a temperature so low that the oil had no appreciable vapor pressure. By an integration process, knowing the vapor pressure of the oil, the rate of dilution with the air and thus the rate of fall of the temperature, it is possible to calculate the size to which the droplets would grow by the time they had cooled to such a low temperature that further growth became negligible. This theory gave quantitative results which were in excellent agreement with all our experiments made during the development of the smoke generator. In fact, by this theory it was possible to calculate the size of nozzle that should be used and the proper pressure of oil vapor in order to get smoke particles of the desired size, 0.60 microns diameter. The smoke generator finally used by the Army contained nozzles 3/16 in. diameter, which was exactly the size that I had calculated by this theory before we had made any experiments to determine the proper size.

In the years 1943 to 1945 Schaefer and I, for an Army project, studied the theory of the formation of rime or ice on aircraft. Experiments were undertaken on the summit of Mt. Washington during the winters of 1943-44 and 1944-45. In the course of this work, we found it possible to develop a method for determining the diameters of the droplets constituting clouds. This was done by a mathematical analysis of data on the rate of deposition of ice on slowly rotating cylinders of various sizes exposed to wind of known velocities.

Since the air that enters the base of a cloud that envelops the top of Mt. Washington usually blows up along the mountain slope until it reaches the summit, the life of the cloud particles should be inversely proportional to the wind velocity and proportional to the vertical height of the summit above the base of the cloud. Since the liquid water content in the cloud under given temperature conditions would generally be proportional to the height of the summit above the cloud base, we can see that the age of the cloud particles which pass the summit should vary in proportion to w/V, where w is the liquid water content of the cloud in grams per cubic meter and V is the wind velocity. Thus, there should be a relation between droplet size and the ratio w/V. The experiments on Mt. Washington show very clearly that this is the case. In fact, an analysis of several hundred sets of observations enabled us to compare the calculated and observed droplet radii. According to the theory, the diameter of the droplets should be given by the following equation:

$$d = 2.46\left(\frac{59 + T_c}{50}\right)\left(\frac{1000\,w}{V}\right)^{0.40} \qquad (5)$$

In this equation, the coefficient 2.46 is empirically determined from the Mt. Washington data, but the form of the equation and the other numerical constants in it were obtained directly from the evaporation-condensation theory. The units in this equation are as follows: The diameter d is expressed in microns, T_c is the temperature in $^{\circ}C$, w is expressed in g/m^5, and V is the vertical component of the velocity expressed in meters/second.

Several hundred sets of data, which give values of T_c, w, and V, and the experimentally determined values of d have been analyzed and the observed values of d have been compared with values calculated from Eq. (5). It has been found that the correlation coefficients between the observed and calculated values of d range from 0.92 to 0.94 in different sets of observations. An analysis of the observational data was also made by the method of partial correlation coefficients. A regression equation was thus derived, and this showed that the regression equation does not agree any better with the observed data than the equation empirically determined, Eq. (5).

I believe that Eq. (5) should be applicable to the growth of water droplets in the clouds of the free atmosphere. During this coming summer, we plan to make experiments in airplanes to test this evaporation-condensation theory. Recently, I have been able to develop the theory much more completely and have been able to calculate the numerical value of β which occurs in Eq. (4); I have been able to determine just what the conditions in the atmosphere must be in order that the distribution of droplets shall remain invariant as the air rises in the cloud.

In the evaporation-condensation theory, it was assumed from the very beginning that there are always in the atmosphere large surpluses of available nuclei suitable for the growth of water droplets. The number of droplets that exist in any cloud is, thus, determined by the rate by which the air rises into the base of the cloud, and does not depend upon the number of nuclei originally present in this air.

ICE CRYSTALS WITHIN CLOUDS

In the course of the work on Mt. Washington and from observations of clouds in the Adirondacks and in Schenectady, Schaefer and I became aware of the fact that ice nuclei are frequently extremely rare in the atmosphere. We became convinced of the fact that, in clouds below the cirrus level and even at temperatures as low as $-20^{\circ}C$, there are normally no ice crystals at all, or at least the concentration of ice crystals in such clouds is not more than about 10^{-9} particles per cm^3, whereas the number of water droplets in clouds usually ranges from 100 to 1000 per cm^3. Only in clouds from which there is visible snowfall from the bottom should it be assumed that there are any snow crystals.

It is obvious, however, from the fact that snow does sometimes form in clouds, that occasionally there are enormously more nuclei than normally occur. If, for example, we have a cloud containing 1 g/m^3 of liquid water, which is a fairly high value for winter clouds, and we consider that all the water in this cloud should be changed to ice crystals or snowflakes each weighing 10^{-5} g, we see that there would then be 10^5 snowflakes per cubic meter. The snowflakes are, thus, about 2.2 centimeters apart and, on the average, there is only 0.1 snowflake per cm^3. Thus, even in a heavy snowstorm, the nuclei are many thousands of times less abundant than are the water droplets normally present in such clouds.

There are many cases where snowstorms are observed in low clouds no part of which are at a temperature of less than $-5^{\circ}C$. It is, therefore, clear that in the atmosphere there sometimes exist nuclei which are responsible for the formation of snow crystals. There are other times when such nuclei are absent. It is clearly not a matter of temperature alone.

During the winter of 1945-46 Mr. Schaefer and I planned to investigate very thoroughly these questions. First, what are the ice nuclei in the atmosphere which lead to snow formation? Second, how can we introduce into clouds nuclei that will lead to the formation of snow? During the development of our interest in this subject, we learned to recognize the characteristic features of clouds which contain snow and to distinguish them from those which do not.

Clouds that contain snow show the following characteristics. Looking up through such a cloud, one often sees a halo around the sun at an angle of 22 degrees around the sun. This can be caused only by a refraction with snow crystals when the light enters and leaves the crystal from faces that form a diehedral angle of 60 degrees. These halos are usually caused by small hexagonal prisms of ice which are oriented at random. If the prisms are falling downward in the direction of their long axes, there will be a reinforcement of the intensity of the halo at a height above the horizon equal to that of the sun. This gives the so-called "sun dogs." If the snow crystals consist of small hexagonal platelets, and if these are not too small, they tend to fall with the plane of the crystal nearly horizontal. Under these conditions, if one looks down from a plane or a mountain top on the top of a cloud of such crystals, one sees a bright spot in the cloud at a distance below the horizon equal to the height of the sun above the horizon. Because of the slight tilting of the crystals from the horizontal, and because of multiple reflections involving two or more crystals, this spot of light reflected from the cloud is often drawn out into a vertical column which may extend both above and below the spot and may even extend above and below the horizon and above the sun itself. Such effects are never produced by water droplets.

When flying through a cloud containing supercooled water droplets, many parts of the plane acquire a deposit of rime or ice due to the interception of liquid water droplets which then freeze in contact with the surface. In clouds containing only ice crystals, no ice or rime forms.

Sunlight that falls on a cloud layer from above is scattered but is not absorbed. Thus, the total light that is intercepted is re-emitted. If the cloud is sufficiently thick so that no appreciable amount of light diffuses through the cloud and so reaches the ground, then one can see from the distribution of light from the top surface whether the liquid water cloud has been changed to ice. For example, from a cloud of liquid water droplets one sees that the light reflected from the cloud at angles not far from the sun is very intense; that is, the cloud is very bright at angles 20 degrees or 30 degrees from the sun. At increasing angles, the light intensity decreases but rises again considerably at a point of about 138 degrees from the sun which is about the location where a rainbow would be seen if the drops were much larger. Then the intensity again becomes much larger at a point nearly opposite to the sun. There one sees a small bright-colored circle of a radius of about two degrees or three degrees, which is called a glory. If the plane is low enough, one usually sees the shadow of the plane in this circle. These color effects are due to diffraction and they indicate that the particles are of very small diameter compared to the wave length of light.

Similarly, if one looks at the sun's disk through a very thin layer of clouds of liquid water, one sees a colored corona that is also due to diffraction from the small droplets. When the sun's disk is seen through clouds of liquid water, the edge of the sun's disk is always sharp no matter how small the particles may be. In our work with the smoke generator, where we produced smoke particles ranging from 0.5 to 2 microns in diameter, we found, when looking up at the sun through a layer of smoke of such density that one could look at the sun without hurting one's eyes, that the sun's disk was brilliantly colored and that the edge of the sun was perfectly sharp and distinct. In other words, one finds no sharp maximum in the intensity of light scattered by diffraction through small angles.

On the other hand, if one looks at the sun through a cloud of ice crystals of sufficient thickness to cut down the light of the sun so that it can be tolerated by the eyes, the edge of the sun's disk looks fuzzy. I have worked out the theory of this effect. It is produced by the great increase in intensity of light reflected from small surfaces when the angle of incidence approaches 90 degrees. The intensity coefficient of reflection always approaches 100 per cent at grazing incidence, but it falls to about half of that at an angle only about one degree from grazing incidence. When the sun's brightness is cut down to 1/10000th (which is necessary in order to be able to look at the sun's disk with unaided eyes), there must be a great deal of multiple reflection. It is for this reason that the edge of the sun's disk becomes very fuzzy. This can only happen when the surfaces from which reflections take place are very large compared to the wave length of light. Large raindrops or snow crystals can produce this effect, but fog particles never do. We have found this a very useful criterium to distinguish between liquid water and ice crystals.

SCHAEFER'S EXPERIMENTS ON THE ARTIFICIAL PRODUCTION OF ICE NUCLEI

During the spring of 1946, Mr. Schaefer obtained a commercial home freezing unit which had a rectangular cold box of about four cubic feet which could be cooled to -25°C. With the cover off, the temperature at the bottom was about -23°C and the temperature rose to about -10°C a few inches below the top. The volume of the part below -10°C was about 70 liters.

Schaefer found that by breathing into this box a few times the box became filled with a cloud consisting of liquid water droplets with sizes very much like those in natural clouds, but that no ice crystals occurred at -23°C. He lined the cold box with black velvet and used an intense beam of light from above to illuminate the cloud. Later experience showed that all ice crystals larger than a few microns can be seen immediately with the unaided eye when illuminated in this way.

Mr. Schaefer tried very great numbers of powdered materials dusted into the box and ordinarily found no trace of ice crystals forming. Sometimes at the lowest temperatures just a few crystals could be seen. This proved that ice crystals, when present, could be seen but ordinarily they were absent.

Early in July, 1946, Schaefer introduced into the cold box containing supercooled clouds, a needle (suspended by a thread) which had been cooled in liquid air. This needle was swung once across the top of the cloud. Immediately the path of air through which the needle had moved was seen to contain an intense blue haze consisting of particles too small to resolve. They gave the characteristic Rayleigh scattering, indicating that the particles were small compared to the wave length of light. Within a few seconds myriads of ice crystals, hundreds of millions of them, could be seen glistening along this seeded path. Within usually 10 to 20 seconds, the seeding of these crystals spread throughout the box, in spite of the fact that there was a very strong temperature gradient which tended to stabilize the cloud in the box and to prevent convection currents. It was seen immediately that the seeded path always surrounded itself with a clear layer of air from which all the particles had been removed by diffusion. The fact that the vapor pressure of ice is less than that of supercooled water, thus, causes the droplets to evaporate and the vapor then condenses on the ice nuclei. The water droplets in the chamber rarely change to ice crystals by contact with ice nuclei.

Experiments showed that to get this effect with a piece of cooled metal it was only necessary to have a temperature below -35°C. With the metal at -34°C no ice crystals appeared. The transition between these two cases appeared to be perfectly sharp.

Schaefer then dropped small fragments of dry ice (solid carbon dioxide) through the fog in the cold box and found that a single minute fragment would leave behind it a track of nuclei. By stirring the air in the box after dropping the fragment of dry ice, one could see that the ice crystals that had formed were less than one millimeter apart so that there must have been at least 10^8 ice nuclei produced.

In August, 1946, I made a theoretical study of the rate of growth of the nuclei that are produced by dropping pellets of solid carbon dioxide through clouds of supercooled water. I was able to show, for example, that a spherical pellet of 0.4 cm diameter would fall with an initial velocity of 14 meters per second, decreasing as the particle becomes smaller by evaporation. It would take about 130 seconds for the particle to disappear and in that time it would fall 1100 meters (in air at -20°C). During this fall, a total of about 60 milligrams of water vapor would be condensed to ice in the cold air film near the surface of the pellet. The air remains cool by contact with the pellets only for a few microseconds and, during this short time, the particles grow in accord with the evaporation-condensation theory which I had already developed.

I thus reached the conclusion that the ice nuclei that are formed can only have a diameter of about 10^{-6} cm and that the number of such nuclei produced during the fall of a single pellet would be about 10^{16}. If each such nucleus could be made to grow into a small snowflake weighing 10^{-5} grams, the total weight of the snow produced would be 100,000 tons, which is the amount of liquid water present in roughly 100 cubic kilometers of cloud. Actually, of course, the nuclei from one pellet could not be distributed through such a large volume.

The conclusion is obvious, however, that with a reasonable number of pellets dropped along a flight path into the top of a cloud, the limiting factor will not be the number of nuclei, but the rate at which the nuclei can be distributed throughout the cloud.

When supercooled liquid water droplets are made to evaporate and condense on ice nuclei, the amount of ice formed is considerably greater than the amount of water which evaporates because the vapor pressure is lower than the water so that there is a lowering of the water vapor content in the cloud. There are, thus, two sources of heat which tend to raise the temperature of the cloud, viz., the heat of fusion and the heat of sublimation of the extra amount of water which is converted from vapor into ice.

In general, with clouds at -20°C the heating effect amounts to 0.5°C to 0.8°C. This heat will cause roughly a change of density of the air of about 0.2 per cent so that the air receives an upward acceleration with a value of g equal to about 2.0 cm/sec^2. This will be the rate at which the air begins to increase its upward velocity because of the seeding. These vertical velocities, however, will lead to turbulence and the energy of the gravitational acceleration will soon be dissipated in turbulence. When this occurs, however, larger and larger masses of air will be brought into circulation and, as the nuclei are thus carried out from the original plane of seeding, the upward velocities will gradually increase. Calculations show that in about one minute velocities of the order of one meter per second will be produced and the effect of the seeding should have spread laterally to a width of about 50 meters. After the seeded volume has spread laterally to a distance comparable to the thickness of the cloud, the spreading should then continue at a uniform rate with vertical currents of the order of five to ten meters per second. The nuclei are thus carried aloft and spread out laterally over the top of a stratus cloud leaving ice crystals which settle down through the cloud and so cause a continued rapid spreading. I thus anticipated in November 1946 that it will only be necessary to seed a stratus cloud along lines one or two miles apart in order to give complete nucleation of the cloud within a period of 30 minutes or so.

FIRST SEEDING OF CLOUDS

On November 13, 1946, Mr. Schaefer and Mr. Talbot went aloft in a Fairchild plane on a day in which the temperature at ground level was $0^{o}C$. In the morning there had been some high stratus clouds but by the afternoon these were disappearing and the day was becoming almost cloudless. Finally a cloud was found about 30 miles east of Schenectady at an altitude of 14,000 feet and a temperature of -20°C. Three pounds of dry ice were scattered from the cockpit of the plane along a line about three miles long over the top of one of these clouds. Observing through field glasses from the Schenectady Airport 30 miles away, I saw a sheet of snow appear rather suddenly about 600 feet below the clouds; within three minutes there developed, along the top of the previously lenticular shaped cloud, some hemispherical cumulus-like bulges. These extended to a height of about 500 feet above the cloud but, in a few minutes more, disappeared into a veil of snow. Within about five minutes, the whole cloud had been turned into snow and this fell about 2000 feet before it gradually evaporated into the dry air. It was realized that the veil of snow that appeared immediately below the snow could not have been produced by snow falling from the cloud but was produced directly by the action of the dry ice pellets which fell into a layer of air below the cloud in which the vapor pressure of water was less than that of the water but greater than that of ice. Subsequent experiments proved that it was always possible to seed a cloud by flying just below the cloud; the thickness of this layer in which such seeding is possible is about 10 meters for each °C below the freezing point. The ice crystals that are thus formed are carried up into the cloud.

Seeding experiments with clouds have been made on the following dates: November 13, 1946, November 23, November 29, December 20, March 6, 1947, March 7, March 12, and April 7. All of these experiments have been completely successful in that they converted large areas of clouds into ice crystals. The tests of November 23 and 29 were made with isolated cumulus-type clouds. The whole of each cloud was changed into ice within five minutes and so began falling from the base of the cloud. However, photographs taken every 10 seconds and projected as movies show that, with such clouds, the air is moving into one part of the cloud and leaving another part so that, in a matter of five minutes or so, an entirely new mass of air is within the cloud. Thus, it was found that experiments with small cumulus clouds are of little interest, for the effects only last a few minutes. A veil of snow, however, could be seen to persist for 10 or 15 minutes after it had left the cloud, usually evaporating slowly in the dryer air below the cloud.

FLIGHT TEST OF DECEMBER 20, 1946

Although on the evening of December 19, the weather forecast had been for "fair and warmer" weather for the 20th, clouds developed at 11 P.M. on the 19th, and in the early morning of the 20th the sky was completely overcast and small single snowflakes could be seen occasionally at distances of 10 meters or so apart. These were graupel type of snowflakes; that is, they had been formed by crystals which had fallen through supercooled clouds and so had acquired a coating of rime. By 9 o'clock in the morning the Weather Bureau in Albany reported that they expected snow by 7 P.M. that day. They said that the storm had moved 1200 miles in 18 hours from the Gulf of Mexico as a "wave" without high-wind velocities. Between 11:20 A.M. and 12:20 P.M. at altitudes ranging from 7000 to 8500 feet, Mr. Schaefer dropped about 25 pounds of granulated dry ice along a line running from southeast to northwest, about 15 miles west of Schenectady. The wind at this height was about 20 miles per hour. At this time, the ground level temperature was -2°C; the temperature reached a minimum of -9°C at 3500 feet and then increased to a maximum of -5.5°C at 6000 feet and then decreased steadily to -11°C at 8500 feet. Radiosonde data at Albany at 10 A.M. showed that between 2500 and 4000 feet the air was dry, the relative humidity being only 30 per cent. Schaefer found the air to be very clear at this height, but about 4000 feet there was a light drizzling rain that collected on the windshield but not on the leading edges of the wings. This means that the rain or drizzle was evaporating as it fell and water or ice was evaporated off the leading edges of the wing but not off the windshield. There was no definite level of ceiling; no cloud layer could be seen above. The ground could still be seen at 9000 feet, but the light drizzle was somewhat more intense at this level. There appeared to be no fog clouds and the poor visibility was due to the drizzle. Since the plane could not fly higher without losing contact with the ground, it was decided to drop the dry ice from the height of 8500 feet.

Flying back along the line of seeding, it was found that the drizzling rain had stopped, and there was snow in the air which was found to drift into the cockpit through a partly opened window. Upon reaching the end of the seeded line, however, the same drizzle conditions were encountered. After three seeding runs along the same line, the plane returned to Schenectady without noting any marked change in the general cloud conditions. The plane then descended to 4000 feet where the visibility was better and flew east to the Hudson River and up along it to Mechanicville, a distance of about 25 miles from Schenectady. From Mechanicville a large cloud of snow was seen which extended from the Green Mountains of Vermont to the Sacandaga Reservoir, a distance of about 35 miles. The plane then flew along the southwest edge of this cloud and found that quite dense snow, consisting of small crystals, was falling and was nearly reaching the ground. This was at about 1:15 P.M. No snow could be seen in any other direction. Over the airways radio, we heard that at 1:45 P.M. light snow began falling at Glens Falls. This had stopped at 2:15 P.M., but it was then snowing at Ticonderoga. Later it started snowing at Burlington, which is about 150 miles from Schenectady.

At 2:15 P.M. it started snowing in Schenectady and at many other places within 100 miles. It snowed at the rate of about one inch per hour for eight hours bringing the heaviest snowfall of the winter. We do not believe that this snowstorm was caused by our seeding experiments, but we do believe that with weather conditions as they were, we could have started a general snowstorm two to four hours before it actually occurred, if we had been able to seed above the clouds during the early morning.

FLIGHT TEST OF MARCH 6, 1947

A B-25 Army plane flew on a north and south line above 15 miles long approximately 10 miles west from Schenectady dropping about 15 pounds of dry ice. They flew just over the tops of the clouds which were at about 6000 feet. The clouds were above 2000 feet thick and covered the entire sky. Soon it was seen that a great deep groove had been produced along the top of the cloud of the seeded area, but the plane did not climb more than a few hundred feet above the clouds and was not able to take good photographs. On the ground, however, we saw great sheets of snow falling along a line which seemed to be about 20 miles long. We could gradually see this snow descend until in another 20 minutes it reached the ground in Schenectady and on hills 20 miles north of Schenectady. During this time, the sky cleared up in a spectacular fashion so that there was soon a cloudless area 20 miles long and five miles wide and there were no other breaks in the overcast in any direction. Around the edges of this clear area one could still see the snow falling for more than an hour until the area drifted far to the east.

FLIGHT TEST OF MARCH 7, 1947

On this day also, the sky was completely overcast but the clouds were only about 1000 feet thick at a height of about 5000 feet. This time the plane, after seeding a line about eight miles in a north-south direction, circled to a height of 2500 feet above the cloud and took a few photographs. Measurements from these photographs show that, after about 20 minutes, the seeded area showed up as a definite dark band about eight miles long and one mile wide. Two photographs were taken which showed that snow was falling to the ground and, in a few places, the ground could be seen through these openings. Unfortunately, the plane did not remain long enough to photograph what we clearly saw from the ground - the cleared area developing where the seeding had taken place.

FLIGHT TEST OF MARCH 12, 1947

On this day there were only broken cumulus clouds at 5000 feet and, although many of these were changed to snow, the results are of comparatively little interest.

FLIGHT TEST OF APRIL 7, 1947

Our technique for conducting these flights and making observations of the results had greatly improved by this time, and the results are recorded in a set of 27 photographs which show, in a very striking way, the kind of results obtained by seeding stratus clouds.

On the ground the temperature was +5°C; overhead was a nearly continuous coverage of cumulus type clouds with bases at about 2500 feet where the wind velocity was 48 miles per hour from the west-northwest. There were a few breaks (about five per cent) between the cumulus clouds and up through these we could see that there was a thin overlying layer of stratus clouds through which the sun could sometimes be dimly seen. The disk of the sun was sharp indicating that the cloud consisted of water droplets. During the flight, the following temperatures were observed; at the cloud base, -4°C; at the top of the upper layer at 6700 feet, -7°C; and at 15,000 feet, where most of the photographs were taken, -17°C.

In flying up through these clouds, it was found that the plane came out through the cumulus clouds into the open at about 5000 feet but the tops of the cumulus clouds were very irregular. At 6000 feet the plane entered the second layer which was of the stratus type about 700 feet thick and this layer was very free from turbulence and the top was very flat.

A seeding run was made at 4:40 P.M. just over the top of the upper stratus layer. This seeding was done in a line forming a letter L; the plane flew for one minute toward the west (magnetic) and during the next minute it turned gradually through a 90-deg angle to the south and then flew for one minute toward the south. Since the plane was flying at an indicated air speed of 205 miles per hour, the total length of the seeded line was about 11 miles. A total of 25 pounds of dry ice was dropped, about half of this being in the form of pellets 1/4 inch in diameter and the other half broken fragments running from 1/2 inch to 3/4 inch in diameter; these larger pieces were used to make sure that the seeding would extend through both layers of cloud.

Immediately after the seeding run, the plane turned in a circle to the left and climbed to 9000 feet. The first photographs, taken six minutes after seeding, showed that the end of the line which was last seeded was 0.3 mile wide, whereas, at a point half way back along the seeded line, the width was 0.6 miles wide. For a total of about one hour, the plane circled the seeded area, first at an altitude of 11,000 feet and then at 15,200 feet. At the higher elevation, the plane flew so that the nearest part of the seeded area was about six miles away so that the whole of the seeded area could be included in photographs which also showed the horizon.

Knowing the height of the plane above the clouds (8500 feet, or 1.61 miles), a measurement of the vertical angles made it possible to calculate the distances of selected points on the perimeter of the area. By plotting these distances, together with the horizontal angles, or azimuths, on polar coordinate paper, it was possible to construct maps showing the development of the seeded area with time.

The L-shaped form of this area was always very distinct. Depending upon the relative position of the sun and the area in question, the seeded area sometimes appeared brilliantly white on the dark background of the cloud, while at other times it appeared as a dark area on a brilliantly white cloud. When the area was between the plane and the sun, the reflection from the ice crystals in the seeded area could be seen clearly, but no such effect was ever observed on the unseeded areas.

The photographs show that, within 30 minutes after seeding, the seeded area had grown to a length of about 15 miles and an average width of about three miles, giving a total area of about 45 square miles. The edges were still extremely sharp, showing that there was no horizontal turbulence within the original stratus cloud. Within the first 10 minutes after seeding, there was some indication of heat evolution which showed that some of the snow formed was carried up above the level of the undisturbed stratus cloud. Gradually the top of the seeded area subsided and, 35 minutes after seeding, the top of the snow was about 1000 feet below the level of the top of the stratus clouds. The photographs showed that the area then looked almost like a canyon cut into the top of the cloud. Probably because of the lower cumulus layer which, was presumably moving at a different velocity, the ground could not be seen through the seeded area, as had been observed in several previous flights.

After about 45 minutes, although the edge of the seeded area remained very sharp, it could be seen that above the snow, which had subsided, new stratus clouds began slowly to be formed. This, however, never covered more than half of the seeded area and there new clouds were very thin.

About 40 minutes after the end of the seeding, a new phenomena was observed. Clouds of cumulus type began forming in long ridges in a general north-south direction. These formed, however, only to the southeast of the seeded area and did not extend to the north, south, or west. They seemed to be first visible in the east and gradually reached the seeded area itself. These cumulus clouds reached heights of about 1500 feet above the stratus level.

Directly above this disturbed area, at an altitude of 18,000 feet, a group of alto-stratus clouds of lenticular form were generated. These were probably produced by the uplift of the lower layers from these ridges of cumulus-stratus extending through the stratus.

I think it is probable that this disturbed area was due to a combination of two effects. With a strong westerly wind, the plane and the seeded area had been drifting toward the Berkshire Mountains in Massachusetts and this caused the underlying cumulus clouds to grow to greater height. However, the Green Mountains, together with the Berkshires, form a continuous wall which gradually increases in height toward the north, but there was no sign of this type of cloud over the Green Mountains. In fact, the cumulus clouds did not extend at all north of the seeded area. I believe, therefore, that the underlying cumulus layer which was seeded had been moving toward the southeast at a velocity somewhat higher than the upper stratus layer, and that the heat evolved by the development of snow clouds in the lower layer contributed to a marked degree to the development of these cumulus ridges. The area thus disturbed seems to be about 150 miles within an hour after seeding.

Unfortunately, we have no observations of the area from which snow was falling from these clouds. Probably little or none reached the ground except in the Berkshire Mountains. In the future, it is planned to use two or three planes in such tests. One plane will be used at about 25,000 feet to take photographs of the seeded area, one plane will do the seeding at the cloud level and will then take photographs about 3000 feet above this level, and the third plane will take photographs below the clouds so as to show the area from which the snow falls.

CONCLUSIONS

The results of these tests show that the nucleation of clouds spreads at a very high rate for at least an hour after the clouds are seeded from a plane flying over the tops of the clouds. The rate of lateral spreading is approximately three miles per hour on each side of the seeded line, so that one can expect a line within one hour to grow to a width of at least five miles. Thus, a plane flying at 200 miles per hour should be able to nucleate completely about 15 square miles per minute of flight, or roughly 1000 square miles per hour. Our experience has shown that, in general, a single layer of clouds in the seeded area within less than a half hour becomes clear blue sky as seen from the ground. Thus, within 15 minutes, it should be possible for a plane to clear a hole for itself down through which it could fly without encountering icing.

Furthermore, it appears in many cases that a plane after leaving the ground should be able to fly up to the base of a stratus layer in which there is dangerous icing and, by dropping dry ice, would be able to clear for itself a path up through which it can fly without encountering icing.

The results would also indicate that it should be possible to seed clouds that are being lifted on the windward side of a mountain range if the tops of these clouds are below freezing. By seeding in these areas, snow should be produced, which should fall down through the cloud and produce rain in the lower layers. In this way, it may be possible to increase greatly the rainfall in mountainous areas during winter months and so produce reserves of rain or snow which can be used for irrigation purposes for the summer months. Since, however, the air moves through such clouds while they remain fixed, it will be necessary to seed them continuously, as long as the rainfall lasts.

We have reports from Australia on seeding experiments which will soon be published in Nature. (A note has already been published in Weather Bureau Topics and Personnel, April 1947, Page 106.) Eight experiments have thus far been made in clouds whose tops average 22,000 feet and with a freezing level at 18,000 feet over a 4000-foot mountain range 150 miles from Sydney. Rain fell within the area within 15 minutes after dropping the dry ice pellets. "On one occasion, the cloud top boiled up to an estimated 36,000 feet with a typical "anvil" formation and one inch of rainfall was reported."

It seems probable that, if dry ice is dropped over incipient thunderstorns as soon as the tops reach the freezing level, the development of the storm may be profoundly modified. The storms should be less severe, but will last longer and hail should be avoided. I have been told by a representative of an insurance company that in three western states the annual damage to crops by hail amounts to $15,000,000. It would seem that much of this damage could be avoided by seeding the tops of the clouds.

USE OF SILVER IODIDE AND OTHER SUBSTANCES AS ICE NUCLEI

Dr. Vonnegut found in November, 1946 that very fine particles of silver iodide at temperatures below -5°C serve as effective ice nuclei. Particles that are effective are about 10^{-6} in diameter. By introducing silver iodide into a flame so as to vaporize it and by blowing a jet of air across the top of the flame to quench it quickly, it should be possible to produce 10^{17} ice nuclei per second from one generator without having any increase in particle size because of coagulation. In the smoke generators which we produced during the war, the number of smoke particles produced per second is also 10^{17} per second and it was shown that these particles did not grow by coagulation. Since the law which governs the coagulation of smoke particles indicates that the coagulation depends only on the number of particles per cubic centimeter and not on the diameter, we may conclude that we should be able to generate the same number of nuclei per second as we did with the smoke generator.

An advantage in the use of silver iodide is that the nuclei that are formed do not evaporate nor melt, and, therefore, they can remain for long periods in the air until they come into the presence of supercooled water droplets and so produce their effects. The nuclei produced by dry ice are, of course, minute ice crystals which will evaporate and melt when the air is dry or the temperature rises above 1°C.

With the silver iodide it should be possible to do the seeding of the cloud over great areas by means of silver iodide generators placed on the ground. This will be particularly useful where it is desired to seed thunderstorms or clouds onthe windward sides of the mountain peaks. In both cases, the nuclei could easily be drawn up into the clouds.

The cost of nucleation of this kind would be very low in comparison to that which requires that planes fly above the clouds. Experiments will soon be underway to try the silver iodide nucleation by flight within supercooled clouds.

WIDESPREAD EFFECTS

The amount of silver required for nucleation by silver iodide is entirely negligible, so the cost of the silver iodide would not be appreciable. Undoubtedly many other substances will be found which will be effective nucleating agents.

If it thus becomes possible to use generators on the ground to introduce ice nuclei into huge masses of air, it might be possible to alter the nature of the general cloud formations over the northern part of the United States during the wintertime. I would anticipate that it would decrease the cloudiness. It would prevent all ice storms, all storms of freezing rain, and icing conditions in clouds. By changing the cloudiness, it would change the albedo and thus change the amount of heat absorbed from sunlight. It should be possible to change the average temperatures of some regions during the winter months. Obviously experiments producing widespread effects should be made in relatively unpopulated regions such as Alaska or Northern Canada.

The nucleation of clouds by dry ice pellets or silver iodide provides an easy way of marking and studying the turbulence within clouds. If we can understand the effects that can be observed after seeding, we should know much more about the internal structure of clouds. This would prove of great value to meteorologists.

III. TECHNIQUES FOR SEEDING CLOUDS WITH ICE NUCLEI

Vincent J. Schaefer

Since July, 1946 when the first experiments were made in our laboratory converting a supercooled cloud to snow, a number of experimental techniques have been developed for seeding natural clouds in the atmosphere. Some of these will be summarized in this report. It has been shown(1) that supercooled liquid water droplet clouds can be forced to form snow crystals by localized cooling below -35°C (-31°F). One of the easiest ways to accomplish this is to use dry ice which has a temperature of -78.5°C (-110°F).

The initial cloud modification experiments were made using granulated dry ice and all subsequent experiments to date have employed this material. From the economic standpoint, it is unlikely that the use of dry ice will be superseded by foreign-particle nuclei except in special cases. Foremost among such special cases will be those conditions where it is desirable or necessary to introduce active ice nuclei in regions of the atmosphere having temperatures above freezing. For such conditions, foreign particle nuclei such as silver iodide, zinc oxide or other active sublimation nuclei will be indispensible since the ice crystals produced by the use of dry ice evaporate unless they are formed in air cooler than 0°C (32°F) supersaturated with respect to ice.

Another instance where foreign particle nuclei assume importance is in situations where dry ice or cylinders of CO_2 are not available. A limitation to the use of foreign particle nuclei is the fact that such particles do not serve as active ice nuclei until the air containing them is colder than -5°C (23°F) and in some instances, depending on the particle size, -10°C (14°F). It is, of course, also necessary, as with dry ice, that the air be supersaturated with respect to ice before water vapor crystalizes to form visible ice crystals.

TYPES OF DRY ICE

Commercial dry ice is normally obtainable in 10-inch cubes, such a block having a weight of 50 to 55 pounds. If allowed to stand unprotected in a room at 20°C, a block will sublime to the gaseous state in about eight hours.

There seems to be, in general, two types of dry ice commercially available. One of these is the by-product of certain chemical processes and contains some impurities. The other is a direct product (containing little impurity) which is formed from coke or other direct sources of CO_2.

1. The Production of Ice Crystals in a Cloud of Supercooled Water Droplets. V. J. Schaefer. SCIENCE, 104, pp. 457-459, (Nov. 15, 1946).

For reducing blocks of dry ice to pieces larger than a grain of sugar and not greater than 3/8 inch in effective diameter, the by-product type of dry ice has proven to yield the greater quantity of useable particles when ice chipping machines are used. This might be related primarily to the method of compression employed in the preparation of the blocks.

It has been found that the highest yield is always obtained with the denser grades of dry ice.

PRESENT METHOD OF PREPARING GRANULATED DRY ICE

The present method used in this laboratory to prepare granulated dry ice is a simple but somewhat tedious procedure. A 10-inch cube of dry ice is broken into eight or ten chunks with a mallet and chisel. These chunks are then passed through a motor or hand-driven ice-chipping machine. By sieving the fragments with 1/2-inch and 1/16-inch mesh sifters, the larger fragments and fine powder are easily segregated from the granular portion suitable for seeding experiments. The fragments which are too large to pass through the 1/2-inch mesh are again put through the chipping machine or are reduced to proper size with pointed or edged tools. About 100 pounds of dry ice can be granulated by two workers in less than an hour.

Powdered dry ice is removed primarily to eliminate caking which occurs if the granulated material is stored for more than an hour or so. It should be mentioned, however, that the "powder" may be used very effectively in certain types of seeding. Caking develops to only a minor degree if moist air is kept away from the powder fragments.

OTHER METHODS OF GRANULATING DRY ICE

Fifty-pound cubes of dry ice may be cut into slabs 3/8 inch wide by using a band saw. Cutting with a coarse toothed saw proceeds along a 10-inch face at a speed of one cm/sec.

Experiments have been tried to reduce slabs of dry ice to small pellets by cracking them by manual methods. The "horny" property of the "ice" makes this difficult to accomplish. It is believed that a mechanical method can be devised which would produce suitable fragmentation. The easiest way would probably employ a pair of rolls having corrugations or spikes spaced so that the thin slabs passing through would be fractured so the resulting fragments would be in the desired size range.

STORAGE OF GRANULATED DRY ICE

After sieving the fragments, the useable residue is stored in corrugated cardboard boxes. We have found that a box 8 by 8 by 6 inches surrounded by a 1-inch layer of pack felt and placed within another box 10 by 10 by 8 inches will hold about 13 pounds of granulated dry ice. More than 50 per cent of loose granulated particles remain when stored for 24 hours in such a container. Fortunately, the granulated particles do not tend to cake when stored in this manner. A slow sublimation occurs which leads gradually to the formation of rounded pellets. A considerable decrease in loss can be achieved by packing the boxes in close contact with each other, particularly if a considerable batch is prepared at one time. It is desirable, if possible, to store them in a cold chamber, or outdoors if the air is cold.

When the boxed granulated particles are placed in the seeding plane, the inner boxes are removed from the insulated storage containers to reduce the bulk. Since the dry ice is generally used within a short time, there is little advantage in retaining the insulation.

PARTICLE SIZES NEEDED FOR VARIOUS TYPES OF SEEDING

On August 16, 1946 in a short report(2) Langmuir included a table showing the distances dry ice pellets of different sizes would fall and the length of time required. These values were based on theoretical calculations which have subsequently been roughly checked by experimental observation. The table is copied directly from Langmuir's report.

TABLE I

The Fall of CO_2 Pellets through the Air at -20°C and at Height 2000 M

Pellet Diameter Cm	Velocity Cm/sec	Time to End of Fall Sec	Distance to End of Fall Meters
2.	2850	760	14,000
1.	2120	350	4,300
0.4	1420	127	1,130
0.2	950	59	330
0.10	564	26	82
0.04	233	8	10
0.02	105	3	1.6
0.01	41	1	0.3

Experimental observations have indicated that the values in the third and fourth column of Table I tend to be somewhat greater than found by actual observation. Since these values are based on quiet air and many actual conditions suitable for seeding involve convective clouds, we have in general used particles as large as one cm in average cross section. Special cases require even larger particles. Very thick clouds or the presence of two cloud layers separated by a thousand feet or more of clear space between them require particles up to two cm in cross section if both cloud systems are to be seeded by one flight over them.

2. Memorandum on Introduction of Ice Nuclei into Clouds. Irving Langmuir, General Electric Research Laboratory (August 16, 1946).

SEEDING TECHNIQUES WITH GRANULATED DRY ICE

Our seeding experiments in November, 1946 showed that considerable effect can be obtained by introducing dry ice in the cloudless region immediately below a supercooled cloud. Langmuir subsequently pointed out that the region under a supercooled cloud is supersaturated with respect to ice and, therefore, if seeded, would produce ice crystals. The vertical distance in which this may be done amounts to about 10 meters per degree centigrade of supercooling. Thus we observed in our November 13 experiment that, when the base of the cloud had a temperature of -18°C, visible draperies of snow formed immediately to a distance of nearly 600 feet below the visible cloud base.

A later flight was made to study this effect. A flight was made at the base of a supercooled cloud. A snow region formed instantly along the seeded region which looked like a trail of smoke. This spread outward and upward into the base of the visible supercooled cloud subsequently seeding it.

In an experiment which produced a snow area more than 35 miles long, all of the seeding was done in the base of a solid overcast. For such experiments, it is wasteful of material if dry ice particles greater than 0.2 cm diameter are used, since the available region rarely exceeds 330 meters below the base of the supercooled cloud.

The method recommended for any large scale seeding with dry ice is to fly in contact or a few feet above the top of the supercooled cloud system. Granulated dry ice, the pellets having diameters between 0.2 - 1.5 cm or larger, (depending on the thickness of the supercooled region) should be released at the rate of at least a pound per mile. If the vertical thickness of supercooled clouds exceeds 3000 feet, the quantity of dry ice released should be doubled. Flight paths at right angles to the wind should be made so that adjoining seeded regions are about three miles apart if the supercooled region is 2000 feet thick. This distance may be increased to five miles if the supercooling extends to a depth of 5000 feet.

SEEDING OF POTENTIAL THUNDERSTORM CLOUDS

For cumulus congestus systems of the type which lead to thunderstorms, the amount used should be further increased. Spectacular results have been achieved recently(3) in Australia using a hundred pounds of granulated dry ice in a localized region. Quantitative experiments should be made this summer with such systems to establish the optimum quantities needed for modifying these highly convective clouds. It is desirable, if possible, to seed such clouds from above although seeding flights through the cloud would also be effective. It should be remembered, however, that dry ice is effective only in the supercooled regions of clouds. Any particles placed in clouds warmer than 32°F (0°C) are totally wasted. See Part V11 of this report for further details.

3. Experiments on the Stimulation of Clouds to Produce Rain. E. B. Kraus and P. Squires. NATURE, 159, p. 489 (April 12, 1947).

USE OF COMPRESSED CO_2 TO PRODUCE ICE NUCLEI

Another convenient and inexpensive source of ice nuclei is available in cylinders of liquid CO_2. When the valve on a cylinder is opened a dense spray of dry ice forms from the sudden cooling of the expanding gas. Since much of the entrained air is brought into an environment below -35°C, vast numbers of spontaneous ice nuclei are formed even if dry ice snow is not produced.

Although cylinders of CO_2 gas are often available when ordinary dry ice is not, the latter is to be preferred from the standpoint of both economy and effectiveness.

In general, the release of compressed CO_2 from a plane or other moving source seeds a line rather than the plane or sheet produced when pellets are dropped into the cloud. The compressed CO_2 is very effective for seeding the region under a cloud, however, and would probably be nearly as effective as crushed dry ice. It is best to release it in the region of greatest turbulence and air velocity on the plane so that the nuclei are effectively scattered. It is also desirable to invert the cylinder so that the escape is at the bottom; this leads to the greatest production of dry ice snow.

DEVELOPMENT OF CONVECTION WHEN A SUPERCOOLED CLOUD IS SEEDED

It has been observed, both in our experiments and others[3], that when a supercooled cloud is seeded a considerable amount of convective movement develops. Calculations by Langmuir, the results of which are included in this report, show that this convection is due to the heat of fusion as ice crystals form. The rise in air temperature occurs at the boundary between the ice crystals and the supercooled cloud droplets and can amount to as much as 0.8°C. This amount of heat might lead to a considerable convective movement, especially in stratiform systems. However, the Australian experiments indicate that, under proper conditions, the convection, even in cumulus, clouds can be accelerated by the sudden introduction of sufficient quantities of sublimation nuclei.

SEEDING METHODS USING SILVER IODIDE

In another part of this report, Dr. B. Vonnegut describes a method by which silver iodide can be produced to serve as ice-crystal nuclei. This method, typified by the "string burner generator" which used a cotton thread impregnated with silver iodide, if used in a plane, would seed a line through the air.

Silver iodide has a considerable advantage over dry ice in the sense that its vapor pressure is so low that it will exist in the air as a finite particle and potential sublimation nuclei for a long time. Thus, even though it is formed or is carried into air at above freezing temperature or low humidity, it serves as an active sublimation nuclei as soon as it enters a suitable environment. Therefore, one of the most effective seeding procedures would appear to be, to do the seeding within or even below the base of a convective type cloud, the particles being carried up and into the cloud. As pointed out previously, even though the base of such a cloud is warmer than 0°C (32°F), the sublimation nuclei formed in that region will become effective as soon as the right temperature is reached and the air is supersaturated with respect to ice.

TEMPERATURE NEEDED FOR SILVER IODIDE TO ACT AS SUBLIMATION NUCLEI

Experiments in the laboratory indicate that, if a particle of silver iodide is to serve as an effective sublimation nuclei, the temperature of the air must be lower than -4°C. Such a temperature seems to be sufficient when the silver iodide particles are larger than 0.01 micron in diameter. When smaller than this size, temperatures as low as -8°C seem to be required for effective activity.

USE OF GENERATORS AT GROUND LEVEL

In considering seeding operations on a very large scale, an attractive possibility exists in the use of generators at ground level. Under atmospheric conditions having a dry adiabatic lapse rate, sublimation nuclei of the foreign-particle type generated at ground level will be carried up and into the clouds. Even better possibilities exist where orographic supercooled clouds form where mountain ranges interfere with the flow of cold moist air, thus forcing it to develop dense cloud systems. Particularly good conditions for seeding clouds by this method exist in the states of Washington and Oregon. Contact has been established with people in that region who are interested and anxious to conduct such experiments. Much information could be gained by establishing one or more generators in that part of the country. If successful, considerable amounts of water, in addition to that already precipitated, could probably be stored as snow on the mountain slopes for later use in irrigation projects.

Preliminary studies along such lines could be made at the Mt. Washington Observatory. By placing a generator at Fabyans or Pinkham Notch (depending on prevailing winds) at the Co-operative Stations of the U. S. Weather Bureau at both places, activities could be synchronized with the Observatory by either radio or telephone. By running a generator off and on during definite time periods, any changes in the properties of the summit cloud and the development of snow on the leeward side could be observed.

SPECIAL SEEDING METHODS

Two additional methods are under consideration for seeding supercooled clouds.

In the case of a slow moving object, such as a K-type airship, which encounters a serious icing hazard whenever it enters a supercooled cloud, it is proposed that an ice-nuclei generator be placed immediately in front of the nose of the ship. The nuclei generated at this location should be in such quantities that all of the supercooled clouds intercepted in flight will be immediately converted to ice crystals. Various methods are available including (1) use of solid CO_2, (2) use of gaseous CO_2, and (3) sudden expansion of air so that its temperature drops below minus 35°C. This latter procedure might be done by a series of high-pressure pop valves, although a "heat centrifuge" powered by an air compressor would probably be much simpler to construct and install.

The second possibility involves the use of projectiles which might conceivably be used to clear a path in front of a faster moving object such as an airplane. Bullets or similar projectiles dispensing compressed CO_2 or silver iodide might be shot from the nose of the ship. If they had a range of two miles, a period of thirty seconds or more would be available for the ice crystals to use up the supercooled cloud droplets before the arrival of the plane.

THE GENERAL APPEARANCE OF WATER DROPLET AND ICE CRYSTAL CLOUDS

It is sometimes important, in making cloud-modification experiments, to be able to determine whether a cloud consists of ice crystals or supercooled water droplets. This is of particular importance just before and immediately after a seeding experiment.

The most important item to check is the temperature of the cloud. If it is below 0°C (32°F), then there are several ways of telling whether the cloud is supercooled or contains ice crystals.

If supercooled, a small black rod 1/8 inch in diameter exposed to the cloud will develop a layer of rime that is easily visible. Upon entering the cloud from the top, if the sun is observed as it disappears from sight as a sharp edged disk, it is a good indication of water droplets. The sun is often, also, surrounded by a luminous, colored corona.

When flying above a cloud, if the shadow of the plane is surrounded by a luminous, colored ring known as a "glory," the cloud contains water droplets. At times a white cloud bow can be seen having the same 42-deg angular displacement of the colored rainbow. Another general feature of a water droplet cloud is its well-defined edges.

Thus, the observable features which denote the presence of a supercooled cloud are:

(1) Temperature below 0°C (32°F);

(2) Ice formation on 1/8-in. collector;

(3) Sharp-edged disk of sun when seen through thick cloud often surrounded with colored corona;

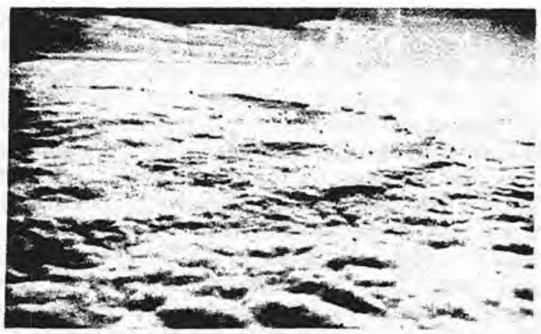
(4) Presence of a "glory" around plane's shadow and occasionally the appearance of a cloud bow.

EFFECTS OBSERVED WHEN CLOUDS CONTAIN ICE CRYSTALS

The optical effects observable when a cloud consists of ice crystals are also quite easily observed. As before, the cloud must be colder than 0°C (32°F). When in the cloud, little or no icing will be observed, although white spots will form on the leading edge of the wings if the snow particles are of appreciable size. The deposit will not grow in thickness, however, unless there is also supercooled water present. The edge of the sun's disk will appear fuzzy without a colored corona when ice crystals are present. Looking toward the sun, brilliant 22-deg and 46-deg halos are often observable sometimes accompanied by sundogs, i.e., bright spots on a horizontal plane with the sun and just beyond the 22-deg halo. When above the cloud, if the observer looks down at the cloud top in the direction of the sun, a bright spot or streak will be seen at the same angle at which the sun is above the horizon. This resembles somewhat the luminous reflecting path of the sun or moon seen on a lake slightly rippled by the wind. This effect is due to the specular reflection of the sun from the flat surfaces of snow crystals and is related to the sun

SEEDED AREA LOOKING SOUTH WITH SUN IN SOUTHWEST

SEEDED AREA LOOKING NNW WITH SUN IN SOUTHWEST



SEEDED AREA WITH REFLECTION OF SUN ON ICE CRYSTALS

FIG. 1

pillar. Snow particles in a cloud are also easily seen when flying through them as either white or bright streaks depending on the illumination. This is not easily seen unless the plane is close to the crystals.

When a cloud consists mostly of ice crystals, it has a satin-like appearance when viewed in the general direction of the sun and its edges are generally quite diffuse. The reflectance from such a region is much different from that of a water-droplet cloud, more sunlight being reflected and scattered in a forward direction than to the rear. Thus, the cloud often appears whiter than an adjoining supercooled region when viewed toward the sun and is often darker when viewed with the sun behind the observer. Such effects are well illustrated by the photographs in Fig. 1.

Thus the features denoting presence of ice crystals are:

(1) Temperature below 0°C (32°F);

(2) No ice on a 1/8-in. collector;

(3) Fuzzy edge to the sun's disk;

(4) Presence of halos, arcs, and sundogs around sun;

(5) Presence of sun streak or pillar in reflectance of sun from cloud;

(6) Visible white or shiny streaks as snow is passed by plane;

(7) General diffuse edges to cloud;

(8) Change in light reflectance as the relative positions of the sun and the cloud change.

IV. INSTRUMENTATION DEVELOPMENTS FOR THE CLOUD STUDY PROJECT

Raymond E. Falconer

In addition to the standard aircraft instruments, including an aerograph, it has been our responsibility to supply the following instruments to be used in carrying out the Cloud Study Project.

AUTOMATIC DRY ICE DISPENSER

This apparatus (see Fig. 2) consists of a wooden hopper mounted over one end of a coarse, motor-driven screw. The hopper is 14 inches high, measuring 8 by 10 inches at the top and 7 by 4 inches at the bottom. The screw is 2 1/2 inches in diameter by about 16 inches long with a 200 to 1 reduction gear box mounted on the driven end. A 1/4-hp, 24-volt d-c, 3600-rpm, aircraft motor operates the worm gear by means of a belt drive from a 2-inch pulley on the motor shaft to a 3-inch pulley on the gear box. This arrangement allows about three pounds of dry ice pellets to be dropped each minute. It was found at first that the dry ice tended to cake in the hopper and would not continuously feed the screw unless the dry ice was kept continuously mixed up with some implement. This difficulty was mostly eliminated by sifting out from the crushed dry ice all the fine "snow" which unavoidably accumulates in the crushing process. A more rugged gear box is on order to replace the one now in use. The new gear box will also allow the dry ice pellets to be dropped at a faster rate.

The pellets of CO_2 are dropped out of the plane through a funnel which was made to fit a 3-inch hole already existing in the floor near the tail of the B-25. The funnel tapers from 8 by 10 inches at the top down to a 3-inch diameter cylinder in a distance of 6 1/2 inches The 3-inch cylinder section extends below the plane about 12 inches.

SILVER IODIDE GENERATOR

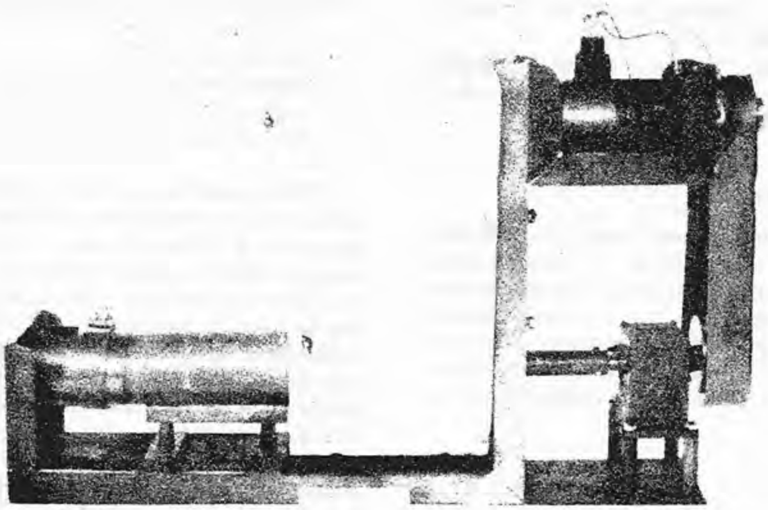
This will be described elsewhere in the report.

ICING RATE EXPOSURE RODS

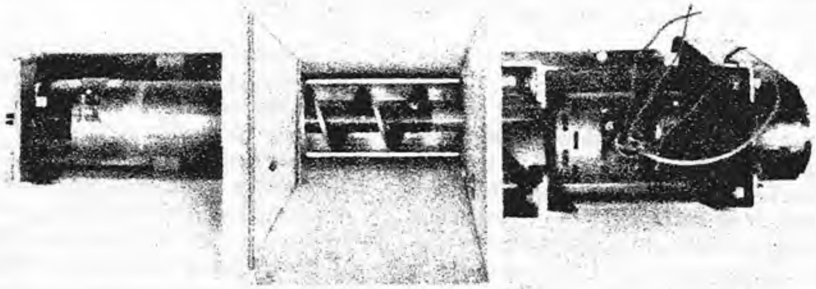
Lacking a suitable instrument for accurate determination of liquid water content of clouds in below freezing temperatures, we can get some idea of whether there is light or heavy icing in a simple manner. This is done by exposing, through a hole in the side of the plane, a length of pipe having two sizes of cylinders mounted on the end. The large cylinder is one inch in diameter by 6 inches long and is made of brass. Threads are tapped in one end so that it will screw onto one end of an 18-inch length of 3/4-inch pipe. The small cylinder is 1/8 inch in diameter by about 2 1/2 inches long and is threaded to screw into the end of the 1-inch cylinder. The rods are exposed with their lengthwise axis at right angles to the airflow. The cylinders were given a coat of black paint to aid in observing the ice formation. Four sets of this type of collector were made.

Another type of collector is a cone turned out of hard wood with a 1/8-inch rod set into the small end and the larger end tapped to fit an 18-inch length of 3/4-inch pipe. The cone itself is 7 inches long tapering from a 1 1/2-inch diameter down to 1/4 inch. This was also given a coat of black paint and, in addition, a scale marked off in centimeters was painted on in white starting from the small end.

When exposed, the rods are kept slowly rotating. The ratio between the amounts of ice collected (by weight and by increase in diameter) on the two cylinders gives the added information necessary to determine collection efficiency, drop size, and liquid water content[1]. The distance along the cone that ice accumulates is also indicative of drop size, etc. A set of numbered glass jars has been provided so that after ice has been collected, the collector and ice can be put into a jar and later the



SIDE VIEW



TOP VIEW

FIG. 2 DRY-ICE DISPENSER

amount of ice collected can be determined by weighing the melted ice.

The advantage of having the small 1/8-inch rod exposed is that occasionally the pilot will fly through a cloud and report no icing. He may report this mainly on his observation that there is no ice building out on the leading edge of the wing. As far as he is concerned, there is no icing to worry about and in that sense, his report is justified. However, if he is in a cloud there will be icing and if the drops are very small, there will be little or no deposit on an object as large as the leading edge of an airplane wing but there will be a deposit on an object as small as the 1/8-inch rod.

CLINOMETER ATTACHMENT FOR CAMERA

It became evident in our early flights that it would be necessary, when taking photographs of the seeded areas, to know the vertical angle at which the camera was pointed. Consequently we made a very simple device to attach to the camera which would indicate its angle of inclination at the time the picture is taken. The device is simply a freely moving pointer-arm which is the radius of a circular scale of degrees. The scale is stamped on the outside vertical face of a right angle made by bending a sheet of 6 by 4 by 1/16-inch brass. The horizontal arm of the brass angle is clamped to the top surface of the camera. Before taking a picture, the pointer arm can swing freely, always remaining in a vertical position regardless of what angle the camera is tilted from the vertical. At the moment a picture is taken, a small finger-operated plunger is pushed which causes a wedge to come against the small shaft on which the pointer arm moves. The friction thus caused will hold the pointer arm in whatever position it is in at the time the plunger is pushed and, therefore, the angle of inclination is indicated directly on the scale.

1.a. A Mathematical Investigation of Water Droplet Trajectories. Irving Langmuir and Kather-

ine B. Blodgett. Contract W-33-038-AC-9151. (December, 1944 to July, 1945.)

b. The Multicylinder Method. Mount Washington Observatory Monthly Research Bulletin. No. 6, Vol. II (June, 1946).

G-E WIRE RECORDER

This instrument is borrowed from the G. E. Research Laboratory and is used to record radio conversation between the airplane making the test flight and the observers in the tower at the Schenectady Flight Test Airport. Notes on ground observations are spoken into the microphone of the recorder and later taken down in writing by playing back the voice record.

CLOUD METER

In preparation for the summer program of cloud studies, other instruments are being developed. One instrument, for the measurement of liquid water content of clouds, is a modification of Schaefer's cloud meter using a porous plug collector(2).

The principle of the cloud meter is to allow water, which seeps through the porous plug, to collect into a small drop on the end of a tiny copper tube. Another similar tube, through which there is a constant suction applied, is mounted so that its open end is within 1/32 inch to 1/16 inch of the other tube on which the drop is formed. The two small tubes act as electrodes and are connected in series with a d-c battery source (6 to 22 1/2 volts) and a G-E Photoelectric Recorder. Whenever a drop is formed on the end of one tube, it will momentarily be in contact with both tubes just before being drawn away by the constantly applied suction. The conductivity of the water drop during this brief contact causes a small current to flow through the P. E. recorder and is registered by a deflection of the needle. Thus, every drop that passes between the electrodes is registered as a deflection on the recorder. By knowing the weight of a drop thus formed and counting the number of deflections, an indication of the amount of liquid water content may be obtained.

The modified version of the cloud meter substitutes a constant suction from an external vacuum source for the original suction obtained from a constant 20 cm head of water maintained in the "dropping" tube. The exposed part of the new cloud meter has a blunt-nosed, bullet shape being about 1 1/2 inch long by 7/16 inch diameter through most of its length. It tapers at the porous plug end to an opening of 5/32 inch. This unit is mounted in the end of a 25 1/2 inch by 3/4 inch bakelite tube which in turn slides through a sleeve mounted in the nose of the plane. This allows the porous plug to be taken out at will and primed, if necessary, and also allows an adjustment of the length the unit protrudes into the airstream. Wires from the recorder to the electrodes and the suction line tubing from the vacuum source (through a water trap) lead from inside the plane through the bakelite tubing to the porous plug.

2.a. Report on G. E. Cloud Meter (Plane Model). V. J. Schaefer. Contract W-33-038-AC-9151. (August 16, 1945.)

b. Report on Icing Studies Underway on Mt. Washington, N. H. and at Schenectady, N. Y. up to January 20, 1945. V. J. Schaefer.

If this cloud meter works satisfactorily, a second one will be built to be mounted at the stagnation point of a 1 1/2-inch sphere. In this way we will have, in effect, a large and small collector so that the ratio in collection efficiencies between the two can be used to indicate droplet size. The two collectors will indicate on the same recorder by using one common lead from the recorder to each collector. The battery in the other lead to one collector will be connected so that deflection in that circuit will swing the recorder pin in a positive direction while the connections in the other collector circuit will show negative deflection.

GLASS ROD EXPOSURE GUN AND AIR DECELERATOR

Another instrument being made for the purpose of getting a rough check on droplet size is a sooted glass rod exposure gun and air decelerator. The air decelerator(3) is merely a series of four concentric cones spaced about one inch apart on three supporting rods. It is mounted horizontally so that the small end of the leading cone points into the airstream. Air of much lower velocity is available at the center of the large end of the rear cone since a good bit of the incoming air is "spilled out" between the preceding cones. The decelerator is attached to the plane by means of a funnel-shaped tube of aluminum whose large end is bolted to the large end of the rear cone while the other end of the funnel, which is a straight 2-inch tube, slides through a special collar built into the nose of the ship. From inside the plane, the exposure gun can be inserted into the 2-inch aluminum tube so that the small sooted glass rod set in the end of the gun can be quickly exposed to the "slowed-down" air available at a point just inside the small end of the rear cone of the decelerator. The exposure is accomplished by a trigger and lever arrangement that moves a cap which normally is set over the end of the glass rod to prevent moisture from touching it. When the trigger is pulled, the cap, of course, lifts up exposing the end of the rod directly to the airstream.

The ends of the 1/8-inch diameter by 1/2-inch long pyrex glass rods are treated with G-E Dri-Film No. 9987 and coated with soot in the same way glass slides have previously been used(4). It is felt the glass rods may be better to use since they can be handled much easier and they very neatly fit the gelatin capsules used for preserving them. The exposure gun has storage space in it for 15 capsules.

3. An Air Decelerator for Use on De-Icing Precipitation Static and Weather Reconnaissance Planes. V. J. Schaefer. (January, 1945.)

4. The Preparation and Use of Water Sensitive Coatings for Sampling Cloud Particles. V. J. Schaefer. Contract W-33-038-AC-9151. (April, 1946.)

ACCELEROMETER, ALTIMETER AND ELEVATOR POSITION RECORDER

An instrument which we will also need is a recording accelerometer and altimeter. This instrument will aid in determining vertical velocities within the clouds as the plane flies through them. Such an instrument is available for our use here in the General Electric Co. with some modification. For instance, the chart speed of the instrument normally is one foot per hour while we need a speed nearer one foot per minute. We are, therefore, making the necessary changes in the chart carriage to obtain the faster speed. The accelerometer now used is rated -5 to +12 g and we have ordered one of ± 5 sensitivity. The record is obtained from a standard altimeter and accelerometer through a servo-mechanism consisting of a small Selsyn transmitter mounted on the face of each instrument while the respective receivers are arranged to move a stylus across the pressure sensitive record paper.

It is hoped that another stylus can be made to operate simultaneously on this recorder so that the movement of the elevator control stick of the plane may be indicated. One way this can be done is by merely connecting a fish line or similar strong cord from the stylus to the elevator control cables so that, with the cord taut, the cable movement will be transmitted through the cord to the stylus. The stylus is connected so that the normal position of the control stick keeps the stylus in the center of the recorder paper and any variations from normal are indicated on the paper by movements of the stylus to right or left.

We are also installing a visual indicator of elevator control position so that the pilot can see in front of him any changes he may make. This will be done by coupling a 50-ohm potentiometer to the elevator actuating arm and mounting a 10-0-10 d-c milliammeter Type DO-40 in the panel in front of the pilot. The milliammeter is connected in series with the potentiometer through a 30-ohm resistor and a 1 1/2-volt battery.

Thus, on occasion, we may ask the pilot to fly through a cloud holding his elevator control in a fixed zero position as indicated by the milliammeter. This would be regardless of what changes in attitude the plane may be forced to make due to turbulence, updrafts, etc. If the pilot is unable to hold his control stick at zero, the recorder will show how much he had to move it so that, with the combination of records on the same sheet, i.e., acceleration, altimeter change, and control stick position, we should be able to figure out the vertical velocities encountered in the cloud. This information will be compared with changes in droplet size recorded simultaneously as a further check in developing Langmuir's "time-of-rise theory."

V. NUCLEATION OF ICE FORMATION BY SILVER IODIDE PARTICLES

Bernard Vonnegut

SUMMARY

A smoke made of large numbers of very small silver iodide particles serves as nuclei for the transformation of supercooled water clouds to ice. Depending on the size of the silver iodide particles, the transformation from water to ice is brought about at -4°C to -8°C or lower. In contrast to the nuclei made of ice produced by low temperatures, silver iodide nuclei are unaffected by warm or dry conditions.

Experimentation is underway on methods for the large scale production of silver iodide smoke for the purpose of nucleating natural supercooled clouds. Generators capable of producing 10^{13} particles per second have been made.

Tests on the effects of silver iodide smokes on natural supercooled cloud formations will be carried out.

DISCUSSION

Experiments made by V. J. Schaefer in this laboratory and by B. M. Cwilong[1] in England showed that a wide variety of powdered solids and smokes was without appreciable effect in nucleating ice formation in supercooled clouds at temperatures above -20°C. This experimentation on foreign nuclei was continued to see whether particles of substances very similar to ice in crystal structure might not serve as nuclei for ice formation at temperatures closer to the freezing point.

A search was made through X-ray crystallographic data for substances resembling ice as closely as possible in crystal system, space group, and dimensions of unit cell. Two substances were chosen which are listed in Table II along with ice for comparison.

These crystalline substances were tested to see if they would act as nuclei for the formation of ice by dusting them as a powder into a supercooled water cloud in Schaefer's apparatus at a temperature of -20°C.

Silver iodide was without apparent effect; however, the introduction of lead iodide powder caused the formation of a number of ice crystals in the supercooled cloud. It appeared that far fewer ice

TABLE II

Substance	System	Space Group	Lattice Const.		
Ice	hex.	D_{6h}^4	4.535	7.41	(2)
AgI	hex. ZnO	C_{6v}^4	4.585_6	7.490	(3)
PbI_2	hex.	D_{3d}^3	4.54	8.86	

1. B. M. Cwilong. NATURE, 155, pp. 361-362. (March, 1945).
2. William H. Barnes. Proc. Roy. Soc. (London), A125, pp. 670-693, (1929).
3. N. H. Kolkmeijer, W. J. D. von Dobbenburgh, H. A. Boekehoogen. Prov. Amsterdam, 31, pp. 1014-1027, (1928).

crystals formed than would have been expected from the number of particles of lead iodide introduced.

The supposition that the lead iodide particles acted as nuclei because one of the dimensions of its unit cell was almost the same as that for ice was discarded when V. J. Schaefer discovered that iodoform crystals and iodine vapor behave in a similar way. The orthorhombic structure of iodine bears little relation to the structure of ice.

Later, investigations were made on the nucleating effect of smokes produced by electric sparks between electrodes of various metals. It was discovered that a single spark between silver electrodes in the presence of iodine vapor produced many thousands of times as many ice nuclei as lead iodide particles or iodine vapor alone. It was then found that silver iodide smoke produced by heating silver iodide on a hot filament or by dispersing it in a flame produced enormous numbers of nuclei. The failure of the initial experiment using silver iodide powder is attributed to the fact that the sample used was badly contaminated with soluble salts, a fact not known at the time. Powdered silver iodide without this impurity has since been found to serve as nuclei for ice formation.

It is believed that silver iodide acts as a very effective nucleus for the formation of ice crystals because it very closely resembles ice in crystal structure. It can be seen that both dimensions of the unit cell of ice and silver iodide are the same to within about one per cent.

According to Dr. D. Harker of this laboratory, the arrangements of the atoms in the unit cells of ice and of silver iodide are almost identical despite their different space groups. The structure of ice is the same as that of silver iodide with the oxygen atoms occupying positions corresponding to the silver and iodine atoms. In silver iodide, each silver atom is bonded tetrahedrally to four iodine atoms. In ice each oxygen atom is bonded tetrahedrally, through hydrogen bridges, to four oxygen atoms.

Iodine vapor alone or fine silver particles alone are without appreciable effect in forming ice crystals, at a temperature of -20°C. If the experiment is carried out using iodine vapor alone in a system closed to the atmosphere of the laboratory, iodine vapor soon loses its property of nucleating a supercooled cloud. It is believed that iodine compounds and iodine vapor act to produce nuclei by reacting to form silver iodide with minute traces of silver in the laboratory atmosphere. Such traces of silver might be caused by sparks from electrical equipment using contacts made of silver or copper that contains silver. Exceedingly small amounts of silver introduced into a supercooled cloud in the presence of iodine vapor cause the formation of very large numbers of nuclei. One breath of air blown over a silver wire heated red will produce many millions of ice nuclei if it is introduced into a supercooled cloud containing a small amount of iodine vapor.

The temperature at which silver iodide becomes effective as a nucleus for the formation of ice has been tested in several ways.

Measurements were made using the cold box in which small amounts of silver iodide smoke were introduced into a supercooled cloud at various temperatures. It was found that silver iodide smoke particles produced by vaporizing silver iodide on a hot wire became active as nuclei at a temperature of about -4°C or lower. The particle size of this smoke was about one micron in diameter. Finer particles in smokes produced by other methods, which will be discussed later, did not become active until lower temperatures. Particles of the order of 0.01 microns in diameter do not serve as nuclei until the temperature is -8°C or lower.

Experiments have been made on the supercooled fog produced by blowing one's breath on the cold, polished surface of a chromium-plated copper block. The water drops thus produced do not freeze until the temperature is -20°C or below in the absence of nuclei. It was found that freezing could be started in this film of liquid water drops by the addition of silver iodide powder if the temperature of the block was about -3.5°C or below. It was found that a piece of silver iodide in a test tube of distilled water made it impossible to supercool the water much below -3.5°C.

GENERATION OF SILVER IODIDE NUCLEI

In experiments using the home-freezer cold box, the generation of silver iodide particles to serve as nuclei poses no problem. Adequate numbers of nuclei to convert a supercooled cloud to ice particles can be produced in a variety of ways in addition to those already mentioned. If an ordinary safety match is rubbed across a silver coin and then struck in the presence of iodine vapor, enormous numbers of nuclei results. The same effect can be obtained if a trace of silver iodide is applied to the head of the match before it is struck.

When one contemplates the use of silver iodide for the large scale seeding of natural cloud systems, the economical production of large numbers of silver iodide nuclei is a more difficult problem. The cost of silver iodide is approximately $20.00 per pound. In order to get the largest number of nuclei per unit weight, it is necessary that the particles be made as small as possible. It has been found that particles as small as 0.01 microns are effective nuclei. Therefore, it is desirable that a method of producing particles should give about this size in order to produce as many as possible. It is interesting to note that a smoke particle one micron in diameter, which would not be considered a very large smoke particle, will make one million particles 0.01 micron in diameter.

Many of the principles worked out in this laboratory on the generation of smokes apply to the problem of making silver iodide smokes. The main limitation in applying existing techniques to generating smokes of silver iodide is that the temperatures at which silver iodide has an appreciable vapor pressure are very high. These high temperatures place a severe limitation on the materials and design of a smoke generator. Data for the vapor pressure of silver iodide and silver are as follows:

PRESSURES IN ATMOSPHERES

	10^{-4}	10^{-3}	10^{-2}	10^{-1}	.25	.5	1.0
AgI Temp Abs.	958	1076	1233	1450	1564	1665	1779
Ag Metal Temp Abs.	1442	1607	1816	2098	2236	2354	2485

The methods of large scale nuclei generation which show the most promise involve vaporization of silver or silver iodide by heating and then the rapid cooling and dilution of this gas to form very large numbers of very small particles. It is essential that the cooling and dilution of the vapor be accomplished very rapidly, as growth from condensation or growth from coagulation would increase the particle size beyond that desired.

In order to evaluate the rate of nuclei production of various types of smoke generators, known volumes of the smoke were introduced into a supercooled cloud in the cold box. The number of nuclei were then estimated by observing the average separation of the resultant ice crystals. Knowing the volume rate of smoke production, the rate of nuclei production can be computed.

A number of different methods for the generation of silver iodide smokes have been considered. A certain amount of work has been done on those showing the most promise. In the following section, these methods are described and evaluated according to the status of the work at present.

SILVER ARC AND IODINE VAPOR METHOD

The large nucleating effect of silver iodide was first observed with a small spark between silver wires in the presence of iodine vapor. A larger generator of this sort was constructed using an arc between two silver electrodes one-half inch in diameter. The arc was run at about 10 amperes and was arranged in series with 220 volts d-c and a bank of resistance. A blast of compressed air containing iodine vapor was blown through the flame of the arc. This arrangement gave of the order of 10^{11} nuclei per second. No measurements have been made on the rate of silver consumption of the arc.

When silver smoke from the arc was introduced into a supercooled cloud without iodine vapor, there were a few nuclei formed presumably from traces of iodine present in the box. However, when a crystal of iodine was moved through the cloud, it left a dense trail of ice crystals similar to the effect produced by a needle at liquid air temperature.

While the silver arc and iodine vapor method of nuclei generation seems to work fairly well, it would seem that methods which vaporize silver metal require considerably more energy than those vaporizing silver iodide. In order to produce the same vapor pressure, silver must be heated 600°C or 700°C higher than silver iodide.

VAPORIZATION FROM HOT WIRE

A simple and convenient method of generating silver iodide smoke is to vaporize it from a filament electrically heated bright red. The particles produced by this method are of the order of one micron in diameter which is too large to make the method economical for seeding any large volume. If a current of air is blown over the heated filament, the particle size is reduced but a large amount of energy is required to maintain the temperature of the filament. In a short time, the filament is seriously attacked chemically by the silver iodide which makes it impossible to run the generator continuously over any period of time.

VAPORIZATION FROM ELECTRICALLY HEATED FURNACE

A small electrically heated furnace was made up for generating silver iodide smoke. The furnace is shown in Fig. 3. The furnace is so designed that, when it is placed in an air stream of about 100 mph, a small amount of the air passes through the furnace. In the furnace is a piece of asbestos paper saturated with molten silver iodide. The air moving through the furnace becomes heated and saturated with silver iodide vapor at the temperature of the furnace, which is around 650°C. As it leaves the furnace, it is diluted and quenched in the air stream. The furnace was operated from a 6-volt storage battery and consumed about 100 watts. The apparatus produced about 10^{10} to 10^{11} nuclei per second in an air stream of 100 mph.

It is believed that methods employing electrical power for silver iodide smoke generation are not economical because of the large power consumption.

VAPORIZATION OF SILVER IODIDE COATED STRING IN FLAME

An effective method for the production of silver iodide smokes is to vaporize silver iodide in a flame

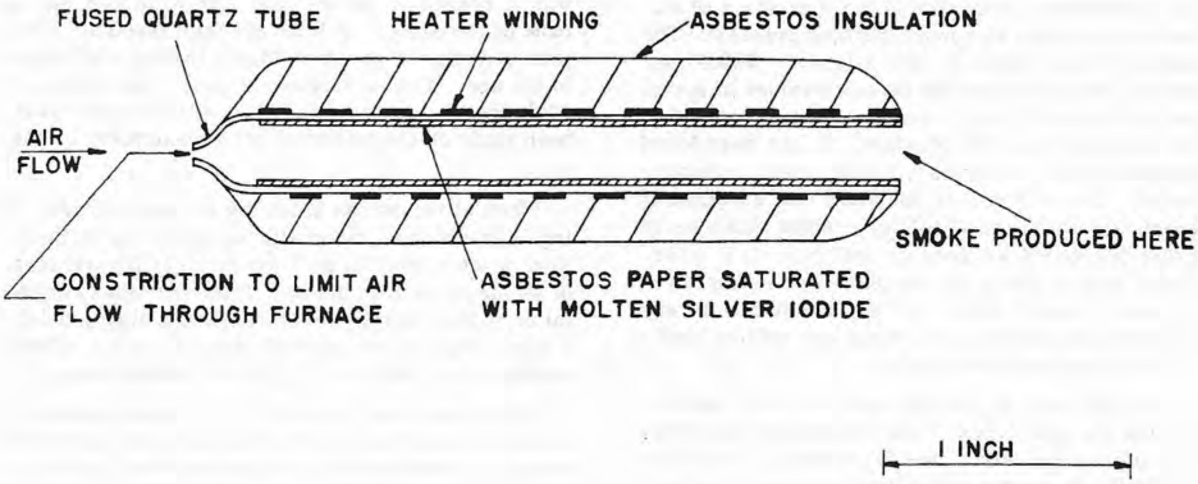


FIG. 3 ELECTRICALLY HEATED GENERATOR

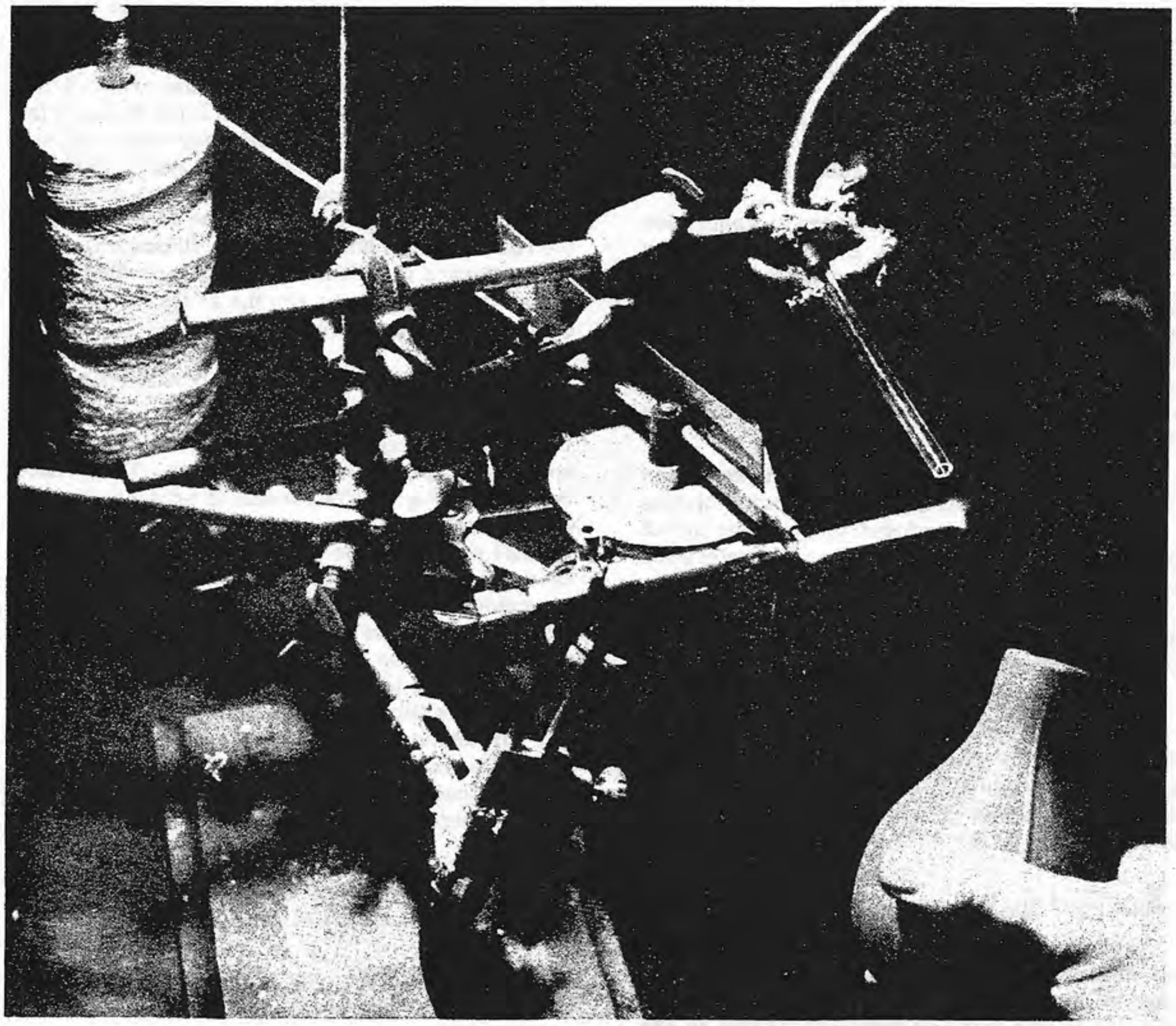


Fig. 4 Silver Iodide Generator

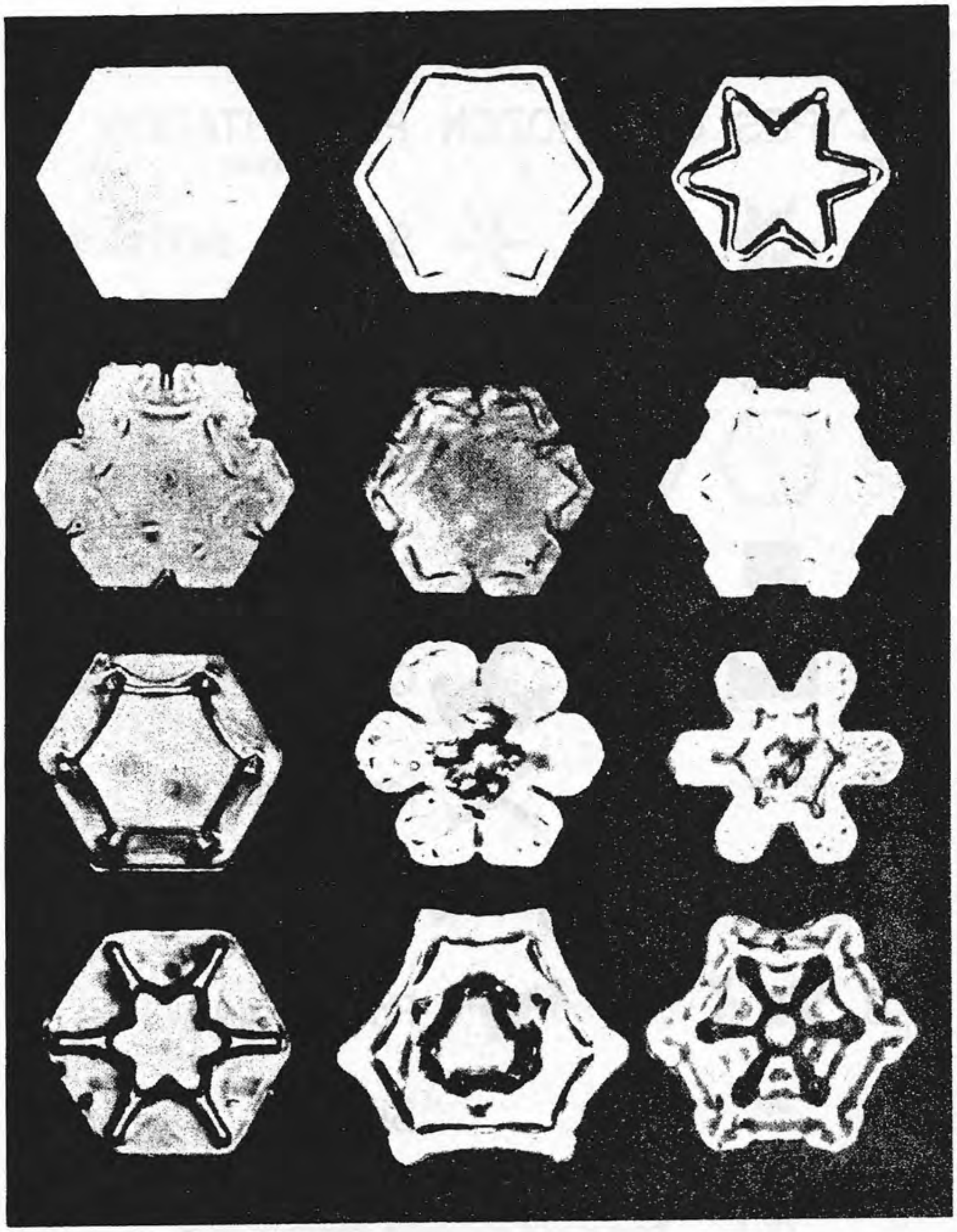


Fig. 5 Examples of solid precipitation produced artificially in the laboratory

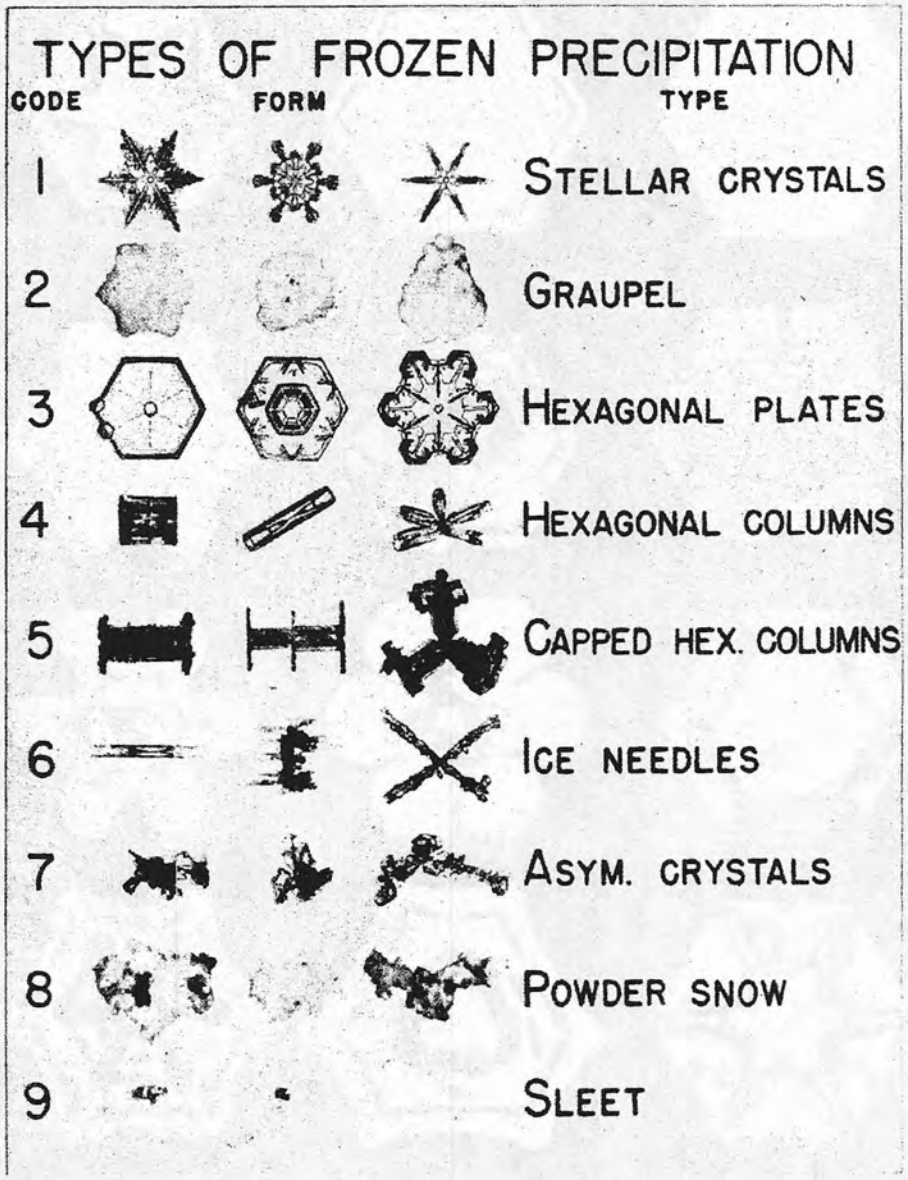


Fig. 6 Types of solid precipitation occurring in nature

TYPES OF SOLID PRECIPITATION
(See Fig. 5)

1. STELLAR CRYSTALS: Six rayed, starlike forms occurring as single crystals or in clumps. Crystals vary in a wide range of form and size. Clumps common, often appearing as cottony flakes sometimes two inches in diameter. Size 1/32 in.-1/2 in.; clumps common.
2. GRAUPEL: Stellar crystals which are covered with frozen cloud particles forming a rime deposit. This results in pellets of soft snow, which range from hexagonal to rounded forms. Size 1/16 in.-1/4 in.; rarely clumped.
3. HEXAGONAL PLATES: Thin, hexagonal, solid or semi-solid plates often containing internal structure due to air inclusions. The smallest form of this crystal and the stellar form is known as Diamond Dust. Size 1/1000 in.-3/16 in.; rarely clumped.
4. HEXAGONAL COLUMNS: Transparent generally flat-ended, sometimes pointed hexagonal prisms mostly of clear ice, many with air inclusions. Often a group of columns grow from a common source radiating in several directions. The former type produce 22^o and 46^o halos around the sun. Size 1/64 in.-1/8 in.; sometimes clumped.
5. CAPPED HEXAGONAL COLUMNS: Similar to (4) with the exception that both ends terminate as expanded hexagonal plates. A hexagonal plate sometimes is positioned midway between the two plates. Many queer forms occur. Size 1/64 in.-3/16 in.; sometimes clumped.
6. ICE NEEDLES: Long slender shafts with hexagonal cross section often terminating with sharp points. Needles occasionally grow in masses in random directions. Size 1/64 in.-3/8 in.; often clumped.
7. ASYMMETRICAL CRYSTALS: Angular crystals without a symmetrical outline occurring as simple or compound crystals. Size 1/64 in.-1/8 in.; often clumped.
8. POWDER SNOW: Dry bits of snow without angular form, often of irregular shape. Size 1/64 in.-1/8 in.; rarely clumped.
9. SLEET: Pellets of translucent to transparent ice often bearing bumps or other protuberances. They are frozen rain drops but are not always round. Size 1/32 in.-1/4 in.; very rarely clumped.

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and then cause the formation of a very fine smoke by rapidly quenching the flame with a blast of compressed air. This was accomplished by the apparatus shown in Fig. 4. A cotton string was impregnated with silver iodide by drawing it through a suspension of powdered silver iodide in water with a small amount of glue to act as a binder. The treated string contained about eight milligrams of silver iodide per centimeter. This string was fed into an oxyhydrogen flame at the rate of nine cm per minute. The heat of the flame vaporized the string and the silver iodide. Two or three inches away from the point that the silver iodide was introduced into the flame, a blast of compressed air was blown into the flame which rapidly cooled and diluted the vaporized silver iodide in the flame to produce a fine smoke of silver iodide. This generator produced active nuclei at the rate of about 10^{12} to 10^{13} nuclei per second.

The smoke produced by this method was examined by precipitating it on a slide and examining it with the electron microscope. This showed that the particles were of the order of 100 Angstrom units in diameter. The rate of consumption of silver iodide by this generator is about 1.2 mg per second. If the particles were uniformly of 100 Angstroms in diameter, 1.2 mg should produce about $4 \times 10^{+14}$ nuclei per second. The discrepancy between the theoretical and actual number of nuclei produced probably arises because all of the particles are not effective nuclei or because some of the silver iodide forms particles much larger than 100 A. The smoke particles produced by this generator are not effective as nuclei until the temperature is -8^oC or lower.

This type of generator is one of the most efficient experimented with thus far. Its main limitation is the source of gas and compressed air needed for its operation.

SILVER IODIDE IN THE ATMOSPHERE

The big question about silver iodide is how it performs in the atmosphere. In the laboratory, tests have been made in which silver iodide smoke is found to maintain its nucleating action after storage in a balloon a foot and a half in diameter for twenty-four hours. At the end of that period, the number of nuclei present had fallen off to a small fraction of the original value. However, the nucleating effect was still very marked. In a closed vessel, the number of particles would be expected to drop off with time because of coagulation and precipitation on the walls. These factors are not important when the smoke is in the atmosphere. Dilution caused by mixing and diffusion lower the concentration to the point that coagulation is negligible. Because there are no walls on which to precipitate, this factor, too, is negligible. There are several mechanisms by which silver iodide particles might lose their nucleating property. The particles may become inactive through long exposure to sunlight. There is no laboratory evidence that this takes place. Certain gases in the atmosphere may act on the particles to render them ineffective. Alcohol vapor in appreciable concentrations has been found to inhibit the action of silver iodide smokes. It is possible that other minor constituents of the atmosphere may have a similar effect. The presence of dust and smokes may act to destroy the nucleating properties of the particles by absorbing them. Rain and clouds can be expected to remove silver iodide from the atmosphere under certain conditions by forming water drops around the particles or by

Fig. 7 Radiosonde balloons carrying baskets of solid carbon dioxide into the upper atmosphere

dissolving them. The answers to these problems will not be known until experiments have been carried out on a large scale.

Several experiments have been made with silver iodide smokes under natural conditions. During the winter a supercooled ground fog at 25 F was successfully transformed to ice crystals for a distance of at least 150 feet by silver iodide smoke produced by vaporizing silver iodide. The silver iodide was vaporized by applying it as a powder on a nichrome wire heating coil which was then brought to a red heat with about 500 watts of electrical heating.

VI. TYPICAL DATA OBTAINED FROM PHOTOGRAPHS OF A SEEDED AREA

Raymond E. Falconer

The best photographs of the flight tests to date were taken on the afternoon of April 7. The 27 photographs taken that day from the B-25 test plane show, in a very striking way, the results which may be obtained by seeding stratus clouds.

The meteorological conditions in the atmosphere over the vicinity of Schenectady during this flight were about as shown in Fig. 8. Immediately after the seeding run, the plane turned in a circle to the left and climbed in a widening spiral for over an hour, finally attaining a maximum altitude of 15,000 feet. During this period, the 27 photographs were taken at various intervals and at various altitudes of the plane.

Each photograph taken showed the horizon just below the top of the picture. By knowing the altitude of the airplane above the clouds and by a measurement of the vertical angles (γ) between its position and the level of the cloud tops, it is possible to determine distances from the position of the airplane to various points on the perimeter of the seeded area.

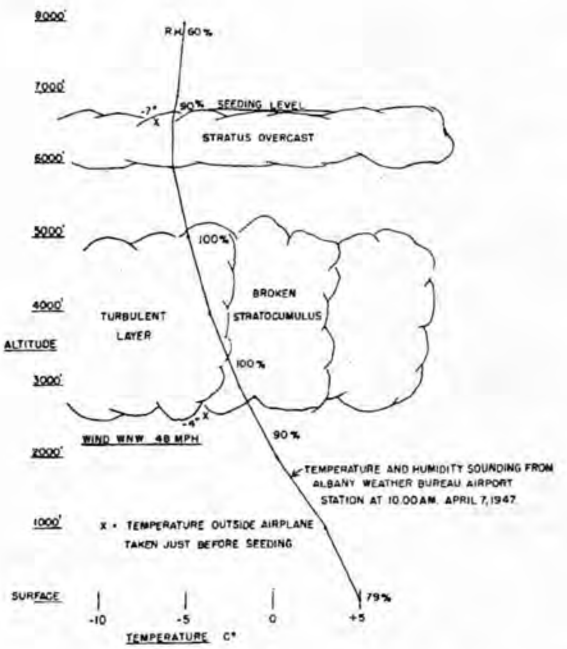


FIG.8 DIAGRAM SHOWING ATMOSPHERIC CROSS-SECTION APRIL 7, 1947

As an example of applying this method, a brief description of the steps involved in working out Photograph No. 16 (see Fig. 9) follows. First of all, azimuth angle (ϕ), indicating the horizontal direction in which the camera was pointed, is determined by considering the known azimuth angle of the sun at the particular time of day together with positions of shadows on the top of the cloud layer as shown in the picture. If true headings of the plane and horizontal angles of the camera with respect to the plane had been available, they could have been used instead. A special grid made of Plexiglass has been constructed marked off in vertical lines (converging at a point some distance below the grid) and spaced for each five degrees of azimuth angle. The grid also has horizontal lines spaced at 5-deg intervals which take into account the curvature of the earth, etc.

To find the depression of the horizon in degrees (α) below the horizontal plane at the elevation of the airplane, the formula

$$\alpha = .56\sqrt{\frac{h}{100}} \qquad (6)$$

is used where h = height of the airplane above the top of the cloud layer. A line α degrees above the actual horizon shown in the photo is then drawn in ink. This line then is the horizon of the plane.

The grid is then placed on the photo with the top horizontal line of the grid coinciding with the line α degrees above the actual horizon. The vertical angles, γ, are measured from the horizon of the plane down along the azimuth angle lines ϕ to various points on the perimeter of the seeded area. Thus, the area may be mapped on polar co-ordinate paper by determining, from the vertical and azimuth angles obtained, the distance x from the airplane to the selected points on the perimeter of the area. The distance x is determined by

$$x = \frac{h}{\tan \gamma} \qquad (7)$$

where h = height of plane in miles above the cloud layer. Table III shows the tabulation of data for Photograph No. 16 (Fig. 9), and Fig. 10 shows the plotted result on polar co-ordinate paper revealing that 44 minutes after seeding, the area was about 7.5 miles long on each leg and 3.4 miles wide at the widest point.

To show how the seeded area grew with time,

Fig. 9 Photograph of seeded area 44 minutes after seeding

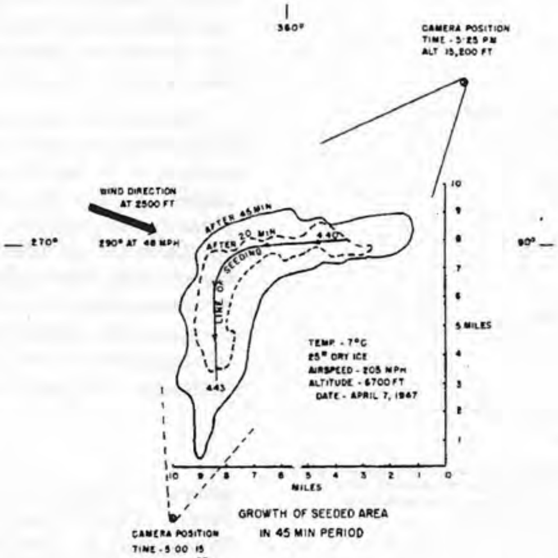


FIG. 10

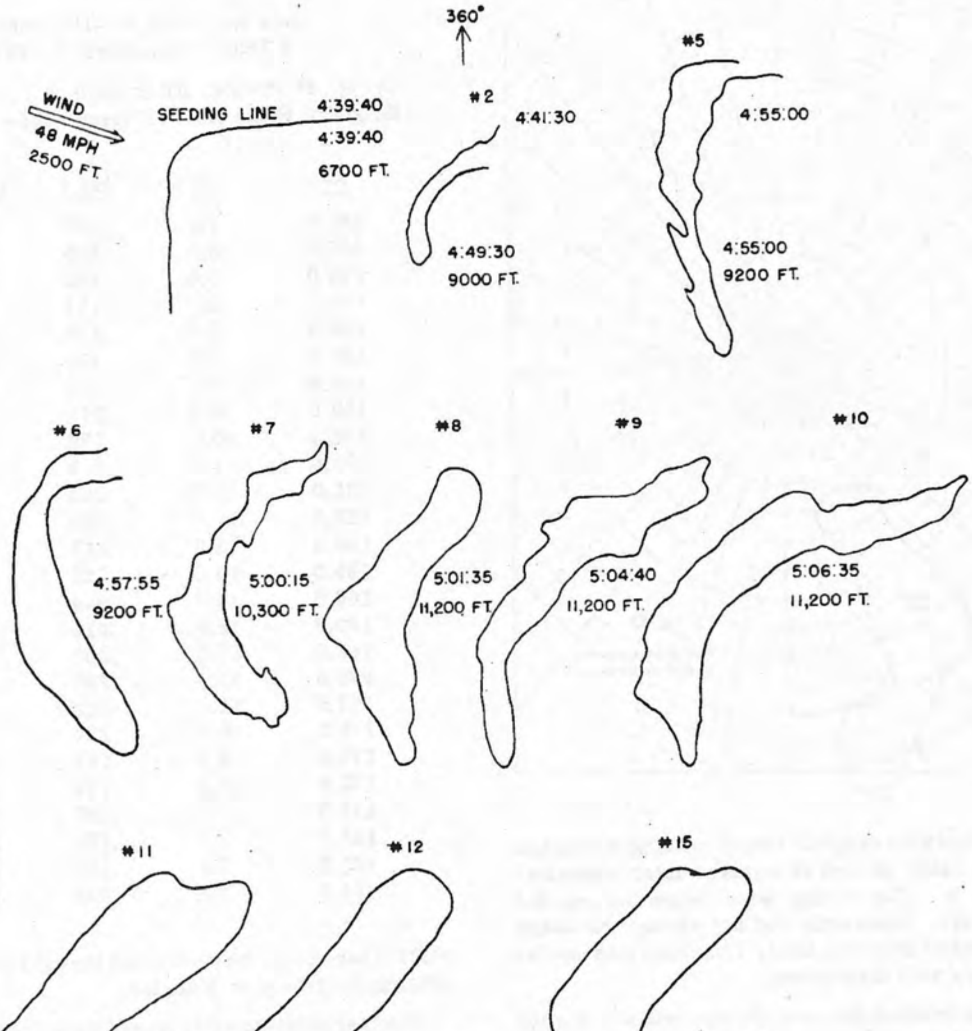


FIG. II

DETAILED DIAGRAM SHOWING GROWTH OF SEEDED AREA AS DETERMINED FROM PHOTOGRAPHS TAKEN AT TIMES & ELEVATIONS INDICATED.

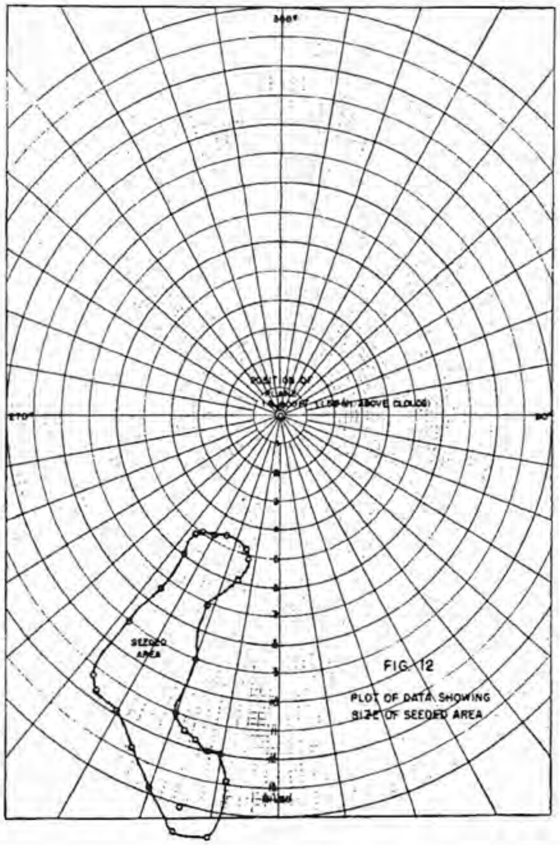


Fig. 11 shows the original line of seeding with maps of photos taken 20 and 45 minutes later superimposed on it. The strong wind below the seeded stratus layer apparently did not change the shape of the cleared area with time. The shape was maintained very well throughout.

A more detailed diagram of the growth and change in shape of the area is shown in Fig. 12. Some irregularities in its shape can be attributed to difficulties in reading the photos and the grid or in determining the true ϕ or γ angles.

TABLE III

Data for Photo No. 16 Taken at 5:24:00 P.M., April 7, 1947

Time: 44 Minutes After Seeding
Height of Plane Above Clouds: (h) = 1.58 Miles

ϕ^o	γ^o	$\tan \gamma$	x (miles)
163.5	7.0	.123	12.9
165.0	6.0	.105	15.0
170.0	6.0	.105	15.0
175.0	6.5	.114	13.8
180.0	7.0	.123	12.8
185.0	7.5	.132	11.9
190.0	7.7	.135	11.7
192.0	8.0	.140	11.3
192.5	10.0	.176	9.0
190.5	12.0	.213	7.4
191.0	15.0	.268	5.9
192.0	17.0	.306	5.2
190.0	18.6	.317	5.0
185.0	18.0	.325	4.8
180.0	19.0	.344	4.6
170.0	18.0	.325	4.8
168.0	17.0	.306	5.2
170.0	15.0	.268	5.9
177.0	12.5	.222	7.1
175.0	10.0	.176	9.0
175.0	8.2	.144	11.0
172.5	7.8	.137	11.5
170.0	7.7	.135	11.7
167.5	7.5	.132	12.0
165.0	7.5	.132	12.0
163.5	7.0	.123	12.8

Further details on this type of photographic analysis are given by Langmuir in another part of this report.

VII. THE ANALYSIS OF PHOTOGRAPHIC DATA SHOWING THE EFFECTS PRODUCED BY SUPERCOOLED CLOUDS WITH ICE NUCLEI

Irving Langmuir

The effects produced in supercooled clouds by seeding with dry ice are very striking and can be photographed very satisfactorily under proper conditions. The object of such studies is to determine what modifications are produced in clouds by the introduction of ice nuclei, how fast these effects propagate through the cloud, and how long they continue. Early experiments showed that the most interesting results were obtainable with unbroken stratus clouds having thicknesses of several thousand feet covering large areas. By dropping dry-ice pellets into the tops of such clouds along a line, very large volumes of the cloud consisting of supercooled water droplets are caused to evaporate and condense onto the ice nuclei, giving snowflakes of a size very large compared to the size of the water droplets. In this process, heat is evolved which can, under favorable conditions, yield 0.8°C.

Because of these changes within the cloud, it was realized at an early date that all the effects produced by seeding should become manifest by observations of the top of the stratus cloud from an airplane high above the cloud. It is true, of course, that we are most interested in changes that take place in the cloud itself and in the precipitation that falls from the bottom of the cloud. However, photographic observation within the cloud is impossible; photographs below the cloud are very difficult to interpret, and trouble is experienced because of loss of visibility due to snow in the air. Since we have been limited, so far, to the use of one plane, it was deemed advisable to gather photographic evidence by flying above the cloud layer.

It has been our desire to obtain a photographic record from which the area of the cloud that is modified by the seeding can be measured and its growth with time determined.

In general, the effects that have been produced are of several types:

1. The immediate effect of seeding is to produce an area in the top of a stratus cloud which scatters light in directions different from those in the case of adjacent unseeded clouds. Thus, with different relative positions of the sun, the seeded area, and the seeding plane, the seeded area may appear light on a dark background or dark on a light background, as is shown in Fig. 1. The line of demarcation between the seeded and unseeded areas is usually very striking.

2. Usually within five to ten minutes after seeding along a line, a groove or trough is produced in the top of the cloud which may be a thousand or fifteen hundred feet deep. This appears to be due to the falling of the snow crystals that are produced. In some photographs, the cloud within the seeded area disappears entirely within 20 minutes leaving a veil of falling snow which may be as much as 4000 feet below the original level.

3. In some cases, wisps of snow seem to be carried upward above the line of seeding, indicating currents of air rising more rapidly than the snowflakes can fall.

4. Between 20 and 50 minutes after the seeding, the seeded area, which usually has well-defined edges, becomes partly filled in with a very thin layer of stratus cloud. These new clouds are clearly formed in place and do not merely drift in from the undisturbed area surrounding the seeded area. They consist of liquid water droplets but they are usually entirely devoid of turbulence.

5. In the areas surrounding the seeded area and adjacent to it on one side, there often appear cumulus clouds which seem to be breaking through the original stratus layer, and they rise to a height of 1000 feet to 1500 feet above the stratus layers. These have been observed in at least three of our test flights and seem to be caused by the generation of heat in the lower layers of the stratus clouds produced by ice nuclei or snow crystals that are displaced rapidly from the original seeded area. The lateral displacement is probably due to the fact that the velocity of the lower part of the stratus cloud differs from that near the top. As seen from the top, these areas usually show no signs of snow crystals, but we presume that when these photographs are taken from the bottom of the cloud, one will see that snow is falling from these areas.

6. We anticipate that, under favorable conditions, the effects produced by seeding may become self-propagating; that is, that new nuclei are generated within the cloud continuously by fragmentation of snow crystals, aided probably by electrostatic effects which seem to prevail in many clouds in which snow is falling. We have not yet encountered any evidence that we have produced such an effect but we are looking for it. They will most likely occur in cases where there is already within the atmosphere a convergence of masses of cold, moist air which is causing a lifting of cloud masses. This is necessary so that, when snow does form, the moisture is not completely removed from the cloud, but new moisture is made available at a rate sufficient to maintain the snowfall.

ANALYSIS OF PHOTOGRAPHS OF THE SEEDED AREA TAKEN FROM ABOVE STRATUS CLOUDS

The technique which we have found most advantageous is to fly a plane in a large circle around and above the seeded area so that a series of photographs can be taken, one every minute. The height of the plane and the diameter of the circle cone should be such that each photograph covers the whole of the seeded area and that the angle through which the plane rotates (in azimuth) between consecutive pictures does not change by more than 15 or 20 degrees. We find that it is desirable also to have the horizon show in every picture. The height of the plane above the cloud level should be as high as practicable so that the irregularities in the level of the top of the cloud become only a small fraction of the height of the plane above the cloud. We have found it best to have a plane fly at a height of at least 15,000 feet above the seeded cloud layer in a circle 30 miles in diameter so that it takes about a half hour to complete a revolution around the seeded area. From the photographic data, we wish to produce a map of the seeded area at any given time and to watch the progressive change in this map as long as the effects continue to be appreciable. The method that we have used for this purpose is to use the photographs to give the horizontal angles (azimuth, ϕ) and the vertical angles or altitude α measured downward from the horizon. If we know the height of the plane H above the cloud layer, then we can calculate the horizontal distance of any observed point by an equation

$$R = H/\tan \alpha \qquad (8)$$

On polar co-ordinate paper it is possible to construct a map of the seeded area by measuring the ϕ and α for a series of points around the periphery of the seeded area.

By comparing the maps taken at successive intervals of time, one can then determine the path of the plane and determine the changes with time that occur in the shape and size of the seeded area. A check on the accuracy of the work can then be obtained by determining whether the successive positions of the plane at different time intervals correspond to a velocity of movement equal to that of the plane allowing, of course, for any difference of wind velocity between the altitude of the plane and the clouds.

To determine from the photographs the values of ϕ and α for any point recognized in the photograph, we have constructed a series of grids on thin sheets of Plexiglass on which lines are ruled corresponding to meridians and latitudes.

METHOD OF CONSTRUCTING THE GRIDS

In formulating the problem, let us assume that the top surface of the cloud, which is represented by C, is parallel to the surface of the earth; that is, it is a spherical surface having a radius of curvature E, which is the radius of the earth, 2.09×10^7 feet. Now let us consider a point D_0 at the top of the cloud layer and assume that at a height H vertically above point D_0 there is an airplane carrying a camera, the center of whose lens is at point 0.

Through the point D_0 in the top of the cloud, we construct a horizontal plane T. Any point on this plane which we may consider will be represented by P_0. If we draw a straight line from O to P_0, we will have to extend this line to a point P_c, before it intersects the top of the cloud layer C, which is on a spherical surface.

Let us now pass a vertical plane through the line OD_0. The line of intersection between this plane and the horizontal plane T is a straight horizontal line which we may represent by A_0D_0, where A_0 represents a point of infinity.

Because of the curvature of the earth, the horizon as seen from the airplane is depressed through a small angle α_c below the line OA_0. The amount of this depression is given by:

$$\alpha_c = (2H/E)^{1/2} \qquad (9)$$

Here α_c is to be expressed in radians.

If, however, we measure H in feet, express α_c in degrees, and introduce E value, we find that

$$\alpha_c = 0.56\,(H/1000)^{1/2} \qquad (10)$$

The distance R_h to the horizon as seen from the point 0 is given by:

$$R_h = (2HE)^{1/2} \qquad (11)$$

If we express H in feet, introduce the value E in feet, and express R_h in miles, we obtain equation

$$R_h = 1.226\,H^{1/2} \qquad (12)$$

Careful analysis shows that for all objects on the cloud level C for which α is more than three times as great as α_c, R_c and R_0 do not differ appreciably; that is, not over three per cent. For larger values of α the effects are negligible.

Thus in analyzing photographs, the first step is to construct on the photograph a horizontal line which is placed above the apparent horizon by an angular amount corresponding to α_c. This allows for a correction for the curvature of the earth which is very appreciable when the plane is flying 10,000 feet or more above the cloud.

Let us assume that the camera at 0 has its axis directed toward A_0 where the line OA_0 is horizontal and assume that the camera axis is tilted down below A_0 through an angle θ. The camera axis will then intersect the line D_0A_0 at a point B_0. The plane of the photographic plate is perpendicular to the axis OB_0, and is at a distance equal to the focal length behind it. Geometrically, however, the problem is the same if we consider the projection of any point B_0 in the tangent plane T onto a plane in front of 0. Actually in the work we have done so far, a camera having a focal length of five inches has been used and the photographs have been enlarged twofold. We are, therefore, interested in calculating the points of intersection of lines OP_0 with a plane perpendicular to OB_0. The axis OB_0 cuts through this plane at a distance F at a point 10 inches from point 0.

The procedure of forming the grid is as follows. We assume that the focal length F and the angle of tilt θ are known. We now take a paper and a large drawing board and draw a straight line on which we put three points, A, B, and D. These are so chosen that the distances AB, BD, and AD, are given by:

$$AB = F \tan\theta \qquad (13)$$

$$BD = F \cot\theta = F/\tan\theta \qquad (14)$$

$$AB \times BD = F^2 \qquad (15)$$

$$AD = 2\,F/\sin 2\theta \qquad (16)$$

The point B is to be used as the center of the grid. Through the point A draw another line perpendicular to AD. We may represent points along this line by J which corresponds to azimuth angle ϕ, measured to the right or left of A as origin. We may select a set of points, J, corresponding to a set of evenly spaced values, ϕ, such as ±5 deg, ±10 deg, etc., up to ±25 deg. Mark a series of points of J along the line as defined by

$$AJ = F \tan\phi/\cos\theta \qquad (17)$$

Connect each of these points J with point D by a straight line. These lines which radiate from D represent "meridian lines" for each of which ϕ has a constant selected value.

The lines of equal altitude, which corresponding to lines of latitude on the earth, are strictly speaking conic sections: hyperbolas, parabolas, ellipses, or circles depending upon the relative values of α and θ. For all practical purposes, however, we can replace these conic sections by circles which have the same curvature where they cut the line AD. We can locate these intersections for the case $\phi = 0$ for the line AD by measuring the distance y above and below the point B on the line AD by equation

$$y = F \tan(\theta - \alpha) \qquad (18)$$

Through each of these points (drawn for values of α, such as 5 deg, 10 deg, etc.), we construct circular arcs having a radius of curvature given by

$$\rho = F/\tan\alpha \qquad (19)$$

It is interesting to note that the radius of curvature is independent of θ.

Using this method, the series of photographs obtained during several seeding flights have been analyzed. Typical results are represented by the analysis of the April 7 flight prepared by Falconer and included in this report.

VIII. PROPOSED FLIGHT PLANS FOR CLOUD STUDIES

Irving Langmuir, Vincent J. Schaefer, and Bernard Vonnegut

The following series of flight plans are proposed as a tentative program for present and future flights in the joint Army-Navy-General Electric Cloud Studies Project. Each plan is subject to revision immediately upon the finding that some phase is impractical or unnecessary. The plans have been drawn up in large part, however, based on practical experience gained in the flights that have already been made by the earlier Fairchild flights of General Electric and the more recent B-25 and B-17 flights by the Army-Navy personnel assigned to the present project.

Strong emphasis is placed on detailed and synchronized observations by all personnel engaged in the flights so that a complete and accurate record of each flight can be made from take off to landing. Such data will be a prime requisite for study and planning of future projects. Some of the flights to date have been informative but none of them have been completely satisfactory. Much progress has been made, however, and good results are expected on subsequent flights.

Much of the success of all flight plans related to cloud modification depends to a large degree on obtaining a complete photographic record synchronized to the second with all of the flight data such as heading, altitude, air speed, and temperature. The best results to date have been obtained with infrared plates, although much experimental work needs to be done with color and other techniques, such as polarizing filters and stereoscopic photography, in order to gather the maximum information possible.

Any revisions in the proposed plans will be issued as memoranda between quarterly reports and distributed to all those on the distribution list of this report.

FLIGHT A

Cloud Seeding of Solid Overcast

PURPOSE

To seed continuous overcast of supercooled clouds with ice nuclei in a recognizable geometric pattern so that development of snow region can be accurately plotted and quantitatively analyzed from above, within, and below the modified region.

PROCEDURE

Use three planes. (1) A B-29 or B-17 at 30,000 feet to obtain complete series of photographs and to keep track of seeding plane and reconnaissance plane. (2) A B-17 to do the seeding at the top of the cloud, take photographs at 15,000 feet and to subsequently explore the seeded region. (3) A reconnaissance plane, AT-11 or Navair, to observe the snow or rain development below the cloud and to make a complete photographic record of everything seen. This plane should have radio communication with top plane.

PLAN OF OPERATION FOR HIGH-LEVEL OBSERVATION PLANE

Synchronize all watches to the second. Check communication system to tower and other planes. Take off and climb immediately at 500 to 1000 feet per minute to 25,000 feet, and commence making a 30-mile diameter circle over assigned area in southern Adirondacks. This involves a 3-deg bank counterclockwise during flight on circle route. Watch for B-17 seeding plane of radar scope which should follow within a few minutes. Obtain complete altitude-temperature record during climb and observe icing and turbulence while passing through cloud system. Readings should be made at every 1000 feet (closer if practicable) during climb and descent. Establish communications with the middle (seeding plane) and start taking pictures one minute before the start of the seeding run. Make a photograph every minute on the even minute ± 2 seconds and record the heading, azimuth, and angle of camera tilt. The co-pilot should record air speed and obtain heading to an accuracy of ± 1 degree, if possible, and make this record at zero seconds every minute, starting as soon as possible after take-off and continuing to the end of the flight. This record should be accurate, since it must synchronize perfectly with the photographer's records. The photographer should include the horizon and the complete area affected by seeding in every picture. If the plane is too close or too far away, the photographer should immediately make this known to the pilot. However, the pilot or the co-pilot should also check the location of the seeded area and keep the plane in the best position possible for proper photographic recording. Contact should be maintained with the seeding plane and the photography continued until the seeding plane announces that it has finished its observations and is heading for the north-south leg of the Albany Radio Range.

The Observation Plane then notes the time and leaves for the range with a heading of either 90 degrees or 270 degrees. Reaching it, the plane notes the time, heads for the cone and notes the time of arrival above it. After reaching the cone, the plane should descend upon instruction from Albany Control Tower and return to port.

> NOTE: Close attention must be paid to the difference in the drift of the seeded area and the plane, so that the seeded area is kept in proper position for photographic observation.

PLAN OF OPERATION FOR SEEDING PLANE

The seeding run with dry ice should be as follows: Approaching the assigned area, a heading of 360 degrees is made two minutes before giving the signal to seed. At zero minutes, the seeding signal is given and the man assigned to this operation starts the dispenser (which should be filled and ready to dump the particles at the flick of switch). Seeding continues at the maximum output of the dispenser for four minutes. Between 0 and +1 minute, 30 seconds the plane should maintain a heading of 360 degrees. It then should head counterclockwise at +1 minute, 30 seconds and at +2 minutes, 30 seconds should straighten out at a heading of 270 degrees and maintain this until +4.0 minutes. At this joint the dispenser is stopped. The plane at +4.0 again swings counterclockwise and by +5.0 minutes should straighten out to a heading of 180 degrees. On this leg, at +6.0 minutes, the seeding signal is given and one pound of granulated dry ice is dumped suddenly. Continuing on 180-deg heading until +7.0 minutes, 100-200 pounds of granulated dry ice are dumped suddenly. When this has been done, the plane immediately climbs to 5000 feet above the cloud top going into a counterclockwise circle around seeded region.

PHOTOGRAPHIC PLAN FOR SEEDING PLANE

The same photographic procedure should be followed as described for the top plane with the pilot maneuvering his ship so that the included angle between the near side of the seeded region and the horizon is between 20 degrees and 30 degrees. The diameter of the first complete circle should probably be about 20 miles with a plane tilt of 3 degrees - 4 degrees. Photography should continue for one complete circle, the photographer making sure that all of the seeded area is included in the picture. The photographer should keep the pilot informed of his requirements during this period and very accurate notes should be made of altitude, heading, tilt angle, and azimuth of camera.

As soon as complete circle is made, the seeding plane should maintain altitude and head over the area and attempt to photograph the ground through the hole. Descend and make detailed observation of the structure and appearance of the modified region. Fly immediately over the top of the area and observe the general appearance. Descend into the region, observe the halo and other optical effects looking toward sun. Attempt to get a color picture of the halo. During the maneuvers, check the icing rate with the cone and small cylinder. After flying through the modified region checking the icing rate, enter the unmodified region, climbing toward the top of the cloud and observe the icing rate in that region. During all of these maneuvers, continue observations on temperature, altitude, and heading. Reaching the top of the cloud again, enter the modified region and explore its lowest reaches, noting whether it is possible to reach the base of the overcast through the hole. If this is possible, attempt to identify the exact geographic spot under the hole. Observe precipitation and any other features that might be related to the experiments. After completing observations, note the exact time and make heading of either 270 degrees or 90 degrees to reach north-south leg of Albany Radio Range. Observe time it is reached and head for cone. Note time it is reached and descend upon instructions from control tower.

Return to port.

PLAN OF OPERATION FOR OBSERVATION PLANE AT CLOUD BASE

If possible a third plane should be used for observing the development of precipitation at the base of the overcast. Since this plane has the shortest distance to fly, it should be last in take off. If possible it should carry at least two persons besides the pilot, one a photographer and the other an observer who makes necessary records, assists the photographer, helps in navigation and directs the course of the observation.

This plane should be in radio contact with the high-level plane and should preferably fly directly below it close to the cloud base during the early stages of the seeding. If subsequent developments indicate that better pictures could be obtained from a different direction, it should be free to maneuver to a more suitable position, staying however close to the cloud base. By maintaining radar and radio contact with the high-level plane, checks on the general location of the complete operation could be easily obtained.

In general, it would be desirable for the low-level plane to maintain a distance far enough from the seeded area to show the extreme limits of the precipitation in one picture. This might involve a distance of 20 miles. If haze conditions do not permit photography at this distance, go closer and attempt to make a panorama with ground features that will permit some degree of matching. All photographs made in the low-level plane should include plane heading, azimuth of camera with respect to heading, tilt of camera, and altitude.

The lower plane should continue to observe from a distance until the seeding plane announces its departure for the radio range location. It may then fly into the affected area and attempt to obtain low-level pictures of any holes produced in the overcast and check the geographic location of the modified region at a specific time.

FLIGHT B

Cloud Modification of
Supercooled High Altitude or Tall Cumulus Clouds

PURPOSE

To seed with ice nuclei high altitude or tall cumulus clouds, the upper portions of which have a temperature below 3°C (32°F) and consist of supercooled water droplets, the object being to explore the possibility of hail prevention, thunderstorm dissipation, and production of rain.

PROCEDURE

Use two planes, one for seeding and exploratory work, the other for observation purposes. These should preferably be a B-17 aircraft and a photo plane of high maneuverability.

Cloud systems ideal for the purpose would be the type which occur rather frequently in the late afternoon from June to September in regions like eastern New York. These often develop into spectacular towering clouds isolated from each other or in lines invading an otherwise clear sky region. They often lead to violent local thunderstorms sometimes accompanied by hail.

PLAN OF OPERATION FOR SEEDING PLANE - FLIGHT B

The seeding plane should immediately upon take off establish communication with observation plane and control tower and then head for the top of a cloud mass which seems to be in an early but active stage of development. Careful check of the temperature-altitude relationships and other essential data (same as Flight A) should be started immediately following take-off and continued until reaching the top of the cloud. Unless the freezing level is at least 1000 feet below the top of the cloud, the seeding operation should be delayed until such a condition develops. Check of the air temperature within the cloud should be made if possible to be sure that a supercooled condition is present.

When the proper conditions are noted, the plane should enter the very top of the cloud and, as rapidly as possible, dump from 100 to 250 pounds of granulated dry ice into the cloud. Care should be observed that all of the dry ice enters the supercooled cloud. Pellets ranging from 1/16 inch to at least 2.0 cm diameter should be used, since the vertical currents within the cloud will probably tend to decrease the effective falling height indicated in Table I of this report.

After seeding the cloud, the plane should immediately climb, if possible, at least 2000 feet above it and circle within five miles of the top in counterclockwise direction for ten minutes and then fly a straight line about two miles to the right of the top of it to afford the chance to obtain good photos looking down. After about ten minutes of elapsed time from the seeding operation, the plane should descend in the cloud to observe the cloud structure and any apparent precipitation as either snow or rain. Reaching the base of the cloud, the plane should increase the distance from the modified cloud, increasing its distance away from it so that most photographs show both limits of falling snow or rain. If air is too hazy to permit this, the plane should approach to positions where photography is possible and take alternately pictures of right and left edges of the precipitation showing its location with respect to recognizable points on the ground. During this period, the plane should attempt to circle the precipitation area to enable us to plot its area and its development with time. We particularly want to know how long the precipitation lasts and whether it increases or decreases with time. Observe and record whether the original cloud seems to be dissipated by the precipitation or whether precipitation increases with time. Also note whether the effect shows any evidence of spreading to nearby clouds.

Throughout all of this period, continuous records should be made every minute at zero seconds, ± 2 seconds of plane heading, air speed, temperature, and altitude.

PLAN OF OPERATION OF OBSERVATION PLANE - FLIGHT B

Upon take-off, communication should be established immediately with the seeding plane and control tower after which the plane climbs immediately to an elevation about 2000 feet above top of selected cloud and at a distance of at least 10 miles where the plane should go back and forth over approximately the same path. The plane should climb to keep pace with the vertical rise of the cloud. The horizontal distance between the plane and the cloud should be such that the azimuth angle with respect to the seeded cloud does not change more than 20 degrees per minute. With this condition, successive photographs will show distant points beyond the top of the seeded cloud in adjoining pictures.

Photographs should only be taken while the plane is moving approximately at right angles to the seeded cloud. This, of course, means that the photographer must alternately use the port and starboard sides of the plane for his photographs.

This plane also must keep an accurate record of heading, altitude, air speed, and temperature besides the tilt and azimuth of the camera, all of such records and photographs being taken every minute at zero seconds ± 2 seconds.

FLIGHT C

Cloud Studies and Attempts to Produce Clouds in Clear Air

PURPOSE

To explore the properties of cirrus clouds and to attempt to induce the development of ice crystal clouds by seeding clear air with ice nuclei when the air is supersaturated with respect to ice but not water.

PROCEDURE

Use either a B-17, a B-29, or a lighter plane equipped for high-level flying. When cirrus clouds are visible, the plane should climb into them equipped with at least 50 pounds of granulated dry ice and with cameras using panchromatic, infrared and color film. It should also have a good temperature-measuring device capable of recording to at least $-40^{\circ}C$ which should be equipped if possible with a recording chart having a speed of at least one foot per minute. It would be desirable to also record altitude on the temperature record.

While still 2000 feet below the lower reaches of the cirrus clouds, the temperature-altitude-recording unit should be started. Previous to this, temperature-altitude records should have been made from the time of take-off every minute at zero seconds. If possible, the plane should climb through the ice crystal cloud and above it. Photographs on either panchromatic or infrared film should be made as the cloud is approached and then color used if any optical effects are observed, such as halos, sundogs, or other similar formations.

After passing through the cloud, the plane should be flown into a region free of visible clouds but level with the tops. A seeding run should be made in the area free of clouds dispensing one pound per mile in the standard seeding pattern, i.e., seed with dry ice in a heading of 360 degrees for 1 1/2 min: counterclockwise swing for one min; heading of 270 degrees for 1 1/2 min; stop seeding. Continue in counterclockwise swing for 1 min; heading of 180 degrees for 1 min at which time 1 pound of dry ice is dumped suddenly; then continue for 1 min with same heading and dump remainder of dry ice (between 10 and 50 pounds).

Since the altitude and temperature would rarely permit climbing above the seeded pattern for photographing, the plane should drop to a level 10,000 feet or more below the seeding level and go into the same type of observation circle recommended for Flight A. Using a circle of from 20 to 30 miles in diameter, a bank of about 3 degrees, and turning at the rate of about 16 degrees per minute, the plane should circle the seeded area and obtain photographs every minute at zero seconds obtaining the same kind of data on heading, altitude, temperature, and air speed as in Flight A. The photographer will obviously use the window on port side as before, but will have to tip his camera up instead of down to obtain pictures. These maneuvers will, of course, be unnecessary if the air is not supersaturated with respect to ice. The photographer should record the time, the tilt of his camera, and the azimuth with each photograph.

After making one complete circle of such a diameter that all of the seeding effect is included in each photograph, circling should continue if any effect is still visible. At least once every five minutes, an observation should be made related to the exact geographic location of the plane with respect to the terrain below. If lower clouds obscure the ground, radar fixes should be obtained whenever possible, as well as accurate time records whenever any radio range is crossed. After making the first complete circle and before the effects disappear or blend with the surrounding cloud systems, it would be desirable, if practicable, to climb to the original seeding level and obtain photographs from this position looking down toward ground.

FLIGHT D

Cloud Modification Dry Run

PURPOSE

Dry runs for developing seeding and photographic techniques by going through complete seeding and photographic operation using a large unsymmetrical lake as a simulated target.

PROCEDURE

Synchronize watches so that all have same time to zero seconds.

Use Sacandaga Reservoir (see map) as simulated seeded area. Make mock seeding run starting from Union Mills at an elevation of 10,000 feet. When above the vicinity of Union Mills, start the run with a heading of 360 degrees for 1 1/2 minute. Then turn counterclockwise for 1 minute to a heading of 270 degrees and continue with this heading for 1 1/2 minute. Again turn for 1 minute to a heading of 180 degrees and continue with this heading for 2 minutes. After completion of the run, start a circular climb in a counterclockwise direction planned so that the diameter of the circle when reaching 25,000 feet is approximately 30 miles and the plane has a tilt of about 3 degrees and turns in a counterclockwise direction about 16/deg/min. Climb at 500 ft/min.

From the time to take-off to landing, make record of altitude to nearest 100 feet and heading within 5 degrees, every minute on the minute ±2 seconds. Make a reading of the temperature for every 1000-foot change in altitude although closer readings should be made during climb and descent from the mission. Also record the air speed.

After making the seeding run and starting to circle, the photographer should begin to take pictures of the reservoir every minute on the minute, recording the angle and azimuth of each shot. The angle should be read, if possible, with an accuracy of ±5 degrees and the azimuth with an accuracy of ±10 degrees. Each photograph should contain features common to the preceding one and should include the horizon, the Batchellerville and Northville Bridges, and all of wide waters.

All observations, where practicable, should be made on synchronized watches exactly on the minute within ±2 seconds unless arrangements can be made to have one person control the timing. However, even though this can be arranged, synchronized watches should be used by all in any event of failure of communications system or the need for using it for other purposes.

After completion of the seeding run and while still at 25,000 feet, head due east or west for north-south leg of Albany Radio Range and record the time at which it is reached. Head for the cone and record the time at which it is reached. Descend making a complete record of temperature-altitude relationships and then return to port.

FLIGHT E

Study of Microstructure of Clouds at Above Freezing Temperatures

PURPOSE

To study the microstructure of clouds having temperatures above freezing. Both stratus and cumulus cloud forms of all types should be studied with as much synchronous quantitative data as possible obtained during flights through them. Such data as liquid water content, particle size, particle-size distribution, turbulence, temperature, humidity, altitude, air speed, vertical acceleration, and the occurrence and amount of falling precipitation should be obtained. The general purpose of such flights is to obtain basic fundamental data for testing present theories on the factors which lead to the formation of precipitation.

PROCEDURE

Have one B-17 fully equipped with recording instruments which will fly into clouds of the types mentioned. Just before entering the cloud, all of the recording instruments are started and checked for their performance. When word is received from the several stations in the plane that everything is working and running satisfactorily, the pilot heads the plane into the cloud and a run of from five to ten minutes is made, the longer period being desirable if the cloud is large enough.

Detailed flight techniques will be developed and described after a few trial runs are completed. For the preliminary flights, the following procedures are proposed. During all of these passes through the cloud, as complete records as possible should be made.

(1) Fly into the cloud at a definite altitude and attempt to maintain this initial altitude as exactly as possible using whatever controls are necessary to do so. Observe and record the amount of movement of the stick which is required to accomplish this maneuver.

(2) Fly into the cloud at a definite altitude and try to keep the plane level, with the stick stationary, if possible.

(3) Start climbing at a rate of 200 feet per minute at least 500 feet below the cloud base and hold the plane to this climb, using the stick as required. Climb for at least 10 minutes at this rate, or until the plane emerges at the cloud top. If the cloud has a thickness greater than 2000 feet, climb at a rate of 300 to 500 feet per minute, the rate being determined by the fact that the flight path in the cloud should not be longer than 10 minutes. Subsequent plans will very likely alter this condition but, for the present planning, we do not desire records much greater than of 10-minute duration.

(4) Same plan as the preceding except that, if possible, the stick should be held stationary throughout the climb.

(5) Enter the cloud just within visible base and maintain specific altitude for five minutes, using the stick whenever necessary.

(6) Same as (5) but keep the plane in level flight.

(7) Enter the cloud just below the top and maintain specific altitude for five minutes using stick as required.

(8) Same as (7) but keep the plane in level flight.

In each instance, it is desirable that the pairs of conditions (1) and (2); (3) and (4); (5) and (6); (7) and (8) are carried out consecutively with as little loss of time between them as possible. Also flights (1), (5), and (7) should be made as another consecutive set of observations as nearly as possible in same cloud with one flight following the other as rapidly as possible.

When isolated clouds are used for study purposes, the shadows which they cast on the ground should be employed whenever possible for maneuvering the plane into specific regions of the cloud. By locating the cloud's shadow on the ground (or a lower deck of clouds), the plane can be maneuvered with respect to it by locating the shadow of the plane and watching it as the shadows come together.

Even though clouds are not present in the air, much important information can be gained in the early stages of this flight program by producing specific movements of the controls and noting the type of acceleration-altitude-time records obtained. This will provide basic information which will lend itself subsequently to quantitative analysis of the type of movements encountered within a cloud system.

More details and modifications of these general flight procedures will be issued as memoranda when progress and experience shows the need.

COMBUSTION OF INFLAMMABLE LIQUIDS CONTAINING SILVER AND IODINE

A method of silver iodide smoke generation which may hold promise is the combustion of liquid fuels containing silver and iodine. These components would be volatilized in the flame and form silver iodide smoke. At the present time very little work has been done on this particular method. This arrangement is attractive because it might prove possible to use oil burners and internal combustion engines as nuclei generators by adding silver and iodine to the fuel. The question of the harmful effects of these substances on the burner or engine would have to be carefully studied. A big problem in using this method is to get the silver into solution in the oil. The iodine offers little difficulty as it is easily soluble in oils and gasoline. Common silver salts have very little solubility in oils. Silver stearate may have sufficient solubility to permit its being used in oil or gasoline.

Silver iodide is quite soluble in acetone as AGI $(NaI)_3H_2O$. A solution of this sort was burned as a spray and gave numbers of nuclei. In the concentration used, about 5 per cent of the presence of the salt seemed to inhibit the burning of the flame, and it was difficult to keep it going. It is possible that this method might be developed into a satisfactory generator of nuclei.

INTRODUCTION OF POWDERED SILVER IODIDE INTO POWDERED COAL OF POWER PLANT FURNACE

A method for dispersing silver iodide nuclei that may be quite simple and effective is to introduce silver iodide into the coal burned in a power plant. The temperature of combustion is high enough to vaporize the silver iodide, and it might be possible to introduce the silver iodide in such a way that nuclei of the desired size and number are produced. A qualitative experiment to disperse silver iodide in this manner was carried out last winter. Twenty-five grams of powdered silver iodide were introduced into the coal being fed to the furnace of a power plant at the Schenectady Works of G. E. From the point where the silver iodide is introduced, the coal proceeds to a pulverizer where it is ground to about 200 mesh. Then it is blown with compressed air into the furnace. The fly ash and other products of combustion are exhausted through a stack about 200 feet high and 12 feet in diameter. The coal is consumed at the rate of about 12 tons per hour. The experiment was carried out when there was an overcast of supercooled clouds in the sky. No effects that could positively be attributed to the silver iodide were observed. No measurements were made on the numbers of nuclei produced because of the difficulties in obtaining samples.

Possible difficulties with this method are inter ference with nucleation caused by soot particles, loss of silver by reaction with fly ash, and wrong size particles.

SILVER IODIDE FLARES

Several dozen flares were made up by a local fireworks company. The composition of the flares was the same as their regular, red signal flare with the difference that 2 grams of silver iodide was substituted for the 2 grams of strontium carbonate used to give the red color. The flares are mostly potassium chlorate and weigh 37 grams. A flare was found to produce about 10^{13} nuclei during its burning, which took about one minute. This is not a particularly efficient source of nuclei compared to others. However, it is a convenient method.

SILVER IODIDE IMPREGNATED CHARCOAL

One of the most hopeful methods of generating silver iodide nuclei in large numbers is burning charcoal which has been impregnated with silver iodide. Much work must yet be done to determine the most satisfactory concentrations of silver iodide in the charcoal and the best method for burning it. At the present stage of development, the method is giving encouraging results.

The impregnated charcoal is made by soaking charcoal briquettes, made by the Ford Motor Company, in a solution made by dissolving 30 grams of silver iodide, 30 grams of sodium iodide in a liquid made of 1000 cc of acetone and 150 cc of water. The silver iodide and the sodium iodide form a double salt which is soluble in acetone. The double salt is soluble in water; however, the concentrated solution precipitates out silver iodide if it is diluted with water. Acetone has the advantage that it can be made as dilute as desired with no precipitation taking place. The impregnation of the briquettes is quite simple and rapid. It takes about five or ten minutes for the charcoal to absorb the solution. After the briquettes have absorbed the solution, they are removed from the liquid, and the acetone and water evaporate, leaving the impregnated charcoal. Ordinary wood charcoal is satisfactory for this method; however, it absorbs the solution more slowly and, for this reason, the briquettes are used. Some experiments were made using coke instead of charcoal. However, it was found that a single piece of coke will not remain burning in an air stream. This rules out the use of coke except in cases where a large enough fire is made to maintain combustion.

To produce silver iodide smoke, charcoal is burned in a stream of air. The heat of the burning charcoal vaporizes the silver iodide at the surface. The resultant silver iodide vapor is rapidly condensed and diluted by the moving air stream to form an invisible smoke. The rate of burning of the charcoal and consequently the rate of vaporization of the silver iodide is determined by the rate of air flow over the charcoal. This means that the rate of air flow which condenses and dilutes the silver iodide increases as the rate of liberation of silver iodide is increased.

The size and number of silver iodide particles produced will depend on the way the charcoal is burned,

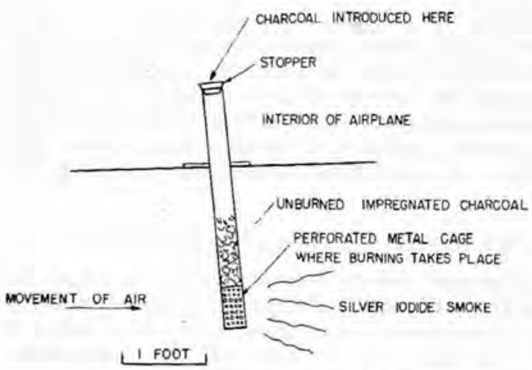


FIG 1 AIRPLANE TYPE SMOKE GENERATOR

the air velocity over it, and the amount of silver iodide in the charcoal. For different conditions, it may be desired to have smokes of different particle sizes. The solution described for impregnating the charcoal gives charcoal with about 1 per cent of silver iodide. This impregnation will be used until a better idea is obtained as to what sort of smoke is most desirable in various applications.

A charcoal burner has been made which is intended primarily for use on an airplane. It is illustrated in Figure 1 and in Figure 2. In operation the burner projects from the bottom of the fuselage. The motion of the plane provides the air stream for the burning of the charcoal in the perforated metal section in the bottom of the tube. Tests have been made with this generator on the ground using a blast of compressed air to simulate the velocity of air flow produced by the plane. It was found that this generator produces about 10^{14} nuclei per second with a consumption of about five pounds of impregnated charcoal per hour. This is a silver iodide consumption of ten milligrams per second, or $1.00 worth per hour.

The burner illustrated in Figures 1 and 2 is intended to leave a trail of smoke behind which will gradually diffuse into the atmosphere. The generator in Figure 3 is so constructed that it will shower out pieces of burning charcoal from the burner beneath the plane. As these drop, they will leave trails of nuclei in much the same fashion as dropping pieces of solid carbon dioxide.

Experiments have been made to determine how far burning pieces of charcoal fall before they are entirely consumed. Results were obtained by regulating a stream of air in a vertical tube so that a piece of charcoal remained stationary in the air stream as it burned. From the amount of air which had flowed through the tube and the diameter of the tube, it was possible to calculate the distance of fall. The results of these experiments are shown in Figure 4 along with similar data obtained with dry ice.

Work is underway to develop a portable generator for use on the ground. It is planned to use a blower

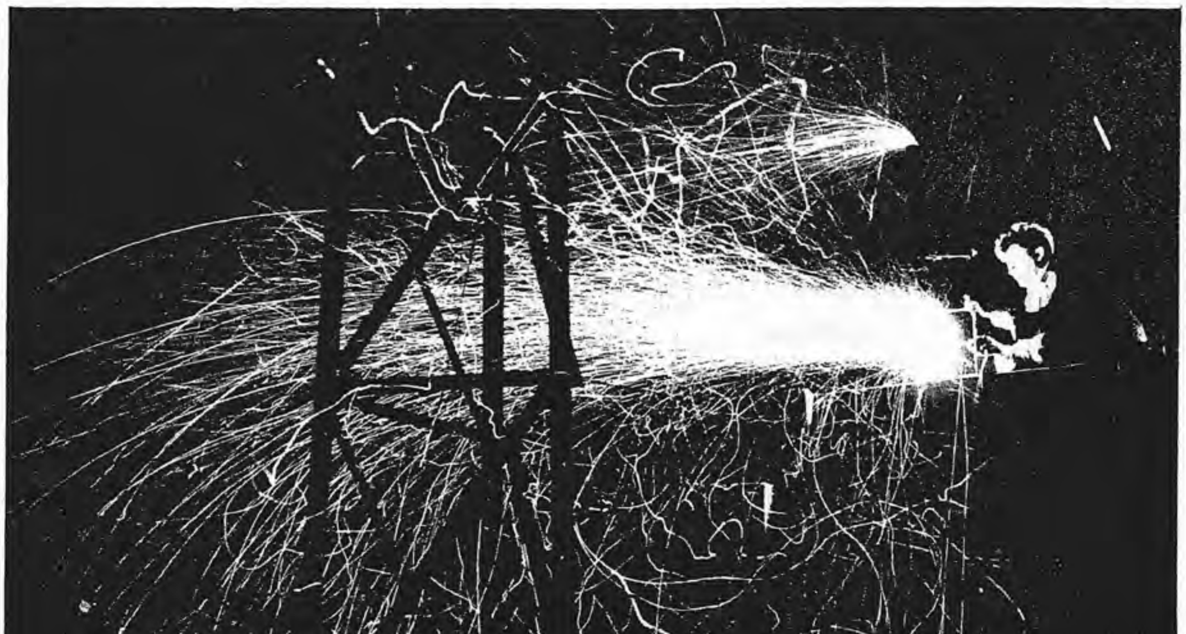
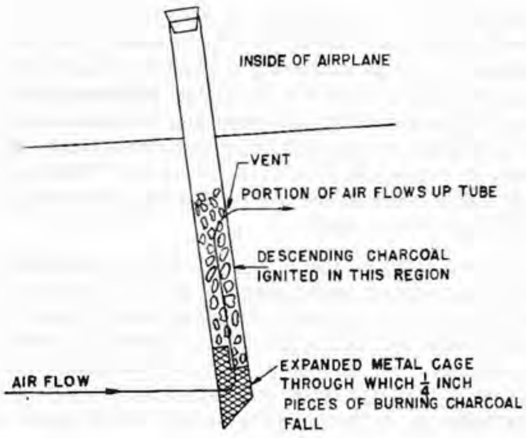


FIG. 2

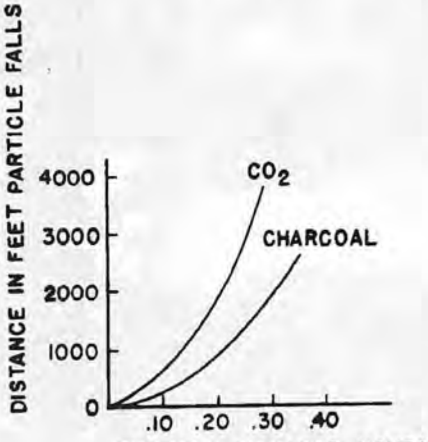


DEVICE FOR DROPPING BURNING CHARCOAL

FIG. 3

to produce the air stream for burning the charcoal. At present the airplane-type generator is being used for work on the roof of the Laboratory. A large quantity of compressed air is required, and it is believed that a blower would be more economical.

In using the burning charcoal method of smoke generation, it is necessary that the air stream be sufficiently strong to prevent any ash building up on the charcoal. If ash does form on the surface, a large portion of the silver iodide is retained in the ash rather than being liberated as a smoke. A wind velocity of 20 miles per hour or greater seems to be sufficient to prevent ash accumulation. It is, therefore, possible to operate a generator in the air moving past an automobile. This may be a useful method in some cases.



DISTANCE OF FALL OF SOLID CO_2 AND CHARCOAL PARTICLES

FIG. 4

SILVER IODIDE IMPREGNATED EXCELSIOR

Work has recently been started to investigate the possibility of producing large quantities of nuclei by burning excelsior impregnated with silver iodide in the same manner as the charcoal. It is believed that this method might be a very convenient way to create the smoke without the need of any equipment. If a sufficiently large mass of excelsior is used, the heat of combustion should create a strong draft for producing the smoke and should help carry the smoke to upper cloud layers. Results thus far on the excelsior are qualitative. It has been found that a burning strand passed through the box produces large numbers of nuclei. The excelsior probably is similar in its operation to the charcoal method as the excelsior in burning forms charcoal, which in turn burns to produce nuclei.

PRODUCTION OF SMOKE BY SPRAYING SILVER IODIDE SOLUTIONS

It is possible to produce smokes of silver iodide particles by atomizing volatile liquids containing silver iodide in solution. When the drops of spray evaporate, they leave behind small particles of silver iodide. This technique has been used to produce nuclei in the cold box. Spraying a saturated water solution of silver iodide or an acetone solution of silver iodide and potassium iodide and allowing the spray to evaporate produces effective nuclei.

The main limitation of this method is the fact that spray nozzles and atomizers don't produce sufficiently small drops to make the method attractive on a large scale. With an atomizer it is difficult to produce a spray with an average drop size much less than 10 microns. An atomizer producing the same number of particles as the charcoal-type generator would be required to atomize several hundred gallons of solution per minute which would require a large amount of energy and equipment.

TESTS USING SILVER IODIDE IN NATURAL CONDITIONS

Several silver iodide flares were tested in a supercooled cloud on Mt. Washington, but no definite results were obtained.

On May 9, 1947, a charcoal-burning generator was tried on a supercooled cloud in a flight made by the Signal Corps. The seeding flight was made two hundred feet below the top of a cloud with a temperature of

-14°C. Some observers in the plane thought that a shallow trough was formed in the cloud, while others could see no effects. The type of generator used in this flight did not release any burning particles large enough to fall an appreciable distance so that the nuclei were left in a line behind the plane rather than dropping through the cloud. It is, therefore, likely that whatever effects did occur were not spectacular.

Experiments have been made to see whether it was possible to operate a silver iodide smoke generator at one position and observe nuclei in a cold box several miles down wind. On April 10, 1947, a charcoal-burning generator was operated continuously from 9:40 a.m. to 10:52 a.m. on the roof of Building 5. At the same time observations were made on a supercooled cloud in a frozen foods cabinet in Alplaus, New York, about five miles down wind from the generator. The observations were as follows:

9:15 a.m.	No crystals observable
9:45 a.m.	No crystals observable
10:15 a.m.	Crystals 6 or 8 inches apart
10:25 a.m.	No crystals observable
10:35 a.m.	No crystals observable
10:45 a.m.	Crystals 2 inches apart
11:00 a.m.	Crystals 8 to 10 inches apart

The wind during the experiment was about 10 miles per hour. While these results are by no means conclusive, it is possible that the effects observed were the results of the silver iodide smoke released.

The next experiments on silver iodide smokes in the atmosphere will involve flights above and below supercooled clouds using charcoal-type generators. It is believed that the technique of dropping burning pieces of impregnated charcoal through clouds will give more significant results than the smoke generator previously used.

THE PRODUCTION OF RAIN BY A CHAIN REACTION IN CUMULUS CLOUDS AT TEMPERATURES ABOVE FREEZING[1]

by

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I. EVAPORATION - CONDENSATION THEORY OF CLOUD DROPLET GROWTH

Because of the effect of surface tension, small droplets in clouds have slightly higher vapor pressures than the larger droplets. The smaller drops thus evaporate to give vapor which condenses on the larger ones. Although the vapor pressure difference amounts to only a few hundredths of one per cent, this phenomenon is very important in determining the rate of growth of the cloud particles within the first few minutes after they are first formed at the base of a cumulus cloud. However, after the droplets have grown to diameters of 20 to 30 microns, this process proceeds extremely slowly, and it is not possible in this way alone to account for the relatively rapid formation of rain which sometimes occurs in cumulus clouds.

This evaporation - condensation theory of the growth of particles in aerosols was developed early in 1942 and led to the design of a screening smoke generator. In the years 1943 to 1945, in connection with the studies of formation of rime or ice on aircraft, measurements were made, on the summit of Mt. Washington, of the rate of deposition of ice on slowly rotating cylinders of various diameters exposed to supercooled clouds blowing over the summit at known velocities. A method was evolved for determining the diameters of the cloud droplets. These data indicated that the droplets increased in size and decreased in number after they were formed at the base of the cloud by the cooling of the air by adiabatic expansion.

The same quantitative evaporation - condensation theory that had been so useful in the development of the smoke generator was again found to be applicable. The following semi-empirical equation, consistent both with the experimental data and the theory was obtained

$$d = 2.46 \left(\frac{59 + T_c}{50}\right)\left(\frac{1000\ w}{V}\right)^{0.40}, \qquad (1)$$

where d is the diameter of the droplets in microns, T_c is the temperature in ^{o}C, w is the liquid water content in g/m^3, and V is the vertical component of the wind velocity in meters/sec.

This equation should presumably be at least approximately applicable to the growth of water droplets in clouds of the free atmosphere. Experiments (Project CIRRUS) are being planned to test this theory in airplane flights and to develop a better knowledge of the growth of cloud droplets.

According to the Mt. Washington experiments, we should expect that droplets in summer cumulus clouds at +20°C should grow to a diameter of about 26 microns in one minute and to about 72 microns in 30 minutes. Under mild winter conditions with cloud temperatures of 0°C, the diameters should be only 14 after one minute or 44 microns after 30 minutes. According to W. J. Humphreys (Physics of the Air) droplets of 100 microns diameter fall with a velocity of only 25 cm/sec and so in 30 minutes in quiet air could fall only 450 meters. However, in actively growing cumulus clouds there are upward vertical currents of several meters per second that would prevent the descent of these droplets and would even carry them to great heights.

Since cumulus clouds often develop rain within less than 30 minutes after their formation, we see that some other mechanism than that assumed in the evaporation - condensation theory must be involved in rain formation.

1. A preliminary account of this work was included in an address before the National Academy of Sciences in Washington, D. C., on November 17, 1947. (See Staff Report, Chem. Eng. News, 25, 3568, 1947.) A paper covering substantially all the material in this report was presented before the American Meteorological Society at the meeting in New York on January 28, 1948. This complete report will also be published in the Journal of Meteorology.

II. NATURAL PROCESSES WHICH CAUSE THE FORMATION OF HEAVY RAIN

Some 15 years ago, T. Bergeron and W. Findeisen emphasized the important role that might be played by the growth of snowflakes in the upper part of a cloud if this reached a temperature below freezing. The vapor pressure of supercooled water at -20°C is 22 per cent higher than that of ice at the same temperature and under these conditions, snowflakes grow thousands of times faster than water drops. Findeisen, even in recent papers, has maintained that rain of substantial intensity can only form after the top of the cloud is above the freezing level and contains ice nuclei.

On the afternoon of a hot day near the end of May, 1944, with a surface temperature of +30°C, I observed very large rain drops falling from a turbulent, broken, relatively small cumulus cloud which I estimated did not have a height exceeding 7000 feet, so that the temperature could not have been below freezing. Later, I found that most Army and Navy pilots who flew in the South Pacific area reported that heavy showers over the Pacific Islands frequently occur from clouds that are wholly below the freezing level. For example, according to a forthcoming publication by Colonel B. G. Holzman *and Major D. L. Crowson* on weather techniques used during Operation "Crossroads," at Bikini, "Showers occurred with great regularity from clouds with bases at 1500 feet and with tops at 5000 to 6000 feet. Air crews complained that it rained harder from these clouds than from larger developed cumulus."[2]

In Project CIRRUS, experiments have been made by the Signal Corps and Navy using Schaefer's method of seeding stratus and cumulus clouds by means of dry-ice pellets.[3] These experiments have all given results which support the theories of Bergeron and Findeisen in regard to the rapid growth of snow as soon as suitable nuclei are present. During the last summer numerous large cumulus clouds have been seeded at 20,000 to 28,000 feet and have always given very heavy rain which reached the ground within 15 to 25 minutes. Usually the clouds subsided rapidly within 5 to 15 minutes, but in a few cases, they grew to greater heights.

The remarkable speed with which heavy rain developed in the part of the cloud below the freezing level indicated that some unrecognized mechanism was acting.

III. ACCRETION THEORY OF GROWTH OF RAINDROPS

In the summer of 1944, I undertook a theoretical investigation of the factors that can cause the formation of large raindrops in clouds, which contain no snow crystals. Some droplets in the cloud, happening to be of more than average size, would fall more rapidly and so would overtake the others and coalesce with them. It was then assumed that this growth by accretion would proceed at first slowly, but the rate of growth would increase rapidly as the drops acquired higher velocities and cross-sections. As the drop falls, it sweeps through an approximately conical volume and a certain fraction E of the droplets within this volume would be intercepted or collected by the drop. By assuming that the velocity of fall increases with the square of the radius in accord with Stokes' Law (only approximately true) and that the cloud contains a uniform liquid water content w, (g/m^3), it was found that the reciprocal of the drop radius decreased linearly as the time increased so that after a definite time t the drop should grow to infinite size. The following equation was obtained (Aug., 1944).

$$t = 18\eta / E g w r_0. \qquad (2)$$

Here η is the viscosity of air, E the collection efficiency, g the acceleration of gravity, w the liquid water content of the cloud, and r_0 the initial radius of the drop (which started falling at time t = 0). Equations were also derived for the growth of droplets in a cloud in which the air is rising with a given velocity. It was realized that the actual size to which the drop could grow might be limited by the thickness of the cloud or by a small collection efficiency.

2. See article by W. J. Kotsch, Bull. Amer. Meterol. Soc., 28, 87 (1947).

3. The Production of Ice Crystals in a Cloud of Supercooled Water Droplets. V. J. Schaefer, Science, 104, 457-459 (Nov. 15, 1946).

IV. DEPOSITION OF RIME ON CYLINDERS, SPHERES, AND RIBBONS

During the winter of 1943-44, Mr. Schaefer and I, in co-operation with members of the staff of the Mt. Washington Observatory, had made studies of the rate of growth of rime on rotating cylinders, and we made experimental and theoretical measurements of the collection efficiency for rime collection.

A theory had been proposed by Albrecht[4], according to which the fog particles, consisting of supercooled water droplets, move with the air around the cylinder when the droplets are very small, but move in trajectories that allow them to strike the cylinder when the droplets are larger. He showed that deposition of droplets of radius r carried by a wind of velocity v can occur on a cylinder of radius C only when rv/C exceeds a certain critical value that depends on the viscosity and density of the air and the density of the droplets. Albrecht's calculations were not accurate. Later, Muriel Glauert in England made more careful computations of the trajectories and of collection efficiencies, but she considered only cases where the wind velocities were much lower than those prevalent on Mt. Washington.

In 1945 (Army Contract W-33-038-ac-9151) we, therefore, made a thorough investigation of the trajectories of spherical particles carried by air flowing around cylinders, spheres, and ribbons. The integrations were carried out by a differential analyzer. The results were given in a report (by K. B. Blodgett and myself) submitted to the Army Air Forces, Materiel Command, in the form of equations, tables, and 12 figures showing families of curves which give the collection efficiency, the distribution of the deposit on the collector surface, and the impact velocities and angles of incidence. This report will be referred to hereafter as the "1945 Report."

These data will probably be published within a few months in the Journal of Applied Physics.

A. Efficiency of Deposition on Collectors. The efficiency of deposition E depends on the wind velocity, the droplet size, and the size and shape of the collector. In the cases considered in the report, the wind velocity and the collector size were assumed to be sufficiently high so that the airflow around the collector was of the aerodynamic type (like that of an ideal frictionless fluid). The data are, therefore, not directly applicable to the case of the collection of cloud droplets by a water drop during its growth to rain drop size, for in this case, the fall velocities are so low that the airflow around the drop is that characteristic of a viscous fluid. For this reason while the differential analyzer was set up for the solution of these droplet trajectories, a few calculations were carried out for the case of viscous flow around the surface of a sphere. It was hoped that these results would be useful in calculating the growth of rain drops by accretion during their fall through clouds.

To understand the factors involved in the problem of calculating the deposition efficiency E for accretion by falling rain drops, we will discuss a few of the concepts that were used in the 1945 Report.

When a small spherical droplet of radius r moves with a sufficiently small velocity v through a gas having a viscosity η, it is acted upon by a frictional force f given by Stokes' Law:

$$f = 6\pi\eta r v. \qquad (3)$$

Stokes' Law does not apply for particles of larger size with higher velocities. In general, however, the force f can be accurately expressed by

$$f = 6\pi\eta r v \, (C_D R/24), \qquad (4)$$

where C_D is the "Drag Coefficient" for spheres and R is the "Reynold's Number" defined by

$$R = 2\rho r v/\eta \qquad (5)$$

where ρ is the density of the air.

The drag coefficient is a function of R only.[5] The values of the quantity $C_D R/24$, which occurs in Eq. (4), are given as a function of R in Column 2 of Table II. For low values of R, it approaches unity as a limit so that Eq. (4) reduces to Stokes' Law, Eq. (3). The calculations of Albrecht and Glauert on the efficiency of rime collection involved the assumption that the force was given by Stokes' Law. Actually, for the wind velocities occurring during riming conditions, the factor $C_D R/24$ is usually very much greater than unity.

B. The "Range" of Cloud Droplets. The dependence of the collection efficiency E upon such variables as the radius of the collector, the wind velocity U and the droplet radius r, can conveniently be expressed in terms of the "range" λ of a droplet of radius r which may be defined as the distance which the particle can move as a projectile when introduced into still air with an initial velocity U. As the velocity of the droplet decreases the resisting force acting on it finally becomes so small that Stokes' Law applies, and the droplet thus comes

4. Albrecht, Physikalische Zeitsch., 32, 48 (1931).

5. Modern Developments of Fluid Dynamics by S. Goldstein, p. 16.

to rest after having travelled a finite distance λ. Actually the range of a high-velocity particle cannot be calculated by Stokes' Law. However, we find that the range λ_s, calculated on the assumption that Stokes' Law does hold at all velocities, is a quantity that has great value in the theory of collection efficiency. The range λ_s is given by

$$\lambda_s = (2/9)\rho_s r^2 U/\eta, \qquad (6)$$

where ρ_s is the density of the spherical droplet.

Let K be the ratio of λ_s to the radius C of a cylindrical collector; then we have

$$K = \lambda_s/C = (2/9)\rho_s r^2 U/C\eta. \qquad (7)$$

The critical condition for which the droplets first begin to strike the cylinder was found to be $K = 1/8$; that is, no droplets can strike the cylinder unless the range λ_s of the droplets exceeds 1/8 of the radius of the cylinder.

This critical condition is exactly fulfilled even if the airflow velocity U is so high that Stokes' Law derivations make the true range λ much less than λ_s.

For the case of rime collectors having the form of spheres of radius S, we have in place of Eq. (7)

$$K = \lambda_s/S = (2/9)\rho_s r^2 U/S\eta \qquad (8)$$

The critical condition for which cloud droplets first begin to reach the surface of the sphere is obtained by putting $K = 1/12$, where K is given by Eq. (8).

The calculation of the collection efficiency E was based on the assumption that all fog particles that strike the surface of the sphere coalesce with it. Later we shall consider the evidence regarding the extent to which non-coalescence (bounce off) may be a factor which limits the collection efficiency.

If, U, the velocity of the airflow past the sphere, and the radii of the fog droplets are small enough, then the motion of droplets with respect to the air carrying them brings into play forces which are in accord with Stokes' Law. Under these conditions, E is a function of K only, and the relation, as taken from the 1945 Report, is given in the second column of Table I.

During the summer of 1947, I developed improved methods of calculating the trajectories of particles carried by a wind close to the surface of a collector for the case of large values of K. I have thus derived the following equation for the efficiency of collection by a sphere

$$E = K^2/(K + 1/2)^2 \qquad (9)$$

The values given by this equation are in excellent agreement with the data of the 1945 Report for all values of K greater than 0.2.

Deviations from Stokes' Law cause E, for any given value of K, to decrease if the product Ur becomes too large. It was found, in general, that E could be expressed as a function of K and of another dimensionless parameter φ defined by

$$\varphi = R_u^2/K = 18\rho^2 SU/\eta\rho_s. \qquad (10)$$

Here R_u is a Reynold's Number calculated as in Eq. (5) except that we replace v by U according to

$$R_u = 2\rho rU/\eta. \qquad (11)$$

It is seen that φ depends on SU but is independent of r, the fog droplet radius.

Under Mt. Washington conditions (-10°C, 785 mb pressure) we have $\rho = 0.00104$ g/cm³, $\rho_s = 1.0$ g/cm³, and $\eta = 1.66 \times 10^{-4}$ g/cm sec so that Eq. (10) becomes

$$\varphi = 0.117\, SU. \qquad (12)$$

In the riming experiments on Mt. Washington, we were dealing with collectors having radii ranging from 0.2 to 5 cm and wind velocities from 10 to 110 miles per hour (4.5 to 49. meters/sec) so that φ ranged from 10 to 2600. For icing of aircraft values of φ of the order of 10000 are to be expected. The data of the 1945 Report showed that with spherical collectors, for $K = 5$, the efficiency E was 0.83 for $\varphi = 0$; 0.71 for $\varphi = 100$; 0.63 for $\varphi = 10^3$ and 0.51 for $\varphi = 10^4$.

C. Efficiency of Deposition of Rain Drops. We wish, however, to know the collection efficiency for falling rain drops. According to Humphreys the largest rain drops have a radius of about 0.25 cm and fall with a velocity of about 8m/sec so that φ never has values greater than 23. This is so small that no appreciable error will be made in considering that the motion of the fog droplets takes place in accord with Stokes' Law.

Whether motion of the air near the surface of the spherical collector or rain drop is of the aerodynamic type (ideal fluid) or of the viscous flow type (Columns 2 and 3 of Table I) depends upon the value of another kind of Reynold's number calculated from an equation like (11) except that the fog droplet radius r is replaced by S, the radius of the spherical collector. We may place

$$R_s = 2\rho SU/\eta. \qquad (13)$$

Comparing Eqs. (13) and (10) we see that

$$R_s = (1/9)(\rho_s/\rho)\varphi. \qquad (14)$$

Under Mt. Washington conditions, we can put $\rho_s/\rho = 1000$ so that $R_s = 110.\varphi$, and, therefore, in our riming experiments R_s (or rather the corresponding quantity R_c for cylinder) had values ranging from 1100. to 290000. and for airplane icing R_c was of the order of 10^6.

The aerodynamic type of flow takes place with very high Reynold's numbers R_S and we are thus justified in using the data of Column 2 for riming experiments with large spherical collectors and possibly for the largest rain drops.

found that for K = 10 (and $\varphi = 0$, i.e., Stokes' Law) that E = 0.64. It was also found that the critical condition (below which E = 0) occurred very nearly at K = 1.0 instead of the critical value K = 1/12 for aerodynamic flow around a sphere.

TABLE I

LIMITING VALUES OF THE COLLECTION EFFICIENCY E FOR SPHERICAL DROPS OF RADIUS S FALLING THROUGH CLOUDS CONTAINING CLOUD DROPLETS OF RADIUS r

(Stokes' Law is assumed to hold for the motion of the cloud droplets)

$K = \lambda_S/S$	Limiting Values of Collection Efficiency E_A Aerodynamic Flow	E_V Viscous Flow
0.0833	0 (crit.)	0
0.1	0.011	0
0.15	0.047	0
0.2	.081	0
0.4	.199	0
0.6	.298	0
1.0	.445	0
1.214	.501	0 (crit.)
1.5	.563	0.066
2.0	.640	.186
3.0	.738	.326
5.	.826	.472
10.	.907	.634
20.	.952	.760
50.	.980	.872
100.	.990	.924
200.	.995	.956

During the early stages in the growth of the falling drops, the value of R_S is far less than 1000, and so it is probable that the viscous type of flow corresponding to Stokes' Law and to low values of R_S will correspond more nearly to the conditions that determine the collection efficiency.

The theoretical flow lines and the velocity components for air motion near spheres are known for both limiting cases (aerodynamic flow and viscous flow) and have been used in the calculations of the 1945 Report. With aerodynamic flow the highest velocity (3/2)U occurs near the surface of the sphere (at its equator), but with the viscous flow the velocities approach zero everywhere over the surface of the sphere and the reduction in velocity of the air extends to considerable distances, falling off at large distances approximately with the inverse square of the distance (inverse cube for aerodynamic flow).

In the 1945 Report, differential analyzer results are given for two sets of trajectories of droplets carried by a viscous fluid around a sphere. It was

During September, 1947, new calculations were undertaken to determine E for viscous flow. With improved methods the result was obtained about October 1 that the critical value of K was

$$K_{crit} = 1.214 \tag{15}$$

During October the theory was extended to cover all values of K and on November 5 the following equation was derived

$$E = 1/\left[1 + (3/4)(\ln 2K)/(K - 1.214)\right]^2 \tag{16}$$

The data in the third column of Table I were calculated by this equation. The value E = 0.634 at K = 10 agrees well with the value E = 0.64 determined in 1945.

In order to be able to use these data to obtain the rate of accretion by falling drops, it is necessary to know the value of K. According to Eq. (7) this requires knowledge of the velocity U at which the drop falls through the air.

V. CALCULATION OF TERMINAL VELOCITY U OF A FALLING DROP

To calculate the velocity we can use Eq. (4) in the form

$$f = 6\pi\eta SU\,(C_D R_S/24), \qquad (17)$$

and can put the force f equal to that exerted by gravity

$$f = (4/3)\pi S^3 \rho_S g. \qquad (18)$$

Eliminating f, we get

$$U\eta(C_D R_S/24) = (2/9)\rho_S g S^2. \qquad (19)$$

If the droplets are so small that Stokes' Law holds, we can put $C_D R_S/24 = 1$ and get for the terminal velocity

$$U = (2/9)\rho_S g S^2/\eta. \qquad (20)$$

To calculate U for larger drops we can eliminate U from Eq. (19) by using Eq. (13) and so obtain

$$S^3 = (9\eta^2/4\rho\rho_S g)\,(C_D R_S{}^2/24) \qquad (21)$$

We may now choose any value of R_S, as in the first column of Table II, and get $C_D R_S{}^2/24$ by multiplying $C_D R_S/24$ in Column 2 by R_S. Then, by Eq. (21), S can be obtained. The values of S in Column 3 of Table II were calculated by taking $\eta = 1.713 \times 10^{-4}$ g/sec.cm, $\rho = 0.001007$ g/cm^3, $\rho_S = 1.00$ g/cm^3, and $g = 980$ cm/sec^2, in accord with the conditions typical of an altitude of 2000 m as given in Table III.

Similar calculations of S and U have also been made for the conditions corresponding to 5000 and 8000 meters altitude as given in Table III. By plotting all three sets of data on double-logarithmic paper using U as ordinates and S as abscissas, it is found that the curves lie close together, within 12 per cent, at the lower ends (small S), but they

TABLE II

THE DRAG COEFFICIENT C_D FOR SPHERES AND THE TERMINAL VELOCITIES U OF FALLING SPHERICAL RAIN DROPS OF RADIUS S IN AIR AT 785 mb PRESSURE AND +2°C

R_S	$\frac{C_D R_S}{24}$	S microns	U cm/sec	U/S sec^{-1}
.05	1.009	15	2.8	1880
.1	1.018	19	4.5	2640
.2	1.037	24	7.1	2960
.4	1.073	31	11.1	3580
.6	1.108	36	14.4	4000
1.0	1.176	43	19.9	4620
1.4	1.225	49	24.5	5000
2.0	1.285	56	30.6	5450
3.	1.37	65	39.	6000
4.	1.45	73	47.	6440
6.	1.57	86	60.	6970
10.	1.78	106	80.	7530
14.	2.01	123	96.	7800
20.	2.29	145	116.	8000
30.	2.67	175	146.	8300
40.	3.01	200	170.	8500
60.	3.60	243	210.	8650
100.	4.59	313	272.	8700
140.	5.40	369	322.	8700
200.	6.52	447	380.	8500
300.	8.26	549	465.	8500
400.	9.82	640	532.	8300
600.	12.97	804	635.	7900
800.	15.81	945	720.	7600
1000.	18.62	1075	790.	7400
1400.	24.0	1309	910.	7000
2000.	32.7	1634	1040.	6400

TABLE III

TYPICAL CONDITIONS AT VARIOUS ALTITUDES

Alt. Meters	Feet	Pressure (mb)	Temp	ρ Kg /cm^3	η	2 o/η
0	0	1000	+15°C	1.21	1.77 10^{-4}	13.7
2000	6600	795	+2	1.007	1.71	11.76
5000	16400	540	-17.5	0.737	1.62	9.06
8000	26200	355	-37	0.524	1.53	6.87

separate gradually until at the highest values of S (1000μ), the values of U for 8000 meters are 29 per cent higher than for 2000 meters. Thus the effect of altitude is not large and for most purposes may be neglected. In the remainder of this paper, we shall use only values of U and S given by Table II, i.e., for 2000 meters.

The data of Table II are subject to two sources of error from factors that have been neglected in their derivation. Stokes' Law, Eq. (3), is based on the assumption that the sphere is rigid. It has been shown by W. Rybczynski[6] that for spheres having negligible internal viscosity (for example, air bubbles in a liquid) the coefficient 6 in Eq. (3) should be replaced by 4. An equation was given for this coefficient in terms of the ratio of the viscosities of the sphere and the surrounding medium. For water droplets at -5°, η = 0.021 while for air at this temperature η = 0.000168. From this we conclude that the coefficient of Stokes' Law should be decreased only 0.27 per cent - a negligible effect.

Drops which are larger than about 2500μ in radius break into smaller drops in falling through the air and the maximum velocity at sea level is about 800 cm/sec, about 880 at 2000 meters and about 1330 cm/sec at 8000 meters.

A more serious effect is produced by the deformation of the falling drops. Large falling drops become flattened and are in a state of constant oscillation, and the resisting force exerted by the air is then increased. Humphreys, in the Physics of the Air, gives a table of the observed velocities (at sea level) of drops of various sizes. For those having radii up to 500μ, the velocities agree well with those of Table II, but with a radius of 1050μ the velocity is 600 cm/sec as compared to about 700 from the data of Table I (adjusted to sea level conditions).

VI. CALCULATION OF THE EFFECTIVE EFFICIENCY E OF DROPLET COLLECTION BY FALLING DROPS

In Table I upper and lower limits are given for the collection efficiency by falling droplets. The upper limit E_A for aerodynamic flow corresponds to high Reynold's Numbers R_s while the lower limit, E_V, for viscous flow, corresponds to low values of R_s.

We may estimate the range of values of R_s over which the transition from E_V to E_A occurs by considering how the relation between U and S in Table II depends on R_s. For low values of R_s the velocity U is given by Stokes' Law, Eq. (20), and in this range U varies in proportion to S^2 and depends on the viscosity η, but not on the density ρ of the air. Thus for low values of R_s or S, U varies inversely as the viscosity η and so from the data of Table III, U increases only in the ratio of 1 to 1.12 as the altitude changes from 2000 to 8000 meters.

The drag coefficient C_D, which can be calculated from Table II, for low values of R_s is approximately equal to $24/R_s$ but at high values decreases more slowly. Thus at R_s = 50, C_D is 1.6 instead of 24/40 = 0.48. At R_s = 1200, C_D = 0.426 and beyond that C_D decreases very slowly to 0.38 at R_s = 3500; then increases to 0.417 at 16000, rises to a maximum of 0.47 at 60000, and decreases to 0.41 at R_s = 160,000. Thus with reasonable accuracy, we can say that for high values of R_s, above 1000, C_D has a constant value of 0.40 which we may represent by C_o. By inserting this value in Eq. (19) and combining with Eq. (13) we find

$$U^2 = (8/3)\rho_s g S/C_o \rho \,. \qquad (22)$$

This limiting expression gives U varying in proportion to the square root of S/ρ. Thus, ac-

6. W. Rybczynski - Anz. Ak. Krakau, p. 40, (1911).

cording to Table III, in this range for any given value of S, U increases in the ratio 1 to 1.39 as the altitude changes from 2000 to 8000 meters.

An examination of the double-logarithmic plot of U(S) from the data of Table II shows, in accord with the limiting expressions of Eq. (20) and Eq. (22), that the lower end of the curve practically coincides with a straight-line asymptote having a slope 2, while the upper end is nearly a straight line of slope 0.5. The point where these two straight lines intersect can be calculated by imposing the conditions $C_D R_S/24 = 1$ and $C_D = C_0 = 0.40$. Thus the intersection occurs at $R_S = 24/0.4 = 60$. A rough approximation to the whole course of the curve U(S) can be had by following the lower line according to Eq. (20) up to $R_S = 60$ and, for higher values, shifting to the other line corresponding to Eq. (22). A much better approximation can be had by constructing any reasonable "transition curve" joining the two limiting straight lines by a smooth curve.

A similar method may now be used to estimate the transitional cases between E_A and E_V. I have adopted the empirical equation

$$E = \left[E_V + E_A(R_S/60)\right] / \left[1 + (R_S/60)\right] \qquad (23)$$

This has the advantage that for values of R_S small compared to 60, E becomes nearly equal to E_V while it approaches E_A when R_S is large compared to 60.

The method of applying this interpolation formula requires careful consideration. The two limiting curves, $E_A(K)$ and $E_V(K)$, were constructed from the data of Table I and are shown up to K = 5 in Fig. 1. It is clear from the nature of the airflow near the stagnation point that for intermediate values of S there will always be a critical value of K below which no deposition occurs, and these critical values will increase progressively from K = 0.125 for $S = \infty$ to K = 1.214 as S decreases to zero. It is reasonable, therefore, to use Eq. (23) to obtain these critical values that lie along the K axis in Fig. 1. However, for larger values of K, where the curves for E_A and E_V are nearly parallel, interpolation can be carried out along vertical lines (constant values of K). For intermediate cases with K less than about 2, I have used Eq. (23) to interpolate along straight lines which radiate out from a point on the K axis at K = 2.5 since these lines cut across both curves approximately at right angles to their tangents. By this procedure, the interpolated curves in Fig. 1 were constructed.

TABLE IV

THE COLLECTION EFFICIENCY E FOR DROPS OF RADIUS S FALLING THROUGH A CLOUD OF SMALLER DROPS OF RADIUS r

(r and S in microns)

	Radius r							
S	r = 2	3	4	6	8	10	15	20
15					.092	.269	.500	.643
25				.050	.277	.411	.613	.724
40				.205	.394	.510	.690	.782
70			.035	.340	.500	.608	.750	.834
100			.133	.418	.564	.660	.793	.862
150		.010	.245	.498	.631	.713	.829	.887
200		.085	.326	.564	.684	.756	.859	.908
300		.213	.425	.643	.749	.810	.892	.929
400	.040	.303	.500	.698	.793	.849	.919	.950
600	.121	.355	.530	.731	.827	.876	.939	.963
1000	.140	.358	.535	.738	.834	.886	.944	.966
1400	.168	.360	.534	.735	.840	.890	.950	.970
1800	.117	.288	.456	.680	.800	.865	.935	.965
2400	.075	.220	.372	.606	.743	.823	.920	.950
3000	.050	.170	.306	.546	.690	.785	.900	.940

Calculated from data of Fig. 1 and Table II by using $K = 1297\, r^2U/S$. For values of S greater than 1000μ, U was taken according to the experimental data to have the constant value of 900 cm/sec at 2000 meters altitude which corresponds to the limiting velocity of 800 cm/sec given by Humphreys and Lenard at sea level.

TABLE V

CRITICAL RADII OF FALLING DROPS
BELOW WHICH NO ACCRETION
OCCURS FOR VARIOUS CLOUD DROPLET RADII r

r	S_{crit}		r	S_{crit}
1.5 μ	600. μ		5.	31.
2.	350.		6.	20.
3.	140.		7.	14.
4.	58.			

Each curve corresponds to a constant drop radius S.

The values of R_S to use in Eq. (23) were taken from Table II. Thus for $S = 250, R_S/60 = 1.05$ and, therefore, by Eq. (23) E is very close to the arithmetic mean of E_A and E_V. It will be seen in Fig. 1 that the curve for S = 250 lies half way between the curves for E_A and E_V.

It is probable that these results are of reasonable accuracy and represent the general dependence of the collection efficiency upon the radii of the falling drops and of the cloud droplets.

Table IV contains data for the collection efficiency E for drops of radius S falling through a cloud consisting of smaller droplets of uniform radius r. If we introduce into Eq. (8) the values of $\rho_S = 1.00$ and $\eta = 1.71 \times 10^{-4}$ for an altitude of 2000 by Table III, we have

$$K = 1297\, r^2 U/S, \qquad (24)$$

where r and S are expressed in cm and U in cm/sec. For any selected value of S the corresponding U/S is given in Table II, and by introducing this and r in Eq. (24) we find K. From these and S, by Fig. 1, we obtain the values of E given in Table IV.

When the cloud droplets are of small radius (below 8 μ) there is a critical size of falling drop below which, E, the efficiency of collection is zero. These values are shown in Table V.

The starting of rain in a cloud thus requires not only the production of some larger drops that can fall out, but requires that the average droplet size in the cloud shall be fairly large.

VII. THE RATE OF GROWTH OF FALLING DROPS BY ACCRETION

When a spherical drop of radius S and mass $(4\pi/3)S^2\rho_S$, falls with velocity U through a cloud containing a liquid water content w, in grams/cm^3, the rate of increase in weight (per second) is $\pi S^2 UwE$. We thus obtain

$$dS/dt = wUE/4\rho_S \qquad (25)$$

The efficiency E, as given by Table IV, varies with S and with r, the radius of the cloud droplets. If z is the height of the droplet above any arbitrarily selected horizontal plane, we also have

$$dz/dt = U. \qquad (26)$$

By division dt can be eliminated from Eqs. (25) and (26):

$$dS/dz = wE/4\rho_S. \qquad (27)$$

In general, w is a function of z while E is a function of S. Therefore, this equation can be solved by integration:

$$\int w\, dz = 4\rho_S \int dS/E. \qquad (28)$$

If the droplet size r is constant throughout a given cloud layer, E depends on S only and the second integral can be obtained from the relation between E and S in Table IV.

If in any layer in a cloud we can regard W as approximately constant, we can integrate Eq. (25).

$$t = (4\rho_S/w)\int dS/EU. \qquad (29)$$

To calculate the rate of growth of falling drops and its dependence on the water content and the cloud droplet size, we need the integrals in the second members of Eq. (28) and (29). There have been calculated, by Simpson's rule, from the data of Table IV (with intervals closer than those shown in that table) and the results are recorded in Tables VI and VII. Let us represent these integrals by the symbols A and B defined by

$$A = 4\int_{S_0}^{S_1} dS/E. \qquad (30)$$

TABLE VI

THE INTEGRAL $A = 4\int_{S_0}^{S_1} dS/E$

S_0 microns	A							
	r = 2	3	4	6	8	10	15	20
15					1.34	1.23	1.11	1.07
25				1.61	1.32	1.21	1.10	1.06
40				1.55	1.30	1.20	1.09	1.05
70			2.43	1.51	1.28	1.18	1.08	1.04
100			2.27	1.48	1.25	1.16	1.06	1.02
150		4.03	2.16	1.43	1.22	1.13	1.04	1.00
200		3.46	2.09	1.40	1.19	1.10	1.01	0.98
300		3.18	1.98	1.33	1.13	1.05	0.97	0.94
400	8.68	3.02	1.89	1.27	1.08	1.00	0.92	0.89
600	7.57	2.78	1.74	1.16	0.98	0.91	0.84	0.81
1000	6.33	2.33	1.44	0.94	0.79	0.73	0.67	0.64
1400	5.26	1.88	1.14	0.72	0.60	0.55	0.50	0.48
1800	4.27	1.46	0.86	0.53	0.43	0.39	0.35	0.35
2400	2.43	0.78	0.43	0.26	0.21	0.19	0.17	0.16
3000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

and

$$B = 4\int_{S_0}^{S_1} dS/EU. \qquad (31)$$

The integration in Tables VI and VII have been carried out between a variable lower limit S_0 and a fixed upper limit $S_1 = 3000\mu$. Above $S = 1300\mu$ the values of U calculated from the drag coefficient C_D for spheres (Table II) are greater than 900 cm/sec, which is probably the maximum fall velocity at an altitude of 2000 m. Assuming the drop, for greater values of S, is an oblate spheroid and considering the effect of the deformation on the weight and on C_D, I have estimated that the ratio of the vertical (minor) axis to the horizontal (major) axis is about 0.78 for $S_{max} = 1800\mu$; 0.67 for $S_{max} = 2400\mu$; and 0.58 for $S_{max} = 3000\mu$. Lenard (Meteorolog. Zeit. -(1904), 249-262) finds that drops break up at average diameters of 5.0 mm, this

TABLE VII

THE INTEGRAL $B = 4\int_{S_0}^{S_1} dS/EU$

S_0 microns	10^3 B							
	r = 2	3	4	6	8	10	15	20
15					10.32	6.95	5.15	4.59
25				9.99	5.32	4.45	3.65	3.37
40				5.05	3.86	3.35	2.88	2.70
70			8.01	3.48	2.84	2.60	2.31	2.18
100			4.94	2.93	2.44	2.25	2.03	1.93
150		9.58	3.78	2.46	2.09	1.93	1.77	1.69
200		5.84	3.28	2.20	1.88	1.74	1.60	1.55
300		4.45	2.77	1.88	1.61	1.50	1.38	1.34
400	11.73	3.94	2.48	1.68	1.44	1.33	1.23	1.20
600	9.13	3.36	2.11	1.41	1.20	1.12	1.03	1.00
1000	7.11	2.62	1.62	1.06	0.89	0.82	0.75	0.73
1400	5.85	2.10	1.27	0.80	0.66	0.61	0.55	0.53
1800	4.74	1.63	0.96	0.59	0.48	0.44	0.39	0.39
2400	2.70	0.87	0.49	0.29	0.23	0.21	0.19	0.18
3000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

being calculated from the weight of the drop by assuming it to be spherical.

For an oblate spheroid like the one I calculated for a drop of $S_{max} = 3000\mu$, the effective radius as used by Lenard would be $3000 \times (0.58)^{1/3} = 2500\mu$ which corresponds to a diameter of 5.0 mm. The value S = 3000 in the first columns of Tables VI and VII represents S_{max} for a drop of effective diameter 5.0 mm.

In carrying out the calculations for A and B for values of S larger than 1300μ, Eqs. (28) to (31) were modified by multiplying the second members by λ, the ratio of the minor to major axis. This is equivalent to assuming a spherical droplet of density $\lambda \rho_S$ instead of ρ_S. In this way, the effect of the deformation can be taken into account.

The integral in the first member of Eq. (28) is the total liquid water in the cloud in the layer covered by the integration, expressed in grams/cm^2, or since $\rho_S = 1$, it is also the depth of the theoretically available precipitation measured in cm. If we represent this precipitable water by ω we have, using Eq. (30),

$$\omega = w\, dz = A. \qquad (32)$$

From Eqs. (29) and (31) we get

$$t = B/w, \qquad (33)$$

where w must be regarded as a mean value of w in the layer being considered.

Let us illustrate the use of these equations and tables by calculating the time required and the distance traversed by a drop (initial radius 40μ) before it has grown to a radius of 1000μ by falling through a cloud in which the droplets are of 8μ radius and the liquid water content is 1 g/m^3 or $w = 10^{-6}$ g/cm^3. From Tables VI and VII, we find A = 1.30 cm and B = 0.00386 sec. Eqs. (32) and (33) then give $\omega = 1.30$ cm and t = 3860 sec.

A cloud layer 1000 meters thick with a liquid water content of 1 g/m^3, ($w = 10^{-6}$), will give a rainfall contribution $\omega = 0.1$ cm. Thus the 40μ drop would have to fall 13000 m through such a cloud before it could grow to 3000μ. We see then that the tabulated figures in Table VI multiplied by 10^4 represent the distances in meters that drops must fall to grow to 3000μ radius.

The required distance of fall varies, of course, inversely in proportion to the water content w.

The time required for this growth, 3860 sec or 64 minutes, also varies inversely as w. The time in seconds required for a droplet to grow from one size to another in a cloud containing 1 g/m^3 is 1000 times the difference between the corresponding tabulated values in Table VII. Thus in the cloud that we are considering ($r = 8\mu$), a droplet would take 5000 sec or 1.39 hours to grow from 15. to 25μ; 0.40 hours more to grow to 40μ, and 2970 sec or 0.82 hours to grow from 40. to 1000μ.

This rapid acceleration in the growth is due to the increase in each of the three factors: velocity of fall, radius, and collection efficiency. These factors were also taken into account in the early work which led to Eq. (2). Inserting the values of η and g this becomes

$$t = 3.1 \times 10^{-6}/EwS_0, \qquad (34)$$

which is to be compared to Eq. (33).

For the example we have chosen with $S = 40\mu$ and $w = 10^{-6}$, we obtain t = 780/E sec, and, if we take the average efficiency, Table IV, to be about 0.5, this gives t = 1560 sec, which is about 40 per cent of the value that we calculated from Table VI. The reason for the low values of t given by Eqs. (2) and (34) is that the derivation was based on Stokes' Law which gives resisting forces lower than those actually encountered by falling rain drops.

It is evident from Eq. (32) and the data of Table VI that in clouds in which there is no vertical motion, rain drops can grow to a size large enough to cause break up only if the clouds have sufficient thickness and liquid water concentration to give a total water content of about $\omega = 1.0$ cm. Only very large cloud masses, 12,000 or more feet in thickness, could meet these requirements and in such large clouds vertical motions always do occur.

In connection with the derivation of Eq. (2) in 1944, I had made some calculations of the effect of rising currents of air within clouds and had concluded that the growth of rain drops would be greatly favored by such motion. However, at that time I did not develop the quantitative theory very far, largely because I had no adequate knowledge of the collection efficiency E.

VIII. HAWAIIAN EXPERIMENTS IN DRY-ICE SEEDING OF CLOUDS ABOVE 0°C

On November 1, 1947, shortly after I had calculated the values of E_A and E_V given in Table I, Lt. Comdr. Daniel F. Rex, Chairman of the Operations Group of Project CIRRUS, showed me a letter he had received from his friend, Maurice H. Halstead, which enclosed a preliminary report prepared by Luna B. Leopold of the Pineapple Research Institute and the Hawaiian Sugar Planters Experimental Station and by Maurice H. Halstead of the U. S. Weather Bureau describing dry-ice seeding experiments made during September and October.

These experiments were undertaken although it was known that, in Hawaii, only well developed clouds reach high enough to penetrate the freezing level and such clouds almost invariably produce heavy rain without artificial inducement.

The most interesting flight was that made on September 23, 1947, over the island of Molokai which lies about 40 miles ESE of Honolulu. This island is roughly rectangular in shape with its long axis oriented almost east-west. It has a length of 36 miles and a width of 6 - 8 miles. The mountains covering the eastern half of the island reach to nearly 4000 feet, and they are generally covered on the north by a solid bank of stationary orographic clouds because of the northeasterly trade winds that prevail.

The tests that will be described were made over a region near the center of the western half of the island. This half is much lower and has only one range of hills, the Maunaloa Hills, which reach a maximum height of about 1300 feet, and thus there are only occasional, scattered orographic clouds which form along the west end of the coastal cliff that characterizes much of the north shore.

A sea breeze usually develops each day along the southern shore of western Molokai and this southerly wind meets the north easterly trade winds over the center of the island. The leading edge of this sea breeze front often gives rise to a line of cumulus clouds over the Maunaloa Hills and even over the sea just north of the north shore. These clouds normally give little or no rain so the cultivated lands of western Molokai are considerably drier than those of the other Hawaiian Islands. In fact, "convective showers are extremely rare" over this relatively dry western part of Molokai.

Before any flights were made, a list was drawn up of the conditions that were considered favorable for the production of rain.

1. Temperature inversions, which might limit cloud growth, should be absent or be abnormally high.

2. Large moisture content should extend to abnormal heights.

3. The trade wind should be relatively weak so as to allow maximum surface heating by the sun on the southern half of the island, giving considerable convective activity and sea breeze flow over the island.

4. The lapse rate should be steep.

For the proposed flight tests, it was arranged to have an observer in the plane and two or more observers stationed on prominent hills to take notes and draw sketch maps of cloud distribution, rain sequences, etc.

Since a short range forecast indicated favorable conditions, the first flight was made on September 23, 1947. Radio sonde data were taken at Honolulu Airport, 60 miles away at 500 (i.e., 5 A.M.) and at 1700 (5 P.M.). The two temperature-pressure curves were nearly alike. The afternoon curve showed that up to 3000 m the lapse rate was nearly constant at 0.60°C per 100 m whereas under these temperature conditions, the wet adiabatic rate would be 0.43°/sec 100 m. The freezing level was at about 15,000 feet and at 5000 feet and 10,000 feet, the winds were only 5 mi/hr with direction from 210°.

At 830 there were three clouds in a row (NNE - SSW) near western Molokai. They had bases at about 2500 feet and the two larger clouds reached to about 7000 feet. The nothernmost cloud extended from the coast to a point about 5 miles north of the north coast. The second cloud was over the hills forming the central ridge. These clouds were 10 miles or more from the nearest of the orographic clouds over the eastern half of the island.

By 1030 the two larger clouds had joined to form a single roughly circular cloud about 8 - 10 miles in diameter having a center over the sea about 2 - 3 miles north of the coast. A flight over the cloud at this time showed that there were two main towering masses of cumulus: The higher tower, denoted by X, was over a part about 3 miles north of the coast while the second one called Y was only slightly lower and was about 4 miles to the SW, directly over the coast line.

The X-peak was seeded with 50 pounds of crushed dry ice just over the top at 8700 feet starting at 1037 and ending at 1042. Almost immediately afterward (at 1045) the Y-peak was similarly seeded. Ground observers reported seeing rain start at 1046, only 9 minutes after the start of the seeding at a point directly under X, the portion of the cloud which was first seeded. This rain continued. Under the Y-peak observers reported seeing virga from the cloud about 15 minutes after seeding Y, but no rain reaching the ground under Y was recorded at that time. About one hour later, at 1145, rain from X had continued steadily and rain was falling over an area of about 2 square miles which had moved roughly 2 miles south from its original position at X. At this time, it was reported that steady rain was also falling from another area of roughly 2 square miles in the position corresponding to the seeding done at Y. This rain area under Y then spread quickly and coalesced with that under X covering most of the Maunaloa Hills. This large single rain cloud moved slowly southward and the rain area also extended to the west. This rain was estimated to have fallen over an area of 35 square miles in the western part of Molokai.

During the day, several other clouds of size comparable to those seeded could be seen from the plane, but none of these produced precipitation within several hours after rain had started from the seeded cloud.

In a second flight, it was noted at 1215 that the two cloud peaks had nearly coalesced and that they had built up to 15,700 feet, a rise of 7000 feet in 95 minutes. From an altitude of 14,000 feet, another seeding was done with 100 pounds of dry ice. During the next 35 minutes a rainfall of 0.80 inches was recorded at the triangulation station, a point almost directly below the seeded cloud top. The total rainfall at this station mounted to 1.25 inches.

During the afternoon, the cloud built up to an estimated 25,000 feet, drifted slowly (2 mi/hr) to the south giving copious rain over the ocean between Molokai and Lanai (another island, 40 miles south of point X) and it rained over a part of Lanai during the night.

The preliminary report of Leopold and Halstead gives a brief summary of other seeding experiments from September 24 to October 11. In 7 out of a total of 10 cases in which clouds over 3000 feet in thickness were seeded, rain was observed to fall within periods of time ranging from 9 to 30 minutes, the average being 16 minutes. However, outside of the tests of September 23, which we have already considered, only in one case (October 11) did more than a trace of rain reach the ground. On that date light rain which began 10 minutes after seeding covered an area of about 18 square miles and gave a recorded maximum of 0.10 inch. The cloud base was at 3600 feet and the top at 7600 feet. The lapse rate, 0.68°C per 100 m at Honolulu, was rather high from the ground up to 6000 feet, but there was a temperature inversion between 6000 and 7500 feet. The freezing level was at about 16,000 feet.

On September 30 a small, nearly circular cloud about 3/4 mile in diameter and 2200 feet thickness was seeded by making several runs through the cloud dropping a total of 125 pounds of dry ice. It was observed that the cloud top rapidly lowered and within 7 minutes from the initial seeding, the cloud totally disappeared. Observers on the ground reported seeing no virga or rain from it.

In every test during September and October, the flight over the cloud produced an initial depression or diminution of height of about 300 feet within the first 3 - 4 minutes after seeding. With the thick clouds which gave persisting rain, the initial drop in height was quickly reversed and rapid building up occurred.

The depressing effect of a flight over a cloud may in part, at least, have been due to the downward momentum delivered by the weight of the plane weighing 6 tons flying for 5 minutes within a cloud which in the September 30 tests, would deliver to the air a downward momentum of 1.5×10^{12} c.g.s. units. A cloud 1 Km in diameter and 500 meters thick contains 4×10^{12} grams of air, so that the whole should be given an average downward velocity of 4 cm/sec by the weight of the plane. Of course, the regions actually traversed by the plane would receive considerably greater velocities.[7]

Each gram of dry ice introduced into a cloud increases the apparent weight of the cloud by 0.34 g because of the increased weight of the CO_2 as compared to the air which it displaces. Besides that, there is an increase in density of the cloud due to the cooling effect of the dry ice. This gives an apparent increase in weight of 2.46 grams - a total of 2.8 grams for each gram of dry ice. Thus the 125 pounds of dry ice caused an effective increase in weight of 350 pounds, giving in <u>each second</u> a downward momentum of 1.5×10^8; in 5 minutes, the total momentum due to this cause would be 4.5×10^{10}, only about 1/30 of that given by the plane. The direct effect of the CO_2 on the motion of the cloud thus seems unimportant.

7. Airplane Tracks in the Surface of Stratus Clouds. I. Langmuir and Alexander Forbes. J. Aeron. Sciences, 3, 385, (1936).

IX. RAIN PRODUCED BY A CHAIN REACTION

The experiments described in the preliminary report of Leopold and Halstead (hereafter called L-H) appear to have been conducted with very great care, and the results were recorded with accuracy. The conclusions that I wish to draw from these experiments are as follows:

1. The proof is excellent that heavy rain was produced by the dry ice seeding runs of September 23.

2. The rain was produced very quickly - within 9 minutes.

3. The rain persisted but spread through the large cloud very slowly although the cloud increased greatly in height.

4. The third seeding at 1212, 95 minutes after the first seeding, produced a very great and sudden increase in the rain intensity and in the cloud height and caused the rain area to spread to about 20 square miles.

5. At the time of the first and second seeding, 1037 and 1045, the lowest temperature within the cloud was about +10°C. According to the Honolulu radio sonde data, the temperature at the height of the cloud top (15,700 feet) at the time of the third seeding (1212) was about -2°C, but at the seeding height (14,000 feet), it was +1°C. However, we have found that the interior of the upper parts of large cumulus clouds is usually a few degrees colder than the surrounding air, so it is probable that the third seeding was done in a supercooled cloud.

It is of interest to compare these results of the L-H flights with our own experiences in connection with the dry ice seeding of large cumulus clouds in Project CIRRUS.[8]

Laboratory experiments, airplane tests, and physical theory have proved that dry ice introduced into clouds of supercooled water droplets (temperature below 0°C) gives almost instantaneously numbers of minute ice crystals of the order of 10^{16} per gram of dry-ice.[3] These nuclei grow rapidly, in accord with the Bergeron theory, into snowflakes. During July and August experiments were made, in Project CIRRUS, seeding high cumulus clouds whose tops reached far above the freezing level which range from 16,000 to 18,000 feet altitude. A comparison of the five conclusions of the L-H report listed above gives:

1. In Project CIRRUS (hereafter called P-C) dry ice <u>always</u> produced remarked effects, turning the whole of the supercooled part of the cumulus cloud into ice crystals. The L-H data, however, showed much more variable results. In the September 23 tests, spectacular results were obtained, but on other dates, usually only traces of rain fell or sometimes no rain at all.

2. The results with the L-H and the P-C tests were alike in that rain, if it was produced at all, fell within 10 to 30 minutes.

3. With the L-H tests, the effect of the first and second seedings spread very slowly whereas in the P-C tests, the effect of the seeding continued to spread rapidly throughout the whole cloud giving the maximum effect within 10 to 15 minutes.

4. The effects of the third L-H seeding on September 23 were very much like those that were normally produced in the P-C project from dry ice seeding.

5. The reason for this similarity is probably that in the L-H experiments at the time of the third seeding, the cloud had reached the freezing level so that the ice nuclei played their customary role.

The mechanism involved in the production of rain by the first and second seedings of the September 23 flights must evidently be very different from those involved in the P-C experiments with supercooled clouds.

In analyzing these data, it occurred to me that the rain production in the above-freezing clouds in the L-H experiments was not caused by the cooling effect of the dry ice, but by the water droplets introduced in the upper part of the cloud by the melting of the thin coating of ice which normally collects on crushed dry-ice fragments due to condensation of moisture of the air. A plane flying through the top of a cloud may also introduce water droplets by the "run-off" of water drops from the trailing edge of wings, this water having been collected from the cloud droplets by the motion of the plane through the cloud.

The drops of water formed in either of these ways would be much larger than the ordinary cloud droplets, and they would fall through the cloud in accord with the accretion theory already considered. These drops, under favorable conditions,

8. A summary of the work done in Project CIRRUS up to June 1, 1947, is contained in a report now on sale by the Office of Technical Services. Mimeographed copies of the report (PB-81842, <u>First Quarterly Progress Report, Meteorological Research</u>) sell for $1.25. Orders should be addressed to the Office of Technical Services, Department of Commerce, Washington 25, D. C., and should be accompanied by check or money order, payable to the Treasurer of the United States.

would grow to such size that they break up into two or more large drops and produce also a relatively large number of small droplets which, however, would be larger than the cloud droplets. Each of these new drops or droplets might again grow to such size that they in turn can break. In the case of a thick cloud with large water content, this process might repeat itself many times, with the result that an amount of rain might be produced which would be very much greater than the amount of water introduced. In each stage of such a process, the number of droplets might increase perhaps by a factor of 10, so that if the cloud were thick enough to give three such stages, there would be an amplification factor of 10^3.

It is evident that even with such a large amplification factor, it would not be possible to account for the formation of amounts of rain comparable with those observed from the first and second seedings of the September 23 L-H flights, where about 0.1 inch of rain was produced within the first hour over an area of perhaps 3 square miles. Such an amount of rain would correspond to about 2×2^{10} grams or 20,000 tons while water introduced by the dry ice would perhaps be at the most a few kilograms, so that we would need an amplification factor of the order of 10^7.

The indications are, however, that the first two seedings of the L-H flights produced a gradually increasing rainfall. This suggests that a true chain reaction was set up. This would be a process in which each rain drop leads to the production of at least one other rain drop under conditions such that the new rain drop has the same chance of producing another rain drop as the original one did.

A. Chain Reaction in Snow Formation. In early studies of the effects to be expected from Schaefer's dry ice seeding technique, we came to a realization that in natural snow storms, there must be a mechanism by which enormous numbers of small ice crystals are generated so as to produce a continuous supply of effective nuclei. This is obvious when one considers that preceding these snow storms, the air normally contains relatively few nuclei compared with those needed to maintain a snow storm.

The main cause of the generation of the ice crystals is the fragmentation of snowflakes produced by contact between snowflakes which accumulate in the upper portions of the cloud. In lower parts of the cloud, vertically rising currents may prevent the newly formed snowflakes from falling. In this way, even when there are relatively few nuclei in the air, the concentration of snowflakes can build up to such a high value that snowflakes coalesce into larger aggregates and these in turn, break apart again producing many small fragments. Another effect is suggested by some observations made by Mr. Schaefer on the growth of ice crystals in the presence of strong electric fields. In such a field, there is a tendency for ice crystals to form long fibers in the direction of the field. This is perhaps due to the dipole attraction between the ice fibers and the supercooled water droplets near them in the presence of the field. With sufficiently large fields, these fibers grow to such size that they are broken apart by the field and thus produce enormous numbers of small fragments. The evidence thus far obtained suggests that in this way, starting with a relatively small number of ice nuclei, an electric field may lead to a great increase in the number of ice nuclei. Schaefer has observed, in fact, that in natural snow storms very-strong electric fields can be observed on the ground, usually stronger than those observed even during summer thunderstorms.

As soon as there is a mechanism within the cloud by which each naturally occurring ice nucleus in the air produces on the average two or more other nuclei and these in turn multiply to produce two or more, we have the conditions required for the production of a chain reaction by which a self-propagating snow storm can be formed which requires no further influx of the naturally occurring ice nuclei. In analyzing the possibility of such a chain reaction, I was impressed by the important role that the vertically rising air currents would play.

B. Chain Reaction for Rain Formation Requires Vertically Rising Air Currents. Let us therefore consider the modifications in the theory which we developed in our derivations Eq. (25) to Eq. (33) which would be necessary if the air within the cloud is rising with a velocity V.

In place of Eq. (26) we then have

$$dz/dt = V - U. \qquad (35)$$

If, by division, we eliminate dt between this equation and Eq. (27) we obtain

$$\int w\, dz = 4\rho_s \left[V \int dS/EU - \int dS/E \right]. \qquad (36)$$

Combining this with Eqs. (30), (31), and (32) we have in place of Eq. (32),

$$\omega = A - VB. \qquad (37)$$

By this equation, we can calculate the growth of drops in a cloud of uniform water droplets which is rising with a steady velocity V.

Let us now consider what the rising velocity must be in order that a chain reaction may occur. At present, for simplicity, let us assume that in the break up of a large drop, small droplets of radius S_0 are formed. In order that these shall be carried upward by the rising air, V must be greater than U_0. The rising drops, however, grow in size by accretion and as they grow their velocity of fall, U, increases until finally at some height z_M the fall velocity equals the velocity of the rising air. At this point, the particle has reached its maximum height and then begins to fall. Let us denote by S_M the radius of the droplet at the time t_M at which it has reached its maximum height z_M. The particle continues to grow and z decreases until finally at some time t_1 the droplet has reached a radius S_1 at which it breaks up to form one or more droplets of radius S_o, the size of the original droplets.

If the height z_1 is lower than z_o, the original height at which the first droplet was produced, then in repetitions of this process the new droplets will be formed at continually lower heights until finally the process terminates when the drop reaches the bottom of the cloud. This apparently does not constitute a chain reaction which can cause persisting rain.

In order that a real chain reaction may occur, it is thus necessary that the final height z_1 shall be at least as great as z_o, the initial height. The conditions under which the chain reaction can first occur are, thus, as in the case of other chain reactions, extremely critical. This critical velocity V_c can be calculated by putting $\omega = 0$ in Eq. (37). To understand this, we must consider that ω is obtained by integrating w over an interval at height z. We can assume that w is a function of z only so that if $z_1 = z_o$, the contribution to ω due to the up motion of the drop from z_o to z_M is positive, while the integral covering the range from z_M to z_1 has a negative value that exactly balances the positive increment. It is for this reason, therefore, in the special case that $z_1 = z_o$, we can put $\omega = 0$. Introducing this condition into Eq. (37) we thus obtain

$$V_c = A/B \qquad (38)$$

The values of A and B are given in Tables VI and VII. By means of Eq. (38) we can thus obtain the velocity V for the different sizes of cloud particles and drop sizes S as given in Table VIII. It should be noted that the values of A and B that go into this equation are those that correspond to the two integration limits S_o and S_1 where in the derivation of Tables VI and VII, S_1 was taken to be 3000μ. The critical velocity V_c given in Table VIII is, therefore, the velocity that corresponds to S_o as given in Column 1.

Table IX contains the droplet radius S_M at the time when the droplet reaches its greatest altitude. These data are obtained by taking values of V_c from Table VIII, and finding from the data of Table II the value of S that corresponds to $U = V_c$, for this is the condition according to Eq. (35) that the altitude of the droplet shall be a maximum.

Table X contains the value of ω_M which represents the water content of the cloud that lies between the horizontal plane at $z = z_o$ and at the plane $z = z_M$. This gives the thickness of the layer in which the chain reaction takes place. The value of ω_M is obtained by

$$\omega_m = A_M - V_c B_M, \qquad (39)$$

where A_M and B_M are the values of the integrals in Tables VI and VII for values of S corresponding to S_M. By comparing the values of ω_M with those of A_o, which according to Eq. (32) should be equal to ω_o, we see that the amount of water needed in the cloud to maintain the chain reaction is very much less than that which would be required for the growth of droplets to large size in a cloud in which there is no updraft. Table XI illustrates this effect for

TABLE VIII

THE CRITICAL UPDRAFT VELOCITY V_c NEEDED FOR A CHAIN REACTION

S	V_c (in cm/sec)							
micron	r = 2	3	4	6	8	10	15	20
15					130	177	216	234
25				161	248	272	302	314
40				308	338	358	379	389
70			304	433	448	455	418	477
100			460	505	515	515	523	529
150		422	572	581	584	585	587	591
200		593	637	637	632	632	630	632
300		715	762	707	703	700	705	702
400	740	768	825	755	750	750	750	741
600	819	828	890	824	815	810	815	810
1000	890	890	900	885	890	890	880	875
1400	900	900	900	900	900	900	900	900

TABLE IX

THE DROPLET RADIUS S_M AT THE TIME t_M AT WHICH THE DROPLET REACHES ITS GREATEST ALTITUDE z_M

S	S_M (microns)							
micron	r = 2	3	4	6	8	10	15	20
15					158	210	252	272
25				192	287	311	346	360
40				354	389	412	436	449
70			349	508	526	538	485	565
100			542	600	617	617	627	637
150		490	703	720	723	725	728	735
200		738	805	810	802	802	800	802
300		937	1035	925	917	912	917	915
400	1000	1042	1137	1023	998	998	998	983
600	1125	1145	1350	1135	1120	1110	1120	1110
1000	1350	1350	1400	1325	1350	1350	1290	1260
1400	1400	1400	1400	1400	1400	1400	1400	1400

TABLE X

THE TOTAL LIQUID WATER CONTENT ω_M THAT MUST LIE WITHIN THE CLOUD LAYER BETWEEN z_o AND z_M WITHIN WHICH THE DROPS GROW AND BREAK UP

S	ω_M (cm of water)							
micron	r = 2	3	4	6	8	10	15	20
15					0.95	0.79	--	--
25				1.04	0.74	0.64	0.56	--
40				0.75	0.60	0.53	0.46	0.43
70			1.15	0.55	0.45	0.40	0.36	0.33
100			0.77	0.45	0.37	0.33	0.30	0.28
150		1.34	0.54	0.35	0.29	0.25	0.24	0.23
200		0.80	0.42	0.28	0.24	0.21	0.20	0.18
300		0.47	0.25	0.20	0.18	0.14	0.16	0.13
400	1.09	0.28	0.15	0.14	0.13	0.11	0.11	0.10
600	0.41	0.18	0.08	0.08	0.08	0.07	0.07	0.06
1000	0.06	0.04	0.02	0.02	0.02	0.02	0.02	0.02
1400	0	0	0	0	0	0	0	0

TABLE XI

THE EFFECT OF AN UPDRAFT OF VELOCITY V_c IN DECREASING THE CLOUD WATER CONTENT REQUIRED FOR THE GROWTH OF DROPS TO LARGE SIZE

(For the example shown r = 10 microns)

S_o microns	V_c cm/sec	ω_o For V = 0	ω_M For V = V_c	Ratio ω_m/ω_o
25	272	1.21 cm	0.64 cm	0.53
40	358	1.20	0.53	0.44
100	515	1.16	0.33	0.28
200	632	1.10	0.21	0.19

a cloud consisting of droplets of 10 microns radius. The values of V_c are taken from Table VIII, ω_o from Table VI, and ω_M from Table X. The last column contains the ratio ω_M/ω_o. If, for example, there is an updraft of 5.15 meters per second and the breaking drops give one or more smaller droplets of about 100 microns radius, then it is seen that the liquid water content of the layer in which the chain reaction takes place only needs to be 0.33 cm. and this is only 28 per cent of that which would be needed to allow large drops to grow in a cloud without updraft.

The time t required for the growth of droplets depends primarily on the liquid water content w and, therefore, can always be calculated by Eq. (33). This can be used not only to get the total time that the particles grow from a radius S_o to the break up point S_1, but can be used to calculate the time for the droplet to grow to any other size.

X. APPLICATIONS OF THE THEORY TO THE LEOPOLD-HALSTEAD DATA

From the data of the L-H preliminary report, it is possible to form an estimate of the conditions within the cloud which was seeded on September 23, 1947. Table XII contains results of calculations from these data. The cloud base was at 2500 feet and the cloud top at 8700 feet. The fourth column contains the average of the temperatures given by the radio sonde at Honolulu at 500 and 1700. The temperatures in the third column have been calculated on the basis that the ground temperature was 28°C and that from there to the cloud base, the temperature decreased according to the dry adiabatic lapse rate of 3.0°C per 1000 feet. Above that, the temperature was assumed to vary according to the saturated adiabatic as calculated from data given in Brunt's book. The pressures were calculated taking into account the temperatures in the third column assuming the pressure on the ground to be 1000 mb. The mixing ratio x in the sixth column expressed in kg/m^3 was calculated from the saturated vapor pressures according to the equation given at the bottom of the Table. The seventh column contains the mixing ratio for liquid water; at any altitude x + y retains the value that it had at 2500 feet. Multiplying y by the density of the air, we obtain the liquid water content as given in the eighth column. Finally, by integrating this in accord with Eq. (32), we obtain the total liquid water from the cloud base up to a given height. The last column contains my estimate of the radius of the droplets. This calculation assumed that within the first 150 meters of rise above the cloud base, the droplets grew in accord with the data obtained in the Mt. Washington observations assuming the air was rising 6 m/sec. It was calculated that at this height the number of droplets was 148 cm^{-3}. At higher altitudes, this concentration was assumed to remain constant, the moisture released by the expansion being used to increase the size of the droplets. From various considerations which will be published elsewhere, I believe that this gives a more reliable result for cumulus clouds than would be obtained by direct application of Eq. (2) for the whole range of altitudes.

A comparison of the values of x at the cloud base and on the ground level gives for the relative humidity on the ground 67 per cent.

In many cumulus clouds, especially those whose altitude is large compared to their horizontal dimensions, large amounts of relatively dry air may be drawn in laterally and mixed with the air in the cloud. Thus w may increase less rapidly than is given by a calculation based on the saturated adiabatic curve. However, the cloud that we are now considering had a vertical height of about one mile and was about ten miles in diameter. It seems, therefore, that no appreciable amount of air could have been drawn laterally into the center of the cloud, but in this cloud, near the center, the air had all risen through the cloud base. In this case, the wet adiabatic curve must apply and the liquid water content can be confidently taken to be that calculated.

We see that the total water content $\omega = 0.37$ cm corresponds by Table X, for an effective droplet radius $r = 15\mu$, to an initial falling drop radius of $S_o = 67\mu$. This means that no droplets less than this diameter can take part in a chain reaction. By Table VIII we see that the critical velocity V_o must have been at least 414 cm/sec and, with an average value of $w = 1.68$ g/m^3, the time for the growth of the droplets from 67μ to 3000μ would amount to 1400 seconds. This is much longer than the time at which visible rain was observed to fall from the cloud.

The data of Tables VIII, IX, and X indicate, however, that there is a wide range of conditions under which chain reactions can occur in such a cloud. Thus it is possible that S_o can have any

TABLE XII

CALCULATIONS OF CONDITIONS FOR THE CLOUD
SEEDED IN L-H EXPERIMENTS OF SEPTEMBER 23, 1947

Altitude z ft	m	Temp ^{o}C	Radio Sonde ave	Pressure mb	x kg/m^3	y kg/m^3	w g/m^3	ω cm	r microns
0	0	28.0		1000	24.44				
2500	762	20.5	21	916	16.90	0	0	0	0
3000	914	19.9	20	900	16.50	0.40	0.43	0.003	8.9
4000	1219	18.7	18	868	15.87	1.03	1.07	.026	12.0
5000	1524	17.5	16	838	15.23	1.67	1.68	.068	13.9
6000	1829	16.3	14	808	14.59	2.31	2.24	.128	15.4
7000	2134	15.1	13	780	13.93	2.95	2.78	.204	16.5
8000	2438	13.8	11	752	13.30	3.60	3.29	.297	17.4
8700	2652	12.9	10	733	12.88	4.02	3.59	.371	18.0

$x = 0.622\ e/(p - e);\ w = y$

value greater than 67μ. The data of Table XIII have been calculated on this basis. The values of V_c are taken from Table VIII and ω_M from Table X. By plotting w and ω against altitude and comparing with values of ω_M, it is possible to calculate Δz, these distances being measured from the top of the cloud down to the height corresponding to z_o. It is, of course, possible when Δz is small enough that chain reactions may simultaneously occur at several levels within the cloud, but the one which takes place most rapidly is that which occurs at the highest altitude, and it is this condition that has been considered in the derivation of Table XIII. The fifth column contains the average value of w within the layer involved in the chain reaction. The last column contains the time calculated by Eq. (33) using values of B obtained from Table VII.

The interpretation of these data should be made with due regard to the observations of Lenard who considered the sizes of the fragments produced when water drops break up in rising currents of air. He found that rain drops of 5.4 millimeters diameter broke up in a rising air current of 8 m/sec in many different ways: Four per cent broke into 2 or 3 nearly equal parts, twenty-five per cent into very fine dust-like droplets, sixty-four per cent gave one large drop and a number of small drops. The fragments ranged in size rather uniformly from 1.5 to 3.5 mm in diameter, but there were relatively large numbers of much smaller droplets very much less than one millimeter in diameter.

We see from Table XIII that the observed rapid development of rain which was observed below the cloud within 9 minutes - 540 seconds - would indicate, according to the Table, that the drops effective in starting the chain reaction have radii greater than 200μ, and the vertical velocities within the cloud must have exceeded 630 cm/sec. How-

TABLE XIII

THE THICKNESS OF THE LAYER, THE VERTICAL
VELOCITIES, AND THE TIME REQUIRED FOR
CHAIN REACTION IN THE L-H CLOUD

($r = 15\mu$)

S_o microns	V_c cm/sec	ω_M cm	Δz m	w ave g/m^3	t sec
70	418	0.36	1620	1.72	1340
100	523	0.30	1130	2.64	770
150	587	0.24	790	2.93	605
200	630	0.20	610	3.09	520
300	705	0.16	490	3.22	430
400	750	0.11	335	3.37	365
600	815	0.07	214	3.45	300
1000	880	0.00	61	3.54	210

ever, these velocities need occur only within a layer a few hundred meters thick in the upper portion of the cloud. The fact that the terminal velocity of falling drops reaches a limiting value of about 900 cm/sec, even when the droplets are still only about 1400μ in radius, makes it possible for the chain reaction to start and produce large drops even with relatively low values of liquid water content. This fact undoubtedly accounts for the occurrence of large water droplets in relatively small turbulent clouds under tropical conditions, or in the cloud that I observed in May, 1944.

From the foregoing analysis, it becomes clear that the conditions necessary to set up chain reactions in such clouds as those studied by L-H are very critical. If the vertical velocities, the liquid water content w, or the cloud droplet sizes r, are not sufficiently large, no chain reaction will occur even though there may be a multiplication of any water introduced into a cloud sufficient in some cases to produce transient virga.

The final report of L-H which was sent me about December 1 contains also records of experiments made during November. Out of a total of about 45 seeded clouds, 11 gave rain which reached the ground between 8 and 12 minutes after seeding. A few others gave merely virga. There were three cases where relatively heavy precipitation was obtained covering large areas. In general, the best results were obtained from the largest and most actively growing clouds.

The results, therefore, tend to support our conclusion that the chain reaction involved in rain production can develop only when there are high vertical velocities and the clouds have a high liquid water content.

Calculations have also been made for the type of cloud referred to in the statement by Holzman and Crowson in regard to tropical clouds in Bikini. Such clouds should contain a liquid water content corresponding to ω = 0.2 to 0.3 cm which would require vertical velocities of 6 m/sec or more to give a chain reaction.

In large, summer cumulus clouds, such as those seeded during July and August by Project CIRRUS, ω may have risen to values of 3.0 cm or even more. With a value of w = 6 g/m^3, it is no wonder that in these clouds chain reactions can occur which bring down such heavy rain.

On the other hand, during the winter, the cloud droplets are smaller, the liquid water content lower, and the vertical velocities in cumulus clouds are lower. In general, therefore, under such conditions, it would not be possible to set up or maintain a chain reaction of the type we have been considering.

In stratus clouds the vertical velocities are very low. In the case of convergent air masses, these stratus clouds would be lifted gradually and heavy rain and snow may result. But in general, these vertical velocities are not over 50 centimeters per second over any large areas. In such clouds, the air does not enter the base of the cloud, but the cloud as a whole rises with perhaps new layers forming under the parts that have risen. The distribution and water concentration within the cloud thus depends mainly on the air masses from which the cloud has been derived and cannot, in general, be calculated from the saturated adiabatic curve.

XI. TYPES OF RAIN AND SNOW IN RELATION TO SPONTANEOUS AND TO ARTIFICIAL SEEDING

A. Stratus Clouds. In clouds of this type, drizzle or moderate rain may fall, presumably due to the gradual coalescence of small droplets to larger drops which subsequently grow in accord with the data contained in Tables VI and VII. These drops ordinarily do not grow to sizes sufficiently large to enable them to break up. For this reason and because of the low vertical velocity, there will be no chain reaction. In most types of heavy rain from stratus clouds, the process is accelerated by the presence of snow crystals in an upper layer which melt into drops of moderate size and increase greatly in diameter during their fall through the lower part of the cloud. In order that rain of this kind can be maintained, there must be a continuous supply of ice nuclei. In most cases, with heavy rain, it is probable that the nuclei are produced by a kind of chain reaction in the upper layers by the fragmentation of snow crystals.

The theory of droplet growth that has been presented in this paper has been based on a knowledge of the collection efficiency E derived on the assumption that the falling drop is of large size compared to the cloud droplets.

It is necessary to develop the theory in quite a different way where we have to consider the growth of small droplets within clouds consisting of fairly uniform droplets of 10 to 20μ radius. The collection efficiency in this case is difficult to calculate. We have, however, been making experiments with glass spheres of various sizes falling through very viscous liquids so that the spheres fall at a velocity of 0.5 cm/sec corresponding to Reynold's numbers very much less than unity. The observations have shown that between equal spheres there are appreciable attractive forces when the distance between them is small compared to their diameter. Thus when the particles come into contact, they remain in contact. When the spheres differ slightly in size, we have apparently obtained contacts that indicate roughly a collection efficiency E of about 0.2. However, much more careful experiments need to be made to determine the variation of E with the sizes of the spheres.

A preliminary theoretical study has indicated that the stability of such clouds depends largely upon a dimensionless quantity

$$P = AEwt/\rho_S, \tag{39}$$

where

$$A = (3/4)dU/dS, \tag{40}$$

and t is the time since the cloud of rather uniform droplets was formed by condensation. Over wide range values of S, A is approximately constant and equal to 6000 sec^{-1}. When P, as defined above, is small compared to unity no rain should fall, but when P becomes comparable to or greater than unity, we may expect a new type of chain reaction, with conditions of instability that lead to a continual production of larger droplets which will subsequently grow in accord with the theory that we have already developed as given in Tables VI and VII. At present, we have practically no knowledge of E. Presumably it varies with the droplet size. In view of the observed relative stability of most stratus clouds, it is seen that the effective value of E must be relatively small; very much less than unity. We hope by the experiments in progress to get some idea of the values of E and in this way, see whether we can develop a better theory of the growth of rain from stratus clouds.

B. Cumulus Clouds. The theory that we have outlined for the development of a chain reaction in cumulus clouds has been based upon assumptions in regard to the structure of these clouds <u>before any rain has occurred</u>. As soon as a chain reaction does set in, profound modifications in the cloud will occur. In the first place, the rain drops by their weight will tend to set up local down-drafts causing covergence in the upper layers and divergence below. The convergence above tends to draw the rain into these down-drafts and thus accelerate the development of a cell structure within the cloud. In general, there will be corresponding increases in the up-drafts in the other parts of the cloud. The down-drafts undoubtedly are largely responsible for the very short time that elapses before the rain reaches the ground after a large cumulus cloud is seeded at a height of 25,000 feet or more. Even in the smaller cumulus clouds of the L-H experiments, down-drafts must have contributed very greatly to neutralize the up-drafts which were general before seeding and finally to produce local down-drafts that helped to carry the rain rapidly to the ground.

C. Artificial Seeding of Clouds. Dry ice seeding of supercooled clouds produce effects that travel rapidly throughout the supercooled part of the cloud. Heat is generated by the freezing of the water droplets and the freezing out of additional water vapor so that the temperature is raised roughly 1°C. This produces turbulence which causes rapid spreading of the ice nuclei throughout the supercooled cloud.

The chain reaction in the production of rain can, under the right conditions, evidently be started by introducing even a single water drop into a cloud. The action should be most rapid when many large drops are introduced near the top of the cloud. For this purpose, it may be desirable to release the water from an airplane by use of a nozzle which directs the water backward with a velocity about equal to the forward motion of the plane, so that the drops are not broken up by coming into contact with the rapidly moving air. Another more convenient method may be to do the seeding by dropping pellets of ordinary ice which in melting in contact with the air will give water drops of fairly large size, distributed through a large height within the cloud. It may be that in this way hail, in a thunderstorm, greatly accelerates the development of the chain reaction in newly rising air masses in the lower part of the cloud.

XII. SELF-PROPAGATING STORMS

It has already been mentioned that when large cumulus clouds with supercooled portions are seeded with dry ice, effects of one of two kinds are observed. The cloud may either rain itself out and soon dissipate or it may rapidly increase in height and intensity and continue more or less indefinitely as a heavy rain storm. Which of these two occurs presumably depends upon the available moisture and stability of the surrounding atmosphere rather than on the conditions within the cloud. We must remember that when dry ice causes water droplets in a large cloud to freeze, it causes a liberation of heat amounting to about 1°C. It is thus possible, in some cases, that this added heat may set up an air circulation around the cloud which draws in new supplies of moisture faster than the rain is precipitated. Such effects when they occur may produce relatively widespread weather modifications.

In clouds that have no portions below freezing, the setting up of a chain reaction by artificial seeding may remove so much water from the cloud that it lowers the weight of the cloud enough to increase the up-drafts, and thus to draw in large masses of new air. Consider, for example, a cloud containing 3 g/m^3 of liquid water. If this is removed by precipitation, the density is lowered by 0.3 per cent and this is equivalent to the lowering of density produced by a rise in temperature of 1°C. It would thus appear, under favorable conditions, that water seeding in a cloud above freezing temperatures may cause a self-propagating rain storm to develop. There is good reason to think that the L-H experiment of September 23 was a case of just this kind, but none of the other 45 experments gave a storm that propagated for any large length of time.

A change of density in a cloud mass corresponding to 1°C gives to the air an acceleration of g/300 or about 3 cm/sec^2. For a short time, the air starts to move with this acceleration so that a velocity of 300 cm/sec may be attained within 100 seconds. However, the neighboring air masses are also involved in this motion and energy soon begins to be dissipated through turbulence. The velocities set up by changes of density resulting from seeding can be roughly estimated by taking an effective acceleration equal to one-half that corresponding to the change in density. When a cloud or air mass is thus accelerated, the maximum velocity reached will be the smaller of the two quantities:

$$V = (1/2)g(\Delta\rho/\rho)t \qquad (41)$$

or

$$V = \sqrt{g(\Delta\rho/\rho)Z} \qquad (42)$$

where Z is the vertical or horizontal dimension of the convection cell, whichever is smaller.

Thus with a seeded cloud height of 1000 m, a 1° temperature rise gives a velocity which increases about 15 cm/sec every second, but this velocity will not increase beyond a limiting value of about 550 cm/sec. It will take about 300 seconds to attain this maximum velocity. After that, the energy will be dissipated by turbulence. These effects are much larger than are expected by many meteorologists, but they seem to be in full accord with the results given by seeding experiments.

A. Spontaneous Seeding of Clouds. The phenomena that occur in the artificial seeding with dry ice or with water are essentially no different from those that occur spontaneously in nature. However, there will frequently be cases where the cloud is not yet ready or ripe for spontaneous development of snow or rain, although it may be possible to produce these effects by seeding. Evidently, a great deal of detailed research will be needed to understand thoroughly the conditions under which the best results may be obtained by artificial seeding.

XIII. WIDESPREAD WEATHER EFFECTS THAT START FROM SMALL BEGINNINGS

When we realize that it is possible to produce self-propagating rain or snow storms by artificial nucleation and that similar effects can be produced spontaneously by chain reactions that begin at particular but unpredictable times and places, it becomes apparent that important changes in the whole weather map can be brought about by events which are not at present being considered by meteorologists. I think we must recognize that it will probably forever be impossible to forecast with any great accuracy weather phenomena that may have beginnings in such spontaneously generated chain reactions.

A NEW PLANE MODEL CLOUD METER

by

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During the past several months, we have attempted to develop the G. E. Cloud Meter for use in detailed analysis of variations in liquid-water content within a cloud. The method of measuring and recording this data (described in the First Quarterly Report) utilizes an electrical counter circuit, whereby completion of the circuit depends upon the growth of a drop of water between a set of fixed contacts. The growth of the droplet to a size sufficient to operate the counter circuit may take several seconds depending upon the amount of liquid water (L_w) being measured. Thus only a few "counts" may be made in, say one minute, which means that we can only detect changes in L_w on the basis of a one minute average. (With very low values of L_w, a two minute average may be necessary.)

In actual flights through clouds, it was realized that the counter system of recording might not give the detail needed in determining small variations in liquid-water content. We, therefore, decided to try another method which had been considered previously but not used.

This method uses the porous plug collector which is connected through a sealed system to a small, vertical capillary tube. The tube is about 20 cm long with the lower end of it rounded smooth. The tube is filled with water previous to exposure, and this head of water applies a suction to the collecting surface of the porous plug. Any cloud droplet arriving at the surface of the collector will then be immediately drawn into the capillary. This excess of water in the system causes water to flow from the rounded end of the vertical tube in proportion to the amount of water being collected on the porous plug.

A moving tape of paper having shallow, close-spaced parallel creases (at 90^o to the direction in which the tape is moving) is kept in slight contact with the rounded end of the capillary tube. Any water that comes out of the end of this tube will be absorbed into the paper and will spread by the capillary action of the creases (and that of the fibers of the paper) in proportion to the amount of water delivered. The material in the paper will, of course, be a factor in the amount and rate of absorption.

If the moving paper tape is treated with a water soluble dye powder, the spread of the water on the paper will leave a continuous stain of varying width being wide for high liquid-water collection and narrow for low liquid-water collection.

This was tried with several grades of paper as well as with different methods of creasing. Some of them worked in the manner we had hoped, but not too well. It was then thought that cloth might provide better capillarity for the spreading of the water stain. When a piece of cotton cloth was tried, immediate improvement was noted in results. This finally led to the use of Fiberglas Tape (glass cloth) and up to the present, this produces the best results.

The glass cloth tape comes in 50 yard rolls, 1 inch wide and .003 inch or .005 inch thick. The .003 inch grade seems to work best since it has a little finer structure due to the smaller diameter of fiber used in weaving the cloth. We have found that methylene blue dye powder worked into the cloth tape acts very well in making the water deposit visible since it provides good contrast between the stained and unstained portions of the glass tape.

An apparatus was built to apply the dye powder to the tape. It is shown in Fig. 1 and consists merely of two pulleys, one for holding a fresh roll of untreated tape, and the other, a motor driven pulley, onto which this tape is wound. Between the two pulleys, the tape is made to drag across a piece of black felt cloth which is heavily impregnated with methylene blue powder. In this way, the blue dye is picked up on the tape. A polished pressure plate is used to keep the tape in frictional contact with the impregnated felt. The difficulty with this arrangement is that the dye is too quickly used up requiring that the felt be replenished frequently. However, this method works well enough for the present. A more efficient system can be devised later. It has been found desirable to treat the tape until it is darkened somewhat by the blue powder. This gives better contrast than if too little powder is applied. If there is danger that the tape may be greasy or dirty, it may be cleaned by running it through a bath of ethylene dichloride previous to the dye treatment.

Figs. 2 and 3 show an experimental model of an instrument using the glass cloth tape as a means of recording minute variations in liquid-water content, In Fig. 2, point A indicates the opening in the lower end of the capillary tube. At this particular time, it was thought there might be some advantage in making the orifice of the capillary tube flush with the rounded surface of a rider bar so that the tape could be kept pulled smoothly and tightly against it. When the cover is on, point A is in contact with the

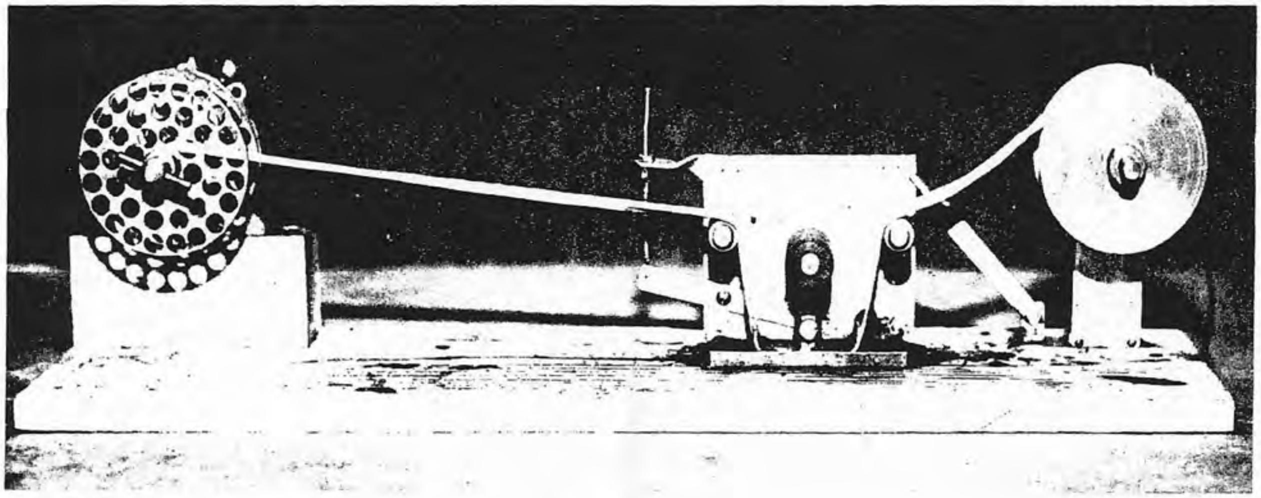

Fig. 1

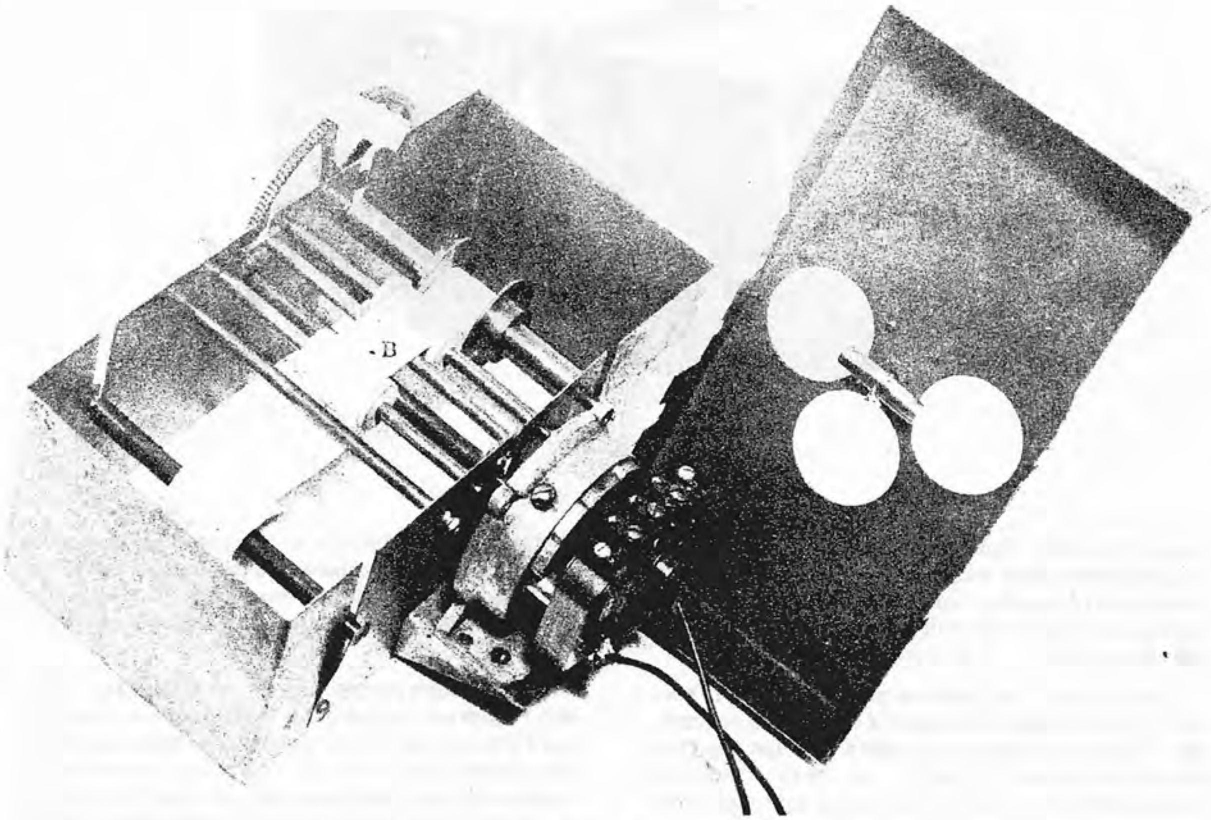

Fig. 2

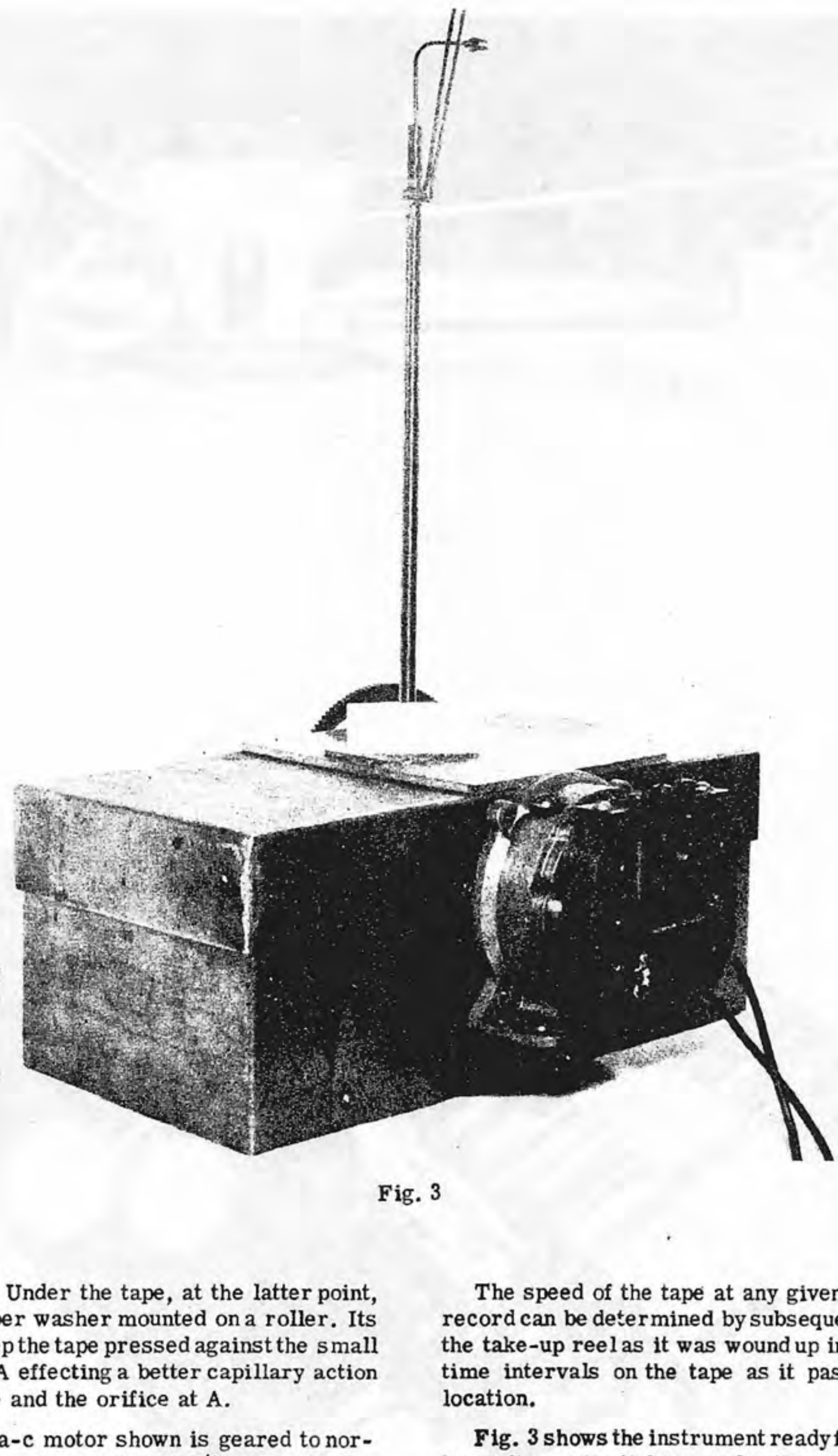

Fig. 3

tape at point B. Under the tape, at the latter point, is a narrow rubber washer mounted on a roller. Its function is to keep the tape pressed against the small opening at point A effecting a better capillary action between the tape and the orifice at A.

The 115-volt a-c motor shown is geared to normally run the tape at a speed of 4 1/2 inch per minute. This speed holds only when the tape has first started on the take-up pulley. As the tape winds up, the effective diameter of the pulley increases, and consequently, the tape speed also continues to increase.

The speed of the tape at any given portion of the record can be determined by subsequently operating the take-up reel as it was wound up in test-marking time intervals on the tape as it passes a specific location.

Fig. 3 shows the instrument ready for a test. The two "fingers" sticking up by the porous collector head are merely to prevent it from twisting around in a strong blast of wind. The collector and the attached vertical capillary tube are free to move up and down inside a slightly larger tube which serves as a more substantial support. The porous collec-

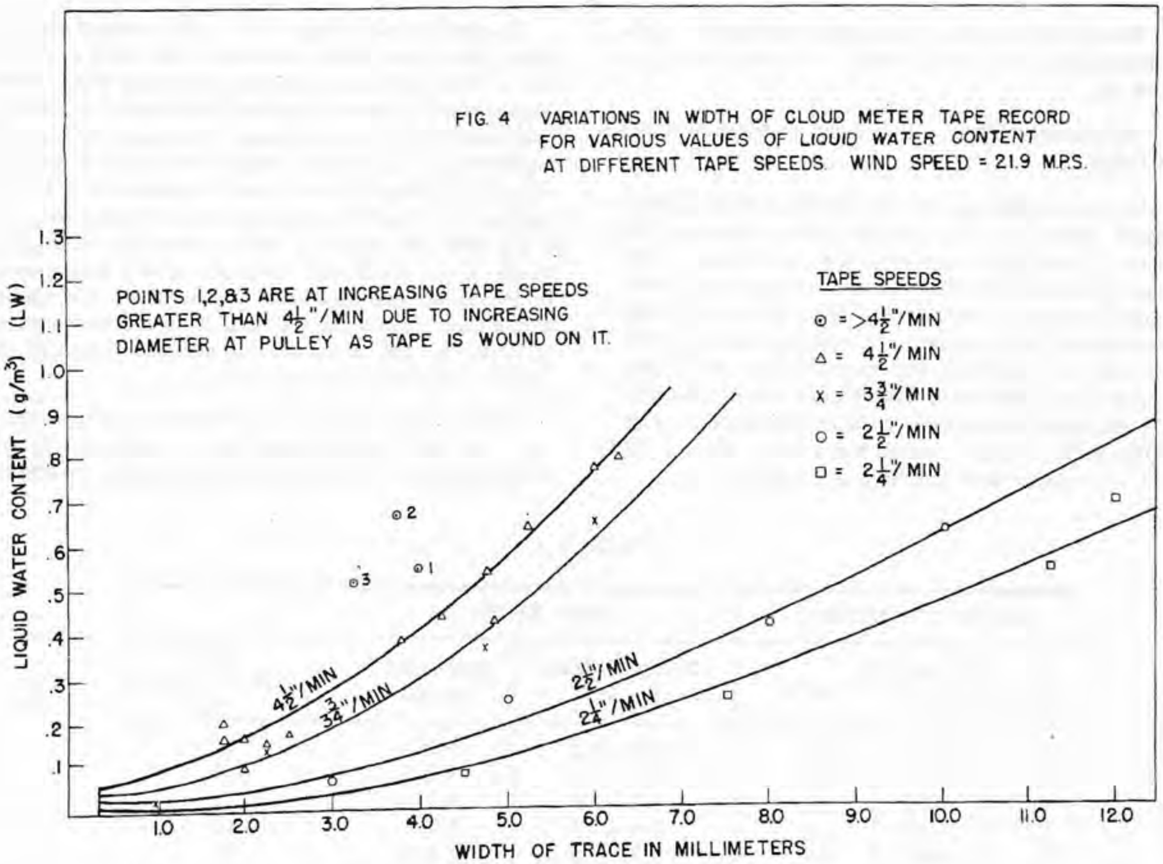

FIG. 4 VARIATIONS IN WIDTH OF CLOUD METER TAPE RECORD FOR VARIOUS VALUES OF LIQUID WATER CONTENT AT DIFFERENT TAPE SPEEDS. WIND SPEED = 21.9 M.P.S.

tor is of the same dimension used in the previously mentioned counting recorder and has an exposed collection area of .159 cm^2.

The instrument was tested in a small wind tunnel in the laboratory and while great accuracy is not claimed, results obtained are believed to indicate that this particular type of recorder will show more clearly variations in liquid-water content, especially over short time intervals. The velocity of the air in the tunnel is provided by means of a 90 lb per square inch air jet. Moisture is provided by introducing a fine water spray into this air stream.

The values of L_w obtained with the recorder are based on comparisons with the amount of L_w collected simultaneously on a small porous cylinder. The cylinder is made of "alumina" and has a diameter of .198 cm. *The cylinder was held in the moist air stream in the tunnel adjacent to the porous plug collector so that both were exposed for the same period of time. The test section of the tunnel in which the two collectors were held was not enclosed; therefore, some L_w content of the air stream was lost through evaporation into the warm air of the room. However, the relative values obtained are thought to be reasonably accurate. The only difficulty in the test arrangement is the impossibility of obtaining higher L_w values, especially at high wind velocities.

Data obtained from several test runs are shown in Table I. In determining the liquid water content of the cloud produced in the wind tunnel using the small porous "alumina" collector, the formula $E_m L_w = \frac{10^4 (W_1 - W_0)}{V_m St (D_{av})}$ was used. Here W_0 = weight of the collector in grams before exposure; W_1 = weight of collector in grams after exposure; V_m = air velocity in meters/sec; S = length of the collector; t = length of time the collector was exposed to the air stream; and (D_{av}) = the average diameter of the collector. E_m, the efficiency of the collector was taken as 100 per cent for preliminary consideration, but actually, it is close to 91 per cent under conditions of the test tunnel.

*See Demountable Rotating Multicylinders for Measuring Liquid Water Content and Particle Size of Clouds in Above and Below Freezing Temperatures, V. J. Schaefer, Contract No. W-33-038-AC-9151, October, 1945. Also, Final Report on Icing Research, V. J. Schaefer, Contract No. W-33-038-AC-9151, August, 1946.

The following values remained constant throughout the tests: V_m = 21.9 mps, t = 60 sec, and D_{av} = .198 cm.

The curves in Fig. 4 are a plot of the data given in Table I.

The instrument, as set up, did not have a variable speed motor, but by varying the voltage with a Variac, some adjustment of speed was obtained. The tape speed for different Variac settings was determined by actually measuring the distance the tape travelled during a minute. In making a comparative run, the recorder tape was started anew on the take up pulley for each test. This was to avoid the difficulty of speed change due to the increasing diameter of the pulley. Tape speed was varied from 2 1/4 inch per minute to 4 1/2 inch per minute.

It appears that the speed of 4 1/2 inch per minute gives about the right variations in width of trace for a wind speed of approximately 22 mps. For higher winds faster speeds will be desirable. especially with high L_w contents. The values of L_w encountered in the tests ranged from .16 g/m^3 to .79 g/m^3. These values were represented by trace widths of 1.5 to 6.5 millimeters at a tape speed of 4 1/2 inch per minute. For a given L_w value, the width of the trace will increase as the tape speed is decreased and vice versa. Therefore, the speed of the tape must be kept constant or at a known rate in order to get accurate L_w values. Samples of typical traces are shown in Fig. 5.

Preliminary tests of this recorder look promising. As soon as, it is possible to make runs from an airplane in clouds where temperatures are above

TABLE I

ALUMINA CYLINDER			TAPE RECORD		
S (cm)	W_1-W_0 (gms)	$E_m L_w$	Width of Trace (m.m.)	Tape Speed (in./min)	Tunnel Spray Pressure (lb)
4.5	.1100	.94	5.5 - 6.0	4 3/8	15
4.5	.0630	.53	4.5 - 5.0	4 3/8	10
4.5	.0206	.17	2.0 - 3.0	4 3/8	5
4.5	.0742	.63	5.0 - 5.5	4 3/8	15
4.5	.0500	.43	4.0 - 4.5	4 3/8	10
4.5	.0192	.16	1.5 - 2.0	4 3/8	5
4.5	.0734	.63	6.0 - 7.0	4 3/8	15
4.5	.0632	.54	4.0 -	<4 3/8	15
3.5	.0600	.66	3.5 - 4.0	<4 3/8	15
3.5	.0468	.51	3.0 - 3.5	<4 3/8	10
3.0	.0158	.20	1.5 - 2.0	<4 1/2	5
3.0	.0606	.78	5.0 -	<4 1/2	15
Tape started new for each of following readings					
3.0	.0618	.79	6.0 - 6.5	4 1/2	15
3.0	.0326	.42	4.5 - 5.0	4 1/2	10
3.0	.0126	.16	2.0 -	4 1/2	5
3.0	.0591	.76	6.0 -	4 1/2	15
3.0	.0300	.38	3.5 - 4.0	4 1/2	10
3.0	.0067	.09	2.0	4 1/2	5
3.0	.0122	.15	2.0 - 2.5	4 1/2	5
3.0	.0538	.69	12.0 -	2 1/4	15
3.0	.0427	.54	11.0 - 11.5	2 1/4	10
3.0	.0060	.08	4.5 -	2 1/4	5
3.0	.0196	.25	7.5 -	2 1/4	7 1/2
3.0	.0484	.62	10.0 -	2 1/2	15
3.0	.0319	.41	8.0 -	2 1/2	10
3.0	.0186	.24	5.0 -	3	7 1/2
3.0	.0044	.06	3.0 -	3	5
3.0	.0500	.64	6.0 -	3 3/4	15
3.0	.0282	.36	4.5 - 5.0	3 3/4	10
3.0	.0130	.14	2.0 - 2.5	3 3/4	7 1/2
2.9	.0014	.02	1.0 (blots)	3 3/4	5

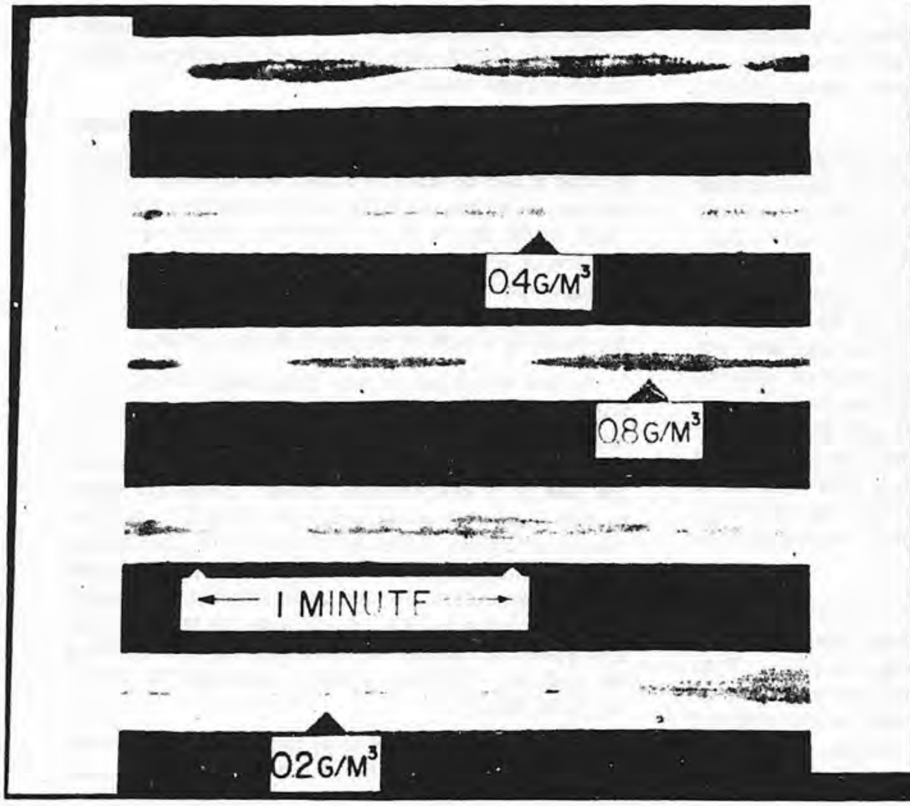

FIG. 5

SAMPLES OF TAPE RECORD OBTAINED WITH THE NEW PLANE MODEL CLOUD METER.

freezing, the practical value of the instrument can be determined. The values of L_W indicated by the curves in Fig. 4 are not presumed to be absolute, but rather can be used to show the relative changes in L_W during a given period. The efficiency of the porous collector and the sizes of droplets encountered were not considered. Both would have considerable effect on the absolute L_W values. The tests were all made at one velocity, 21.9 mps because of the difficulities with evaporation at higher velocities. As soon as the wind tunnel can be set up to give higher values of L_W at high wind velocities, a great deal more necessary information can be obtained in the range of velocities encountered in an airplane.

After the above tests were made, it was decided that another recorder should be built which would be self-powered using a spring driven motor. With no dependency on electrical power source, such an instrument could be used for tests on the slopes of Mt. Washington or other locations where power is not conveniently available.

Consequently, an old spring-driven phonograpn motor was found and a recorder built around it as shown in Fig. 6. Certain changes and additions were incorporated in this model.

It was felt that some method of marking the tape speed would be necessary so an alarm clock mechanism was arranged to mark the tape at one minute intervals. To do this a cam was put on the shaft in place of the minute hand in such a way that it allowed a small hammer to fall on top oi the tape at each revolution of the cam. An inked pad was placed directly under the tape, and each minute as the hammer falls, it presses the tape against the inked pad thus making a small ink mark. The speed can then be determined by measuring the distance between marks. The clock, hammer, and inked pad can be seen to the right of the left-hand pully in Fig. 6.

It has been found that the rider bar and the narrow, rubber-roller arrangement shown at A and B, in Fig. 2, works better than merely rounding the end of the capillary tube and pressing the tape against it with a strip of spring bronze. This arrangement is shown pictorially in the center of Fig. 6. There is an arm with a vertical adjustment just to the left of the capillary tube which makes it possible to push the tape down and away from the end of the rider bar when the collector is not in a cloud. This prevents the tube from possible drainage and consequent loss of suction on the porous collector since capillary suction has a tendency to drain moisture from the collector tube.

The collector is mounted as shown, pointed into the wind. The collector is protected from possible damage during transportation by two metal shields which slide up past it.

The small horizontal cylinder shown in the upper right compartment of the recorder is used to prime the capillary tube system. The cylinder is filled with water, and a length of small diameter rubber hose is connected from it to the bottom of the capillary tube. By holding the cylinder higher than the porous collector, water, in seeking its own level, will be forced into the capillary system and out through the collector. This "reverse flush" primes the system making it ready for exposure and, at the same time, serves to flush away any dirt or other contaminating materials which may be picked up in flight through clouds. Care must be taken that there are no air bubbles in the tubing since this destroys the suction necessary to draw in the water from the collecting surfaces.

For installation in an airplane, it will, of course, be necessary to have the recorder inside and the porous collector outside (in the air stream). This requires that the collector and recorder be at some distance from one another. As long as the vertical distance between the collector and the bottom end of the capillary tube is kept the same, the horizontal section of the capillary lead can be extended considerably without altering the amount of suction applied to the porous collector.

The portable recorder shown in Fig. 6 has fittings in the capillary lead (just above the top of the box) so that it can be used in either of two ways. It can be used as shown, with the porous collector mounted right on the top of the recorder or a horizontal extension of capillary tubing can be put in one of the fittings and the porous collector connected onto the outer end of it thus allowing remote recording of L_W such as would be required in an airplane.

A new recorder is now being built which, it is hoped, has further improvements over the two models just described. The new model will have a choice of several constant tape speeds through the use of a synchronous motor. Constant speed is accomplished by allowing the tape to pass between two rollers (like a wringer) which are driven by the synchronous motor. A take-up pulley keeps the tape wound up, but due to its friction drive, only enough tension is put on the tape to keep it taut. The speed of the tape is controlled by the speed of the rollers. The motor speed is varied by changing gear ratios.

A telechron motor is to be used for automatically marking the time each minute in an arrangement

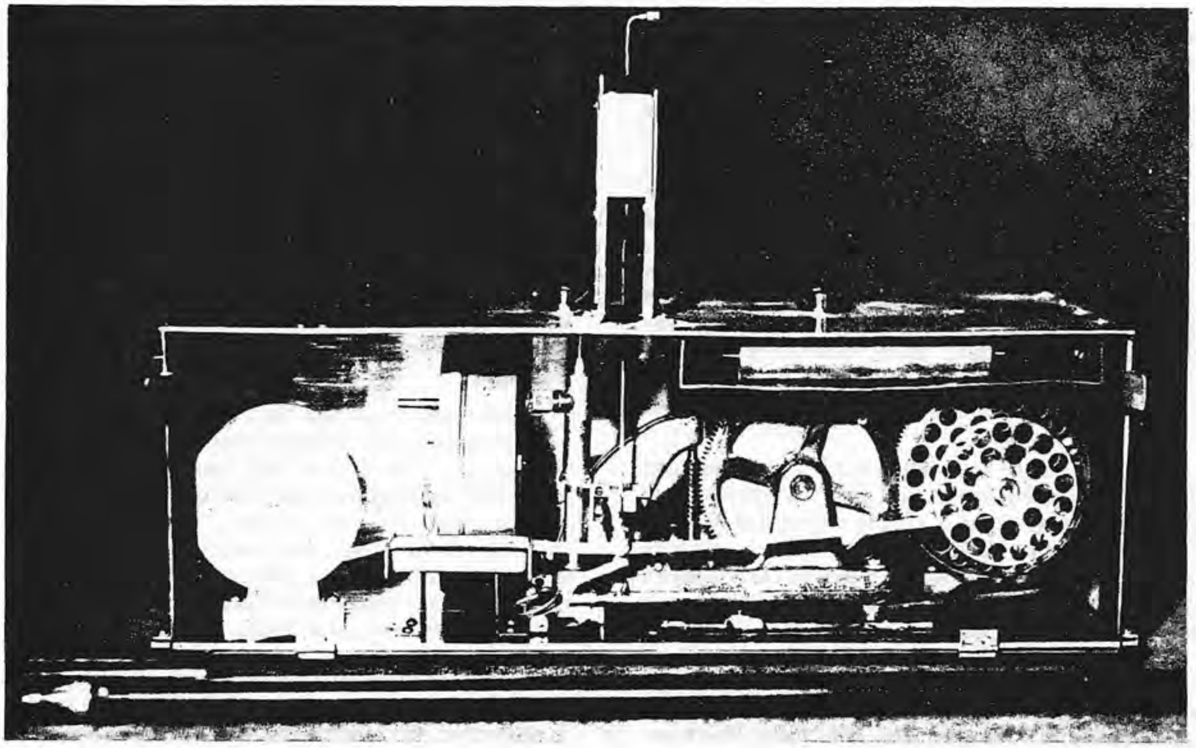

Fig. 6

similar to that used in the second model. In addition, provision will be made for manually marking the tape by means of a plunger arm extending up through the top of the box. The latter is for check purposes in case of operations on a power source that varies from 60 cycle alternating current.

It is also planned that a solenoid will be installed to lower the moving tape from contact with the lower end of the collector tube which may be operated by the meteorological observer. This will also actuate a signal light on the photo panel. Whenever the plane leaves a cloud, the tape will be depressed and when the cloud is entered, it will again be engaged. Besides providing an indication of cloud contact, it will also tend to keep the cloud-meter collecting head fully primed so that it should respond instantly to the liquid water content of the cloud.

Much of the design of these new units is due to the efforts of Mr. W. K. Kearsley of the staff of the G. E. Research Laboratory.

The new recorder should be ready for actual flight tests as soon as the season of above-freezing clouds arrives.

SOME EXPERIMENTS ON THE FREEZING OF WATER

by

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Although the supercooling of water is recognized as a very common occurrence, numerous reports have recently been published about it.

In our research we have found that the freezing of water without supercooling would be much more surprising, since we have so far been unable to find anything that will cause freezing at 0°C, except in contact with ice. Normally, water will not freeze until it is cooled to about -20°C.

Lately, Rau[1] claimed to have cooled water to -72°C before it froze. He accomplished this by means of a "system of successive sterilization of the nuclei of solidification." After the publication of this work, Bangham[2], Frank[3], and Ubbelohde[4] attempted to explain this phenomenon and also to predict certain properties of water in the low temperature range. Since then Cwilong[5] has tried to repeat Rau's experiment and has proven Rau's measurements to be invalid.

Another reported case of the low temperature freezing of water is stated by Oltramare[6]. He reported that R. Pictet and L. Dufour had cooled water to -40°C, but no paper by either Pictet or Dufour states this value.

Martin[7] cooled water to -26°C by repeated distillation in vacuo without ebullition.

The above experiments were carried out on water in bulk. On the other hand, Vincent J. Schaefer[8] found that a supercooled water droplet cloud dispersed in air, in the absence of sublimation nuclei, spontaneously changes to an ice crystal cloud when any portion of the cloud is cooled to -38.9°C or lower. A few ice crystals can be observed at a slightly higher temperature, but the above temperature may be regarded as being critical.

Bernard Vonnegut[9] found a number of foreign particles, most notably silver iodide, which cause the transformation from a water droplet cloud to an ice crystal cloud at considerably higher temperatures. He obtained varying results, depending not only on the material of which the particles were composed, but on their crystalline structure, size, etc.

Cwilong[10] has also made measurements of the sublimation temperature in the atmosphere and claims a value of -41.2°C for spontaneous ice crystal formation in pure air and about nine degrees warmer for impure air.

In Cwilong's experiment in a Wilson Cloud Chamber, the minimum temperatures reached were calculated and not measured. Furthermore, the presence of ice crystals were shown by their seeding action on a sample of supercooled water. In Schaefer's experiment, the temperature was measured directly and held constant, and the ice crystals observed visually and samples obtained. The validity of his results seems beyond criticism, and his temperature of -39.8°C should, therefore, be accepted as more exact.

Cwilong's assumption that ions act as sublimation nuclei has not received support from our experiments. In a forthcoming paper, Schaefer will describe a number of foreign-particle sublimation nuclei and their relative effectiveness at various temperatures.

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7. Martin, W. H. Trans. Roy. Soc. Canada, 111, (3), 7, 219-220, (1913).
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   b) Second Quarterly Progress Report (Project CIRRUS) Contract No. W-36-039-SC-32427, p. 6, (Nov. 15, 1947).
9. The Nucleation of Ice Formation by Silver Iodide. B. Vonnegut. Journal of Applied Physics, 18, pp. 593-595, (July, 1947).
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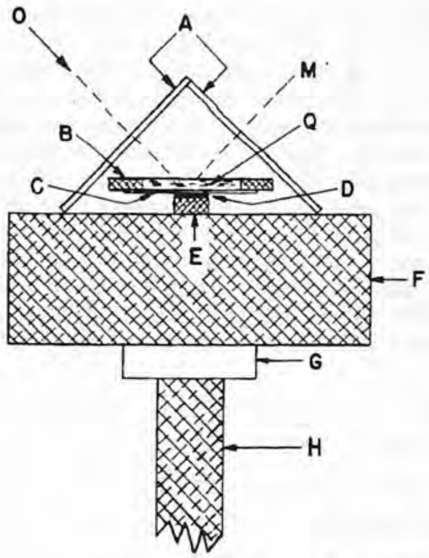


A TWO POLAROIDS IN SAME PLANE
B COPPER SAMPLE HOLDER
C KODAPAK MEMBRANE
D FLATTENED MERCURY DROPLET
E COPPER STUD
F COPPER COOLING BLOCK
G LANGMUIR DIFFUSION PUMP HEATER
H COPPER COLUMN IMMERSED IN COOLING BATH
O SOURCE OF DIFFUSE LIGHT
M OBSERVER
Q WATER SAMPLE

APPARATUS USED FOR FREEZING EXPERIMENTS WITH WATER

I. Langmuir[11] has conceived of a mechanism for the spontaneous nucleation of a supercooled cloud. His explanation is based on the existence of an air-water interface. According to the Langmuir hypothesis, it should be possible, therefore, to cool water out of contact with the air below the critical temperature found by Schaefer and in contact with air down to this temperature.

In an effort to test this hypothesis, the following freezing experiments were carried out which, although not yet complete, are significant.

The water sample to be frozen was supported on a Kodapak membrane (a certain type of cellulose acetate) stretched across a 3/4-inch hole in a 1/8-inch copper plate. Originally, it was planned to eliminate the air-water interface by laying another Kodapak film across the water surface, thereby completely enclosing it. The first experiments described below were done, however, without this cover, and the water sample was exposed to the air. The sample was then lowered onto a mercury covered copper stud about 1/4 inch in diameter and in thermal contact with a cooling system whose temperature could be accurately controlled. In this way, no air-solid interface, below 0°C, was in contact with the liquid. The presence of ice, clear or opaque, could be recognized by means of a polarized beam of light which passed through the sample, was reflected from the mercury surface, and reached the observer through another polarizer with its plane of polarization parallel to the first. The presence of ice caused birefringence which could be easily detected.

11. Contained in a paper not yet published.

Considerable work was done in devising techniques for satisfactorily cleaning the surfaces and purifying the water. It was found that loosely adhering dust on the fresh Kodapak surface could best be removed by simply rolling drops of distilled water across it. Examination under a microscope was used to make sure no dust or dirt remained. Various methods of purifying water were tried, among them distillation, condensation, diffusion through a formvar membrane, and pressure filtering.

Many freezing runs have shown the crystallization temperature to be independent of the rate of cooling, the previous history, such as previous freezing, and the temperature to which water has been raised to between freezing cycles.

Data from four sets of experiments give an average crystallization temperature of -19.2°C with a maximum of -18.0°C and a minimum of -20°C.

1. -19.0°, -18.0°
2. -19.5°, -20.5°
3. -20.0°, -19.2°
4. -18.0°, -20.0°

These results show that the supercooling of water is not at all an unusual phenomenon. The normal temperature at which water freezes is, therefore, in the absence of any known foreign nucleating materials, very close to -20°C, and not as is commonly believed at 0°C. It might also be mentioned that considerable vibration was present during all of the above tests, and it had no observable nucleating effect. Various means were employed to make sure that the exact temperature in the sample was known, and they indicated that the readings were reliable. One method was to check on the melting point of the ice when the temperature was rising, and another was to continuously bombard the sample surface with ice nuclei streaming from a tiny piece of dry ice held directly above it, and observing when freezing took place. This method of preventing supercooling was suggested by Vincent J. Schaefer.

A number of powdered materials were introduced to the sample in an attempt to make the water freeze at 0°C. So far, nothing has been found which can effect this. Some results follow:--

Recently LaMer and Yates at Columbia University[12] conducted experiments on the precipitation of sulfur from dilute solutions of sodium thiosulfate and H Cl. They found that ultra-sonic irradiation of the water of which the solutions were subsequently made caused a delay in detectable precipitation of approximately four times the normal. This technique was tried in our experiments, and we found that irradiating a sample in a methyl methacrylate container, at one megacycle for thirty seconds, had a pronounced effect on the crystallization temperature of the water. This water retained this property even after standing two months in a glass bottle.

Material	°C	Average °C
Aquadag	- 7.2, - 6.8, - 6.8	- 6.9
Silver Iodide	- 8.0, - 9.5, - 9.0, - 9.0	- 8.8
Graphite "280"	- 8.8, - 9.8, - 9.8, - 9.8	- 9.5
Zinc Sulfide	-11.0, -11.6, -12.2, -12.3	-11.5
Zinc Oxide	-13.0, -13.5	-13.3
Iodoform	-13.7, -13.7, -13.2	-13.5
Lead Sulfide	-11.8, -12.3, -14.3 -13.8, -15.3, -13.9	-13.9
Sulfur	-15.0, -14.8, -15.6	-15.1
Zinc Oxide (dri-Filmed)	-18.0, -17.0, -16.5	-17.1
Pepsin (surface)	-20.3, -16.5, -17.0	-17.9
AgI ppt. from acetone	-18.0	-18.0

There is one interesting conclusion to be drawn from the above observations. Graphite has been tried in many ways as a sublimation nuclei for ice, and is found to be practically without effect. However, as a freezing nucleus (in water), it seems to be even more efficient than silver iodide. This means that we must distinguish between "sublimation" nuclei and "freezing" nuclei and recognize that the mechanism of nucleation in each case is different.

The possibility immediately suggests itself that very often crystallization in bulk water may be started by a chance contact with a "sublimation" nuclei, rather than by a "freezing" nuclei already contained in the liquid. It also suggests the possibility of cooling water considerably below 0°C and keeping it there indefinitely when care is taken to eliminate the introduction of sublimation nuclei as well as freezing nuclei. Having pure water is not enough.

12. Influence of Ultra-sonic Radiation upon the Phase Transition in the formation of colloidal Sulfur. V. K. LaMer and J. W. Yates, Columbia University. Paper presented at National Academy of Sciences, Nov. 18, 1947.

Five measurements of crystallization temperature were made on this water, each measurement being made on a new surface using a new sample of water.

1. -38.5°C
2. -28.7°C
3. -28.5°C
4. -30.0°C
5. -29.0°C

All these measurements were made with the water sample in contact with air, and in each test, the temperature was checked by noting the melting point with rising temperature.

It was found that freezing took place in two different ways at low temperature. Often the water seemed to freeze with great rapidity from many locations to form an opaque, milky ice easily recognized by the naked eye. However, the freezing sometimes took place in an altogether different manner, and could only be observed through polaroids. In these cases, single, beautifully colored crystals could be seen to grow slowly out from widely separated nuclei. Sometimes only one crystal developed in a whole water sample.

SMOKE FROM SMELTING OPERATIONS AS A POSSIBLE SOURCE OF SILVER IODIDE NUCLEI

by

Raymond E. Falconer and Bernard Vonnegut

The fact that large numbers of nuclei for snow formation can be formed from small amounts of silver iodide(1) has suggested the possibility that large numbers of silver iodide nuclei may inadvertently be introduced into the atmosphere in the course of chemical operations involving silver or silver iodide.

The release of large numbers of silver iodide particles might be expected to have an effect on the weather by increasing precipitation from supercooled clouds.

The most likely sources of silver iodide nuclei are smelting operations carried out on ores containing appreciable quantities of silver. The best and most direct method of finding the number of nuclei produced by smelting operations is to make measurements on the nuclei content of these smokes where they are produced. However, this has not yet been feasible. Therefore, investigations have been limited to determine if meteorological records show evidence of effects that might be attributed to such nuclei and if it is reasonable to suppose that sufficient nuclei are produced to influence the weather.

Through the co-operation of Mr. C. Dodge of the Phelps Dodge Corporation in New York City, arrangements were made for a conference with Mr. W. H. Osborn, director of their research laboratory. At this conference, Mr. Osborn and members of his group furnished a list of smelting plants in the United States and their location in order that meteorological data might be checked in their vicinity for possible evidence of increased precipitation. Mr. Osborn outlined the various operations of smelting and the manner in which they were carried out and furnished data on typical smelting operations. The following information was obtained:

1. The stack losses of silver in smelting operations are small. These losses are determined by subtracting the sum of measured mechanical slag losses and silver yield from the silver content of the ore. In a typical report of operation, these losses varied from 0.33 per cent to 1.14 per cent in a typical report. Because of inaccuracies in analysis, these losses can sometimes be reported as a gain. The estimated silver loss for this country on the basis of one half of one per cent stack loss is of the order of a pound of silver per hour.

2. In order to reduce stack losses, bag house filters and Cottrell precipitators are generally used which greatly reduce the number of solid particles lost from the stacks. Bag house filters have been in general use as far back as 1880.

3. In order to insure the efficient operation of smoke filters, the stacks of a smelter are constantly watched for escaping smoke resulting from filter failure. No particular meteorological phenomena associated with these flue gases have been noticed, although phenomena of the sort that might be expected from nuclei might pass unnoticed by an untrained observer.

4. Iodine is not known to be present in the ores commonly smelted. That the occurrence of iodine in the mining region of Utah and Colorado is probably small is indicated by state measures which have been taken to supply iodine in salt to remedy a dietary deficiency of this element.

5. The flue gases resulting from smelting operations frequently contain as much as several per cent of sulphur dioxide.

If the silver lost in smelting operations were efficiently dispersed as particles of silver iodide, enough nuclei might be released to seed as much as ten to one hundred thousand cubic miles of atmosphere per hour with one particle per cubic inch.

For efficient production of nuclei, several conditions would have to be met. The particles of silver iodide would have to be of the order of 0.01 to 0.10 microns in diameter. Sufficient iodine would have to be available to form silver iodide with the silver. It seems unlikely on the basis of the evidence thus far that either of these conditions are met. In addition, sulphur dioxide and other impurities are present in such large amounts that it is possible no nuclei could form.

On the basis of the information available at present, it seems very doubtful that sufficient nuclei are released by smelters to have an appreciable effect on the weather.

(1) First Quarterly Report Meteorological Research. July, 1947.

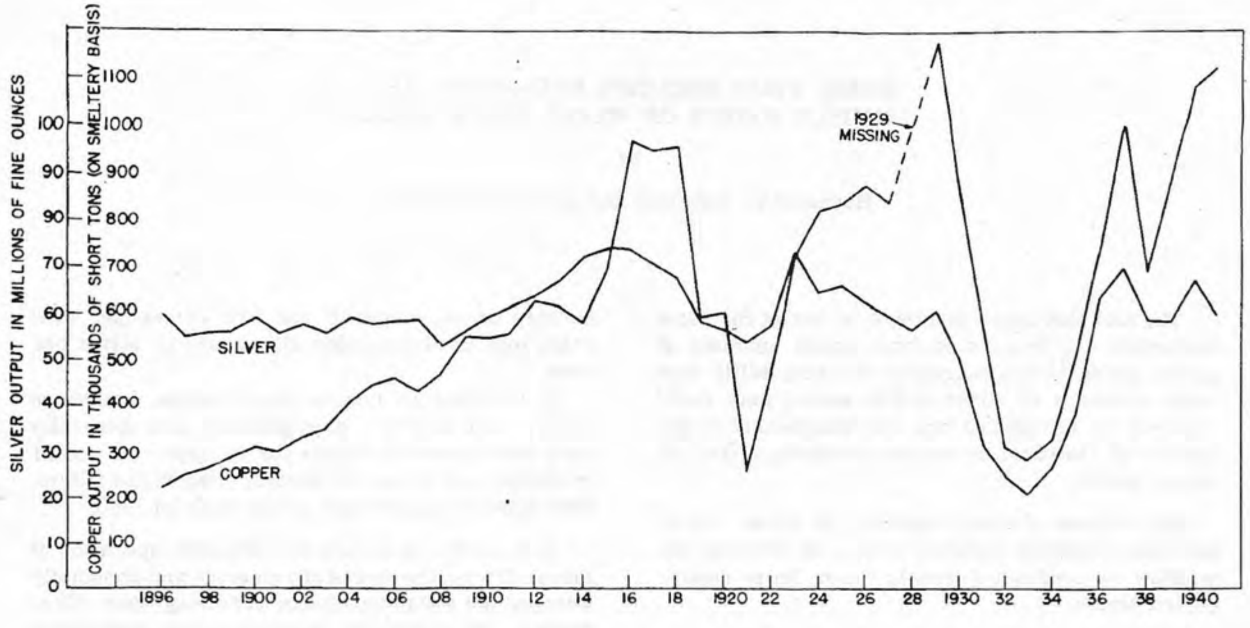


FIGURE 1.

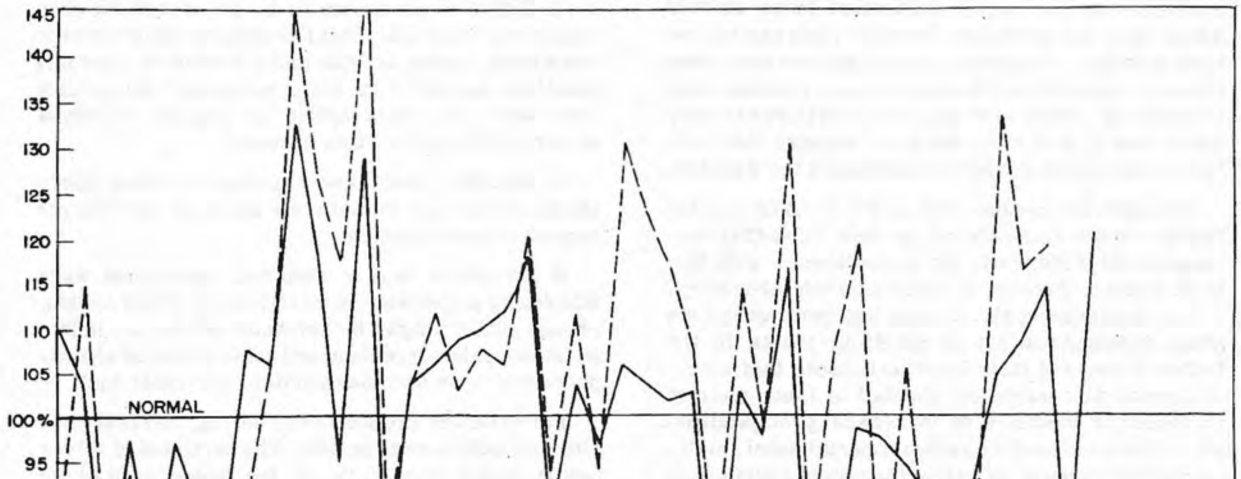


FIGURE-2 ANNUAL DEPARTURE FROM NORMAL PRECIPITATION

Meteorological records have been checked for possible evidence of the effects of silver iodide nuclei near smelters.

The state of Utah, particularly that section north and east of Great Salt Lake, has a large number of lead, copper, and silver smelters in operation so it was decided to investigate the precipitation record for the state and compare the annual precipitation amounts with the yearly output from the smelters. If there were any effects of silver iodide on the amount of precipitation, it should become evident by this comparison and would be indicated by above normal amounts of rain or snow during years of high smelter production and vice versa. In other words, the precipitation curves would follow the smelter output curves fairly well.

The map of Utah's annual precipitation distribution shows two areas of maximum rain and snow fall in two directions extending from the vicinity of the smelters – one area to the north and the other to the east. Each area is about 150 miles long and about 20 - 30 miles wide. The annual precipitation there is 20 inches or more. There are several smaller areas of similar amount scattered in a line across the state from NE to SW.

One might think at first glance that the presence of silver iodide in the atmosphere could account for the two heavy precipitation areas being just to leeward of the smelters. However, these areas also extend along the ridges of the mountains where greater precipitation normally occurs.

The curve of annual production of silver[2] in the United States (see Fig. 1) shows a steady output level from 1896 to 1908. There was then an increase in production up to a peak in 1916 followed by a decline to 1921. There was a sharp increase in 1922-23 and then another decline with a minimum in 1932 (the depression years). Another increase in production occurred from 1932-37 followed by a small decline in 1939 and then, in 1940, production was on the way up again.

The curve of copper production[3] shows a more or less steady increase from 1896 to 1914 with a sharp increase during the early World War I years, 1914-16. From 1916 to 1941, the curve follows closely that of silver production during the same period.

In Fig. 2 are plotted curves of annual departure from normal precipitation for the state of Utah and for all of the United States west of (and including) the Rocky Mountains.[4] Data is for the period 1896-1940. It will be seen that precipitation for the state of Utah closely follows that for the whole western third of the country.

The curve for the latter section shows a deficiency in precipitation from 1897 to 1904. Beginning in 1904, the tendency was toward above normal conditions up to 1916, followed by a very dry period from 1928 to 1935. The wettest year was 1906 while the driest was in 1924.

A study of Figures 1 and 2 shows that the copper and silver production curves do not particularly follow the annual precipitation curve for the western U. S. and since the precipitation curve for Utah follows that of the western U. S., it seems reasonable to conclude that there is no definite relation between the amount of precipitation in areas of smelter operation and the output from these smelters.

Complete data (1896-1940) was not found for precipitation at any individual station in the heavy precipitation areas east and north of Salt Lake City so that a more local comparison between smelter output and precipitation could not be made. However, the curve of annual departure from normal precipitation for Salt Lake City has been found to closely follow the curves in Fig. 1 and probably is representative of other localities near the smelter operations.

It seems safe to say then that there is no apparent large scale effect of smelter operation on the amount of precipitation. This is probably due to the precaution taken to filter the smokes during the smelting process. If any silver or silver iodide crystals do escape into the atmosphere, their effect on precipitation is probably negligible and not enough to be evident in meteorological records.

(2) a. Summarized Data of Silver Production, U. S. Department of Commerce, Bureau of Mines, Economic Paper 8.
b. Year Book of the American Bureau of Metal Statistics. 1941.

(3) Summarized Data of Copper Production. U. S. Department of Commerce, Bureau of Mines, Economic Paper 1.

(4) Climate and Man. U. S. Department of Agriculture, 1941.

PRODUCTION OF ICE CRYSTALS BY THE ADIABATIC EXPANSION OF GAS

In experiments on a supercooled cloud produced in a home freezer, V. J. Schaefer [1] showed that at temperatures of -38.9°C or lower water vapor spontaneously forms ice crystals in very large numbers. By the adiabatic expansion of air in a Wilson Cloud Chamber, B. M. Cwilong [2] found similarly that ice crystals were produced at temperatures below -35°C. Simple and interesting experiments can be performed by a combination of these two techniques.

A child's pop gun fired into a supercooled cloud in a cold chamber produces very large numbers of ice crystals. The adiabatic expansion of the air as it is released from the gun reduces its temperature to below -38.9°C with the consequent production of large numbers of ice crystals. If the cork is not put into the gun tightly enough, the temperatures produced are above -38.9°C and no ice crystals result.

In order to rule out the possibility that the loud noise from the pop gun might have caused nucleation, a mixture of potassium chlorate and sulfur was exploded in the supercooled cloud. Although the report was far louder than the pop gun, no ice crystals were observed.

A bottle of carbonated beverage having sufficient pressure produces large numbers of ice crystals when it is suddenly opened in a supercooled cloud. Bottles of carbonated drinks kept in the freezing compartment of a household refrigerator often become supercooled. Frequently, these bottles do not freeze until the cap is removed. If such a bottle is watched as the cap is removed, many ice crystals can be seen to form at the surface of the liquid and spread throughout the bottle. A miniature snow storm produced in the gas in the neck of the bottle starts the crystallization of the contents. It has been observed that a bottle of supercooled beverage can be caused to freeze by tapping the surface of the container. Such a tap undoubtedly causes adiabatic compression and expansion of any minute bubbles in the liquid which could momentarily reduce their temperature to below -38.9°C, thus starting the formation of ice crystals.

The vapor trails which sometimes stream off the propeller tips and wings of airplanes flying at low temperatures probably are similar to the foregoing phenomena. As the propeller or wing passes through the air, it causes adiabatic expansion of the air in certain regions. If the temperature of the atmosphere is sufficiently low, this expansion will momentarily reduce the temperature to a value at which ice crystals form spontaneously. If the atmosphere is supersaturated with respect to ice, these ice crystals will grow into a visible vapor trail.

The surprisingly large number of ice crystals produced by the rapid expansion of even a small quantity of air can be shown by bursting a small rubber balloon in a supercooled cloud. A balloon about 1.5 mm in diameter when burst in a supercooled cloud at -20°C produces at least $3 \text{ by } 10^7$ snow crystals or about $1.6 \text{ by } 10^{10}$ crystals per cc of expanded air.

Experiments under carefully controlled conditions are being conducted in this laboratory by V. J. Schaefer to determine quantitative relationships between the number of crystals produced and the temperature, pressure, volume, and humidity of the expanded air.

1. a) V. J. Schaefer. The Production of Ice Crystals in a Cloud of Supercooled Water Droplets. SCIENCE, 104, 457-459, (1946).

   b) V. J. Schaefer. The Production of Clouds Containing Supercooled Water Droplets or Ice Crystals under Laboratory Conditions. BULLETIN OF AMERICAN METEOROLIGICAL SOCIETY, 29, No. 4, 175-182, (April, 1948).

2. B. M. Cwilong. NATURE, 155, 361-362, (1945).

NUCLEATION OF SUPERCOOLED WATER CLOUDS BY SILVER IODIDE SMOKES

A. INTRODUCTION

About a year and a half ago, it was found that silver iodide smokes had the property of causing snowflakes to form in a supercooled cloud.(1) It is believed that silver iodide particles are good nuclei for ice formation because of the close resemblance of their crystal structure to that of ice. Experimentation has been underway to learn more about the production and behavior of these smokes. The work to be described in this account should be regarded as preliminary. The techniques and apparatus used in the work frequently leave much to be desired in the way of precision. The results are tentative and await confirmation by better experiments. This work, despite the uncertainties in it, nevertheless sheds light on the mechanism of nucleation and suggests new experiments and improved techniques for giving a more complete picture of the phenomena associated with nucleation by silver iodide.

B. APPARATUS AND TECHNIQUES FOR MEASUREMENTS ON SMOKES

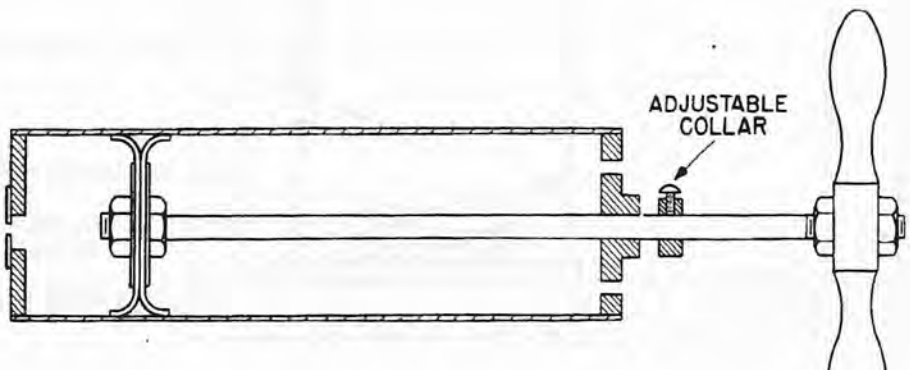
1. Wind Tunnel

In order to determine the output of a source of silver iodide smoke, it is necessary to secure a sample of smoke for testing that is a known fraction of the total output. This was accomplished by diluting the output of the smoke generator with a large known flow of air, and taking a known volume of this dilute smoke for testing. The smoke generator was placed in front of a quarter horsepower electric fan, three feet in diameter, which sucked the smoke along with a large volume of air into a crude wind tunnel four feet square in cross section and twenty-four feet long. The stirring action of the fan and the turbulence in the tunnel mixed the smoke with the air to produce a more dilute smoke which was discharged at the other end of the tunnel where samples were taken. When a heavy white oil smoke was introduced into the tunnel, it appeared to be quite uniformly mixed and diluted as it left the tunnel. The rate of flow in the tunnel, as determined by measuring the velocity with a vane-type anemometer, was 4 by 10^6 cm^3/sec.

Of the silver iodide smokes used, all except the ones having the largest particle size were completely invisible under the conditions of the experiment. The smokes having the largest particles were quite transparent and of a pale blue or purple appearance in the sunlight.

2. Smoke Sampling and Diluting Syringe

In many of the cases, only a fraction of a cubic centimeter of the smoke from the tunnel is needed for a test. Precipitation on the walls of a container of this size would be very rapid. Therefore, a syringe was constructed for taking a sample of the smoke and diluting it quantitatively to any desired amount. The syringe, (Fig. 1), consists of a metal tube three inches in diameter with a piston and leather washers which can be moved back and forth a fixed distance. A sample of smoke was taken with the syringe and then diluted to the desired concentration by moving the piston in and out the requisite number of times in smoke-free air, up-wind from the tunnel.



SMOKE SAMPLING AND DILUTING SYRINGE

FIG. 1

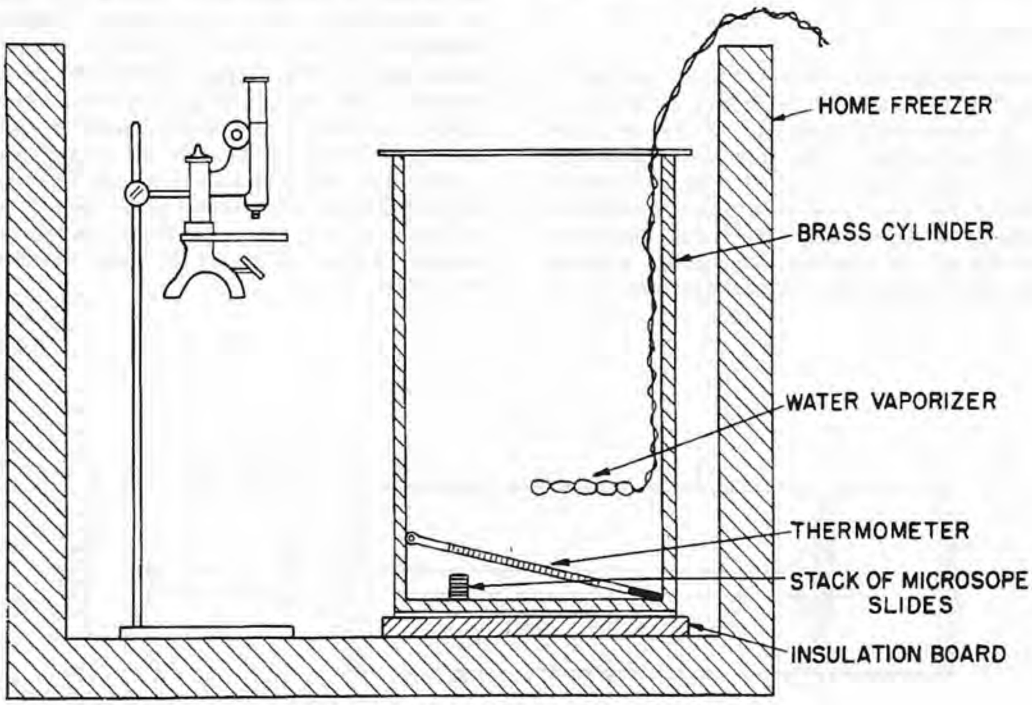
3. Cold Chamber

The early measurements on the number of nuclei contained in silver iodide smokes were made using Schaefer's technique.[2] A measured volume of smoke was introduced into a supercooled cloud in a home freezer, and the number of snow crystals produced per cubic centimeter was visually estimated.

This technique has been slightly modified in the more recent work and the apparatus used is shown in Fig. 2. The tests were carried out in a brass cylinder 15 inches high and 12 inches in diameter having walls 1/2-inch thick to provide good thermal conductivity.

The chamber, which was closed at the bottom, was maintained at a low temperature by placing it in a four cubic foot home freezer. The freezer thermostat was used to regulate the temperatures. A supercooled cloud was maintained in the refrigerated cylinder by evaporating water from wet paper toweling wound around a 15-watt electric heater placed in the lower part of the cylinder. A hinged masonite lid was used to close the top of the cylinder during tests. The temperature at the top of the cylinder was found to be about 2°C warmer than at the bottom. The minimum temperature obtainable in the chamber was -20°C. In future experiments, it is highly desirable that lower temperatures be obtainable and that provisions be made for better temperature regulation.

Smokes were tested by introducing them from the sampling syringe into the supercooled cloud in the cylinder. A stack of cold microscope slides was placed in the bottom of the cylinder. The snowflakes, produced by the action of the smoke, settled on the bottom of the cylinder and on the topmost microscope slide. At intervals, two minutes apart, the slide on which the snow had fallen was removed, thus exposing the slide beneath. The slide which was removed was then examined under a microscope kept in the freezer. By means of a Whipple eyepiece, the number of flakes collected per square millimeter in a two-minute period was counted. When the rate of snowfall had dropped to a low value, the total number of flakes which had fallen per square millimeter was determined by adding the numbers which had fallen in each two-minute sample. The total number of snow crystals which would have been produced by the entire output of the generator could then be calculated from the area of the bottom of the cylinder, the volume and dilution of the smoke introduced, and the volume rate of production of the smoke.



APPARATUS FOR COUNTING NUCLEI IN SMOKE

FIG. 2

4. Electron Microscope Examination of Smoke

Smokes being tested were examined with the electron microscope to determine their appearance and particle size. Samples of smoke were precipitated on a formvar film supported on a fine wire screen by moving it for about a minute in and out of the smoke stream about three feet from the generator. The smoke stream at this point is still quite warm. The sample screen, because it is in the smoke only a moment at a time, remains cool so thermal precipitation may play a part in the collection of the smoke.

Under these conditions of precipitation, it is quite likely that particles of a certain size may be selectively precipitated, so that the sample obtained is not entirely representative of the smoke. A more reliable method would be desirable so that more trustworthy data can be obtained.

The smoke samples were photographed using the electron microscope. Determinations of the particle size and the number of particles per cc of material were made from these photographs.

5. Smoke Generator

The smokes used in these tests were produced by a smoke generator constructed from a commercial compressed air atomizing nozzle of the sort used for paint spraying and humidifying (Binks No. 174). The generator is shown in Fig. 3. Compressed hydrogen gas at 20 pounds per square inch was applied instead of air to the air inlet of the nozzle and a solution of silver iodide was used as the liquid to be sprayed. The hydrogen stream as it left the nozzle was ignited. The heat of the flame vaporized the silver iodide in the spray into a gas which, upon mixing with the atmosphere, condensed into a smoke of small silver iodide particles. In order to prevent the hydrogen flame from being blown out by the wind, a flame holder consisting of a piece of 3/4-in. pipe two and one-half inches long was placed 1/2 inch from the spray nozzle. At a pressure of 20 pounds per square inch, the spray nozzle used about three cubic feet of hydrogen per minute (measured at atmospheric pressure).

6. Silver Iodide Solutions

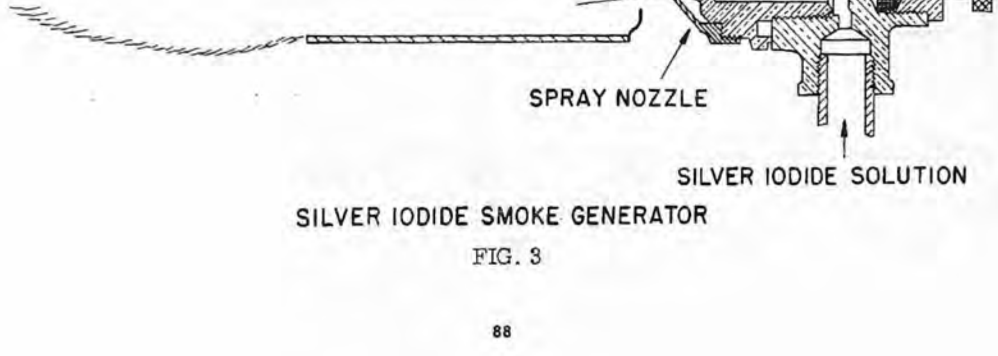
Although silver iodide is very insoluble in water and organic liquids, it is quite soluble in acetone or water solutions containing a soluble iodide such as sodium or ammonium iodide. The solutions used in this work were made by dissolving 200 gms of AgI and 100 gms of NH_4I in a mixture of 750 cc of acetone and 250 cc of water. A dilute solution was also used which was made by diluting the above solution to ten times its volume with acetone. Solutions can be diluted any desired amount with acetone; however, dilution with water causes precipitation of the silver iodide. Ammonium iodide was used in the solutions for these experiments because it probably is completely decomposed in the hydrogen flame, thus leaving a smoke of uncontaminated silver iodide.

The rate at which silver iodide was fed into the smoke generator was varied by controlling the rate of flow of solution by adjusting the valve on the nozzle and by using solutions of different concentrations.

C. EXPERIMENTAL RESULTS

1. Decrease in Rate of Snow Formation after Seeding

There was found to be a large difference in the behavior of the supercooled cloud when it was seeded



SILVER IODIDE SMOKE GENERATOR

FIG. 3

with the low temperature air produced by a pop gun and when it was seeded with silver iodide smoke. From Fig. 4 it can be seen that although many snow crystals were produced by the low temperature from the pop gun, all of these crystals had precipitated to the bottom of the container at the end of ten minutes. When the cloud was seeded with silver iodide smoke, however, a measurable number of ice crystals were still precipitating at the end of almost an hour. The rate of snowfall decreases to one half each two or three minutes. This rate of decrease was not found to vary significantly with temperature or with the particle size of the smoke although, as it will be seen, the total number of snow crystals varied over several factors of ten, depending on the temperature of the supercooled cloud.

2. Precipitation of Smoke in Syringe

One possible source of error in these experiments is that which might be caused by coagulation and precipitation of the smoke in the sampling syringe. In order to evaluate this rate of disappearance, tests were made in which small smoke samples were withdrawn from the syringe after it had been in the syringe for varying periods of time. The number of effective nuclei in a sample of smoke was found to decrease by one half every twenty minutes. The time required to take, dilute, and discharge a sample into the cold chamber was never more than a minute or two so that the changes in the smoke occurring during this time were not large.

3. Number of Ice Crystals per Gram of Silver Iodide

The results of experiments carried out with different settings of the smoke generator and in supercooled clouds at different temperatures is shown in Fig. 5. In this graph, the results are also given for the electron microscope examination. The number of particles of silver iodide per gram of silver iodide was computed by measuring the approximate mass of silver iodide on a given area of the sample and then counting the number of particles in the same area. The computation was based on the assumption that the density of the particles was the same as that of silver iodide crystals. Figure 6 shows electron photomicrographs of a typical smoke.

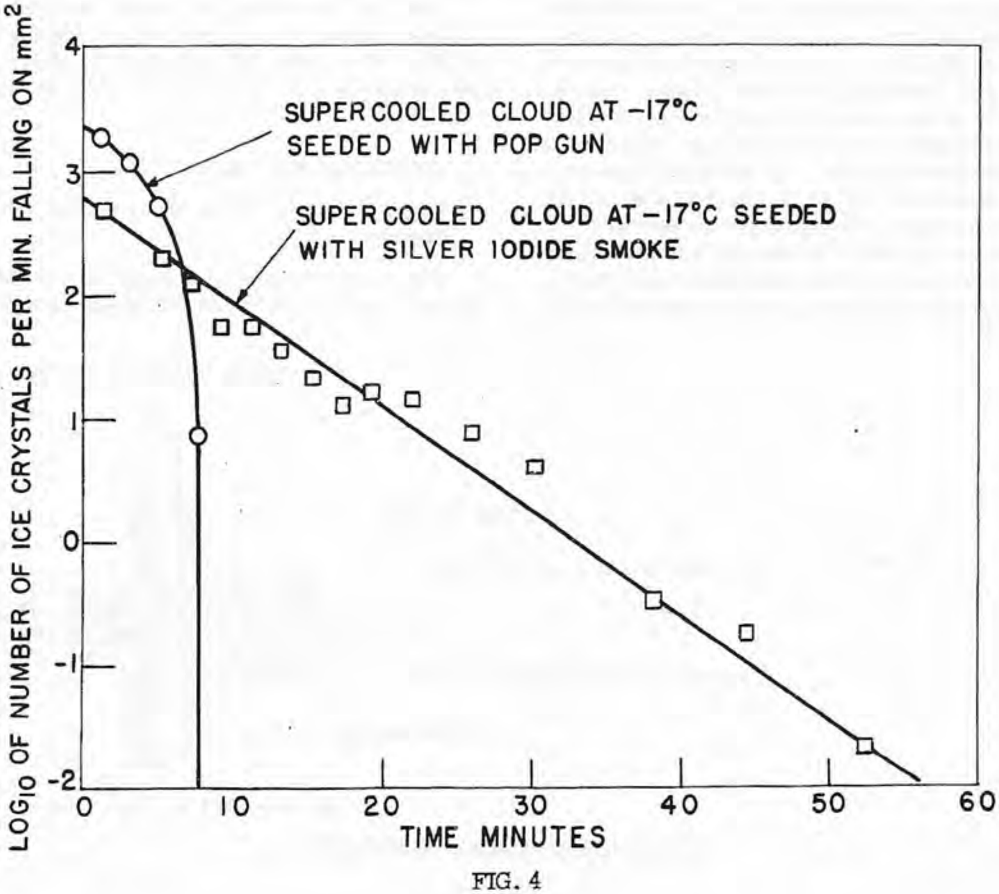


FIG. 4

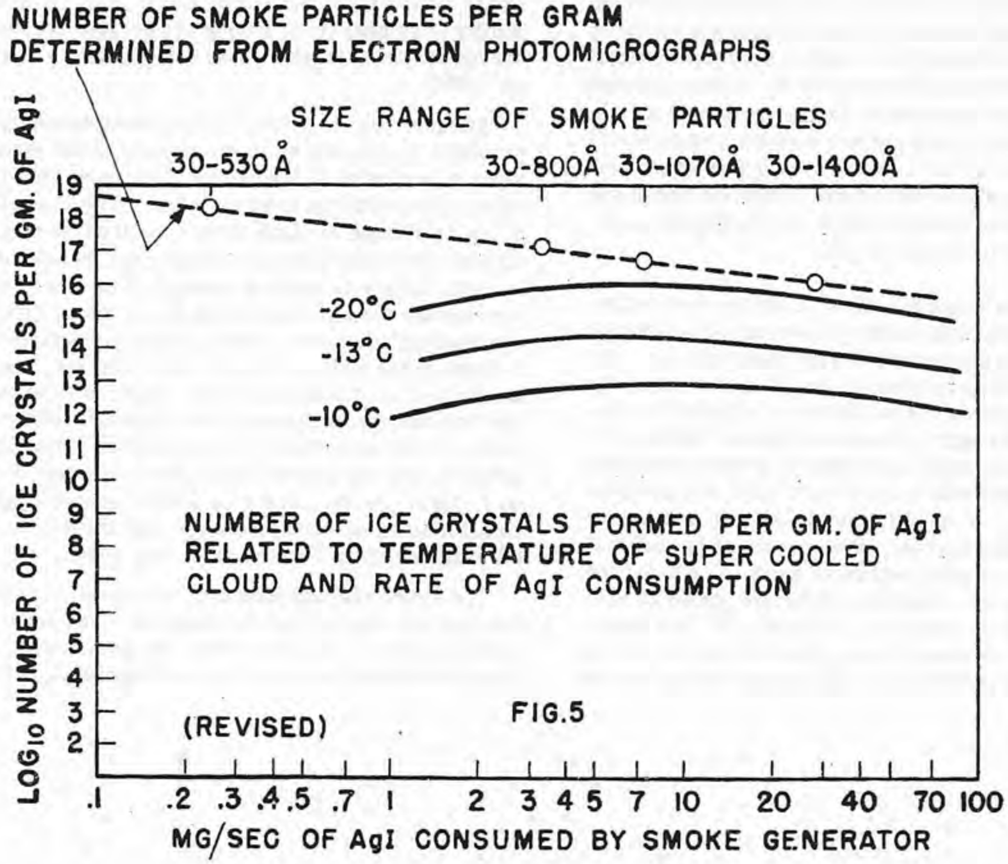


FIG.5

D. DISCUSSION OF RESULTS

The work thus far is not of sufficient scope to give straightforward answers to many questions which arise concerning the mechanism of silver iodide nucleation. It is the purpose of this discussion to venture some possible explanations for the experimental observations.

1. Formation of Ice Crystals

Figure 4, which shows the number of snow crystals precipitating per minute after seeding, illustrates a significant difference between the behavior of a cloud seeded with silver iodide and one seeded by a pop gun. Seeding with a pop gun or dry ice produces very large numbers of small ice crystals by cooling a small region of the cloud to a temperature at which spontaneous nucleation takes place. These ice crystals then mix with the cloud and grow at the expense of the supercooled water drops. From Fig. 4, it can be seen that although a large number of ice crystals is produced by the pop gun, all of these crystals have precipitated out at the end of ten minutes. Now if all of the silver iodide particles put into the cloud formed ice crystals at the time they were introduced, they, too, should have precipitated out at the end of ten minutes. However, at the end of almost an hour, ice crystals are still precipitating. This leads one to the conclusion that all of the silver iodide particles do not form ice crystals immediately and that even at the end of half an hour or more, appreciable numbers of silver iodide particles have not yet formed snow crystals and are still present in the cloud.

There are various possible explanations for the time required for silver iodide particles to initiate the formation of ice crystals in a supercooled cloud. One possibility is that in order for an ice crystal to form on a crystal of silver iodide, a certain critical number of water molecules must by chance arrange themselves on its surface in the structure of ice. According to this explanation, a silver iodide particle would not act as a nucleus until this event took place. The presence of a silver iodide surface might be regarded as merely greatly increasing the probability of the formation of ice.

If we take a simplified view of the theory of nucleation as advanced by Gibbs, in supercooled water or in a region supersaturated with respect to ice, the water molecules by chance, from time to time, arrange themselves in the lattice of crystalline ice. If these minute aggregations are smaller than a certain size, their vapor pressure is greater than that of the supersaturated region and they are unstable and break up. If, on the other hand, they are larger than a certain size, their vapor pressure is such that they are stable and continue to grow. The lower the temperature, the smaller will be the critical size necessary for stability. Schaefer [3] has found, using clean air free of dust, that the rate at which nuclei occur is very small at temperatures above -38.9°C. However, in the presence of a silver iodide surface, it is possible, because of the close similarity between ice and silver iodide, that the probability of the chance formation of a nucleus is greatly increased and is large even at temperatures as high as -10°C.

Another way of looking at the phenomenon is to consider the growth of an ice crystal as the formaation of a crystal of ice on ice. We know that this takes place with the greatest ease. The formation of ice on a large surface of ice requires the formation of very little new ice surface and hence there is little change in surface energy. For every new ice surface formed, an almost equal ice surface is covered up. However, when a new ice surface is formed in the absence of any other surface, large amounts of surface energy are required relative to the free energy decrease in the formation of the interior of the new phase. Because of the close similarity of ice and silver iodide, the formation of ice on a silver iodide surface probably involves only a small amount of surface energy, and therefore, the the chances of this taking place are good.

The lower the temperature, the smaller will be the critical size of a stable nucleus. Because the critical size is small at low temperatures, the chances of a nucleus forming are, in general, better.

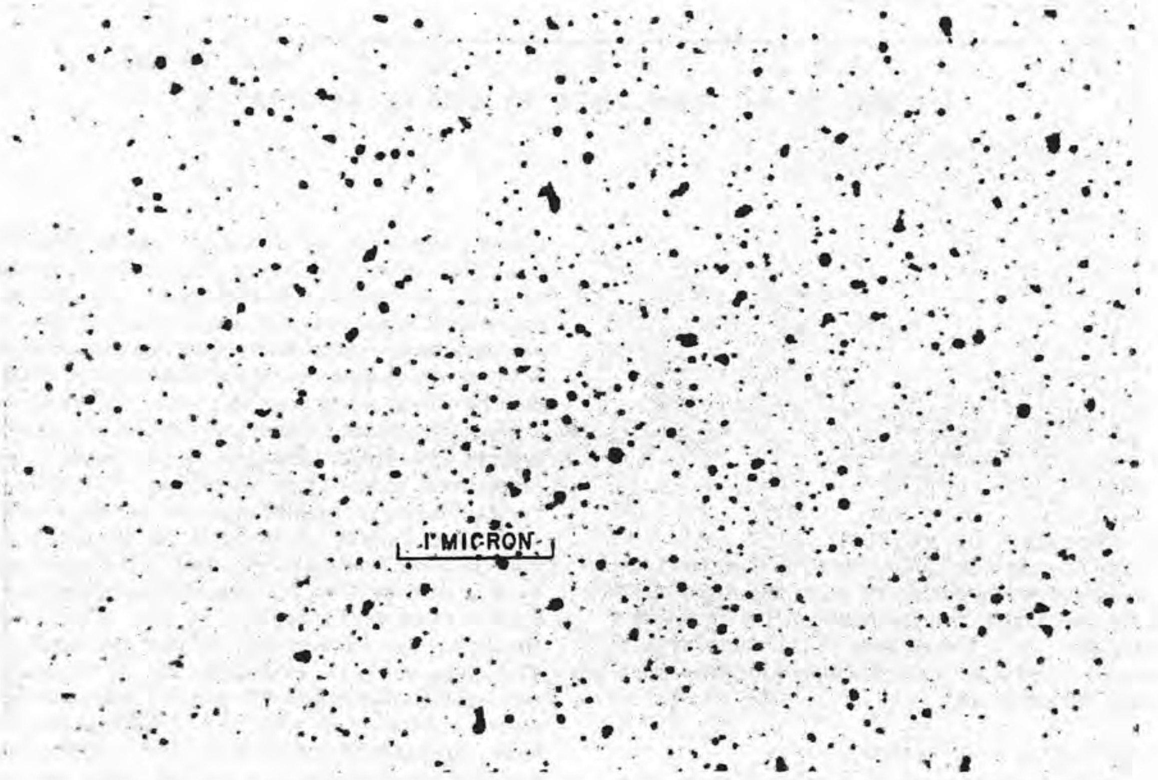


FIG. 6 ELECTRON MICROGRAPH OF SMOKE PRODUCED AT 2.3 MG/SEC AGI CONSUMPTION

Hence, the rate of nucleus formation is generally greater at low temperatures.

Another possible explanation for the time required for silver iodide particles to form ice crystals can be based on the assumption that the silver iodide particles produced by the generator are not all in the hexagonal form which is similar to ice. Possibly they might exist in a metastable condition as a supercooled liquid or as some other modification. In this case, the rate at which they react to form ice crystals would be determined by the rate at which they transform into the stable hexagonal form. However, it appears for several reasons that this factor is probably not large in these experiments. It has been found that the silver iodide smokes used in these tests will nucleate silver iodide solutions supersaturated with respect to the hexagonal form and that the crystals which result are of the hexagonal variety. The number of such nuclei in a given volume of smoke is of the same order of magnitude as the number of particles determined by the electron microscope. It, therefore, seems probable that at room temperature most of the smoke particles are of the hexagonal structure. In addition, one would expect, if the rate-determining factor involved the transformation of the silver iodide particles themselves, that smokes aged for a period of time at low temperature would show a different rate of falling off of ice crystal formation when they are put in a supercooled cloud. This has not been observed.

Another possibility is that the formation of an ice crystal under the influence of a silver iodide particle can take place only in the liquid phase. In this case, the rate of ice crystal formation might be limited by the rate at which silver iodide particles entered into supercooled water drops. This could occur either by diffusion of the particle to the drop or by condensation of a drop on a particle. It has been found that when a suspension of silver iodide particles in water is sprayed into a supercooled cloud, ice crystals are formed. It is, therefore, probably that silver iodide particles can act as nucleating agents in a liquid water drop. However, it has not been definitely established that this is a necessary condition for silver iodide to act. If we assume this to be the rate governing factor in these experiments, we are faced with the problem of explaining the large effect of temperature on the total number of ice crystals produced. As will be discussed later, the variation of the number of ice crystals produced with temperature can be explained on the basis that the rate of nucleation increases greatly with decreasing temperatures. There is no reason to expect that the rate at which particles enter water drops is particularly temperature sensitive. It is quite possible that the time required for a particle to enter a water drop is of considerable importance in these experiments but it is probably not the most important rate-governing factor.

The interpretation of results is further complicated by the possibility that the small particles of silver iodide smoke may dissolve in water drops before they have a chance to start the formation of an ice crystal. At $25^{o}C$ the solubility of silver iodide in water is about 1 by 10^{-8} mols/liter.(4) A water drop 10 microns in diameter on this basis should be capable of dissolving a silver iodide particle about 100 Å in diameter. The solubility should be somewhat greater for particles of this small size. However, the effect of particle size should be counteracted to some extent by a decreased solubility at the lower temperatures. If these factors are of importance, the kinetics of the nucleation may be dependent to a large extent on the rate of solution of the silver iodide particles in the water drops.

The author is inclined to favor the explanation that the rate of ice crystal formation is governed primarily by the rate of spontaneous ice nucleus formation on the silver iodide particles. In some as yet unreported experiments on the nucleation of supercooled water and supercooled tin, the author measured at constant temperature the rate of solidification of systems composed of a number of independent supercooled drops. It was observed that the drops did not all freeze at once, but froze at a rate which steadily decreased with time. This rate of freezing greatly increased as the temperature was lowered. In these experiments, foreign particles and surfaces were present which undoubtedly served as foreign nuclei. The time required for these drops to freeze could be best explained on the basis of the chance formation of stable nuclei on the foreign surfaces. It seems reasonable to believe that in the case of nucleation by silver iodide that similar phenomena play a dominant role.

If we proceed on the assumption that silver iodide merely increases the rate of the chance formation of spontaneous ice crystals, it is possible to come to some conclusions as to the magnitude of the rate and its dependence on temperature. The particles of silver iodide introduced into the cold chamber undoubtedly become lost as potential nuclei by precipitation on the walls of the chamber. The rate of precipitation on the walls is probably large because of thermal diffusion resulting from the 15-watt heater in the vaporizer. One would expect the rate at which particles disappear by precipitation on the walls to be proportional to the concentration of the particles. On the basis of this assumption, the concentration of particles would decrease exponentially with time. If the rate of snow formation is proportional to the concentration, this, too, should decrease exponentially with time. This is experimentally observed to be the case.

On the basis of the foregoing assumptions, one can analyze the situation mathematically.

If c is the number of silver iodide particles per unit volume at a time t then:

$$\frac{dc}{dt} = -(K_1 + K_2)c \qquad (1)$$

where K_1 is the rate at which the silver iodide particles form ice crystals and K_2 is the rate at which they are being removed from the cloud by precipitation or other causes. By integrating Eq. 1, we obtain an expression for the concentration c at any time:

$$c = c_O e^{-(K_1 + K_2)t} \qquad (2)$$

where c_O is the concentration at time t = O. If N is the number of ice crystals formed per unit volume then,

$$\frac{dN}{dt} = K_1 \cdot c = K_1 c_O e^{-(K_1 + K_2)t} \qquad (3)$$

which when integrated gives for the number of crystals formed at time t:

$$N = \frac{K_1 c_O}{K_1 + K_2} \; 1 - e^{-(K_1 + K_2)t} \qquad (4)$$

Or when precipitation is complete

$$N = \frac{K_1}{K_1 + K_2} \cdot c_O \qquad (5)$$

or

$$\frac{N}{c_O} = \frac{K_1}{K_1 + K_2} \qquad (6)$$

The fact that the rate at which the rate of snowfall decreases with time is not greatly influenced by temperature, while the total number of crystals produced increases by a large factor with a small temperature decrease, indicates that at higher temperatures K_2 is far greater than K_1. This is another way of saying that at higher temperatures the rate at which the silver iodide particles form snowflakes is so small that a large majority of them precipitate on the container walls before they have a chance to form snow crystals. At -20°C the number of snow crystals obtained is about the same as the number of particles determined from the electron microscope so that it is reasonable to assume that at this temperature practically all of the smoke particles form snowflakes.

If we assume that the rate at which precipitation decreases with time at the higher temperature is determined solely by K_2, then K_2 computed from the curve in Fig. 4 is approximately 6 by 10^{-3} per sec. From the data in Fig. 5, N_1 and c_O can be estimated and from them and the above value for K_2, values for K_1 for different smokes at different temperatures can be computed.

These values expressed as half life in hours are as follows:

Mg AgI/Sec	Range of Particle Diameter	Half Life in Hours -13°C	-10°C
1.5	30 - 700Å	5.5	173
7.5	50 - 1070Å	1.9	75
37.5	130 - 1400Å	1.4	67

If this data is extrapolated on the assumption that the log of the nucleation changes linearly with the reciprocal of the absolute temperature, we find that at -5°C the half life is several years while at -20°C it is a few seconds and at -25°C a few milliseconds.

This large effect of temperature on the nucleation rate is of the same order of magnitude as that observed in the measurements on supercooled water drops and on supercooled tin drops.

The curves in Fig. 5 show a maximum for the number of nuclei produced per gram of silver iodide at a certain rate of silver iodide consumption. This is probably because at a low rate of consumption, the particles produced are so small that their reaction rate is small and many of them precipitate out before they have a chance to serve as nuclei. At high rates of consumption, the particles formed are larger and react more rapidly, but because they are larger, fewer are formed per gram of silver iodide.

2. Diffusion Coefficient of Smoke

An average diffusion coefficient for the silver iodide smoke can be calculated from measurements made on the rate at which the smoke precipitates on the walls of a container. In the experiments which were made to find the rate at which the number of nuclei falls off as a function of the time the smoke is held in the sampling syringe, it was found that the half life of the smoke was about twenty minutes. This was for a smoke produced when the generator was consuming 20 mg/sec of AgI.

Langmuir has derived the following expression for the rate of precipitation of a smoke of particle diameter A on the walls of a container having a volume V and an internal area A with slight convection caused by a slightly higher temperature at the bottom than the top.

$$\frac{d \ln c}{dt} = \frac{0.64 \, A \, D^{2/3}}{V} \qquad (7)$$

where c is the concentration of the smoke at any time t.

Using this equation the diffusion coefficient is calculated to be approximately 6 by 10^{-5}.

Langmuir has also given the following expression for the diffusion coefficient as a function of particle radius:

$$D = \frac{2.04 \times 10^{-16}}{a^2} + \frac{1.18 \times 10^{-11}}{a} \qquad (8)$$

where a is the particle radius.

According to this expression, the diffusion coefficient 6 by 10^{-5} corresponds to a particle diameter of 400 Å. This is a reasonable agreement with the measurements from the electron microscope which show this smoke to have a particle diameter ranging from 100 Å to 1400 Å with a median diameter of about 300 Å.

As has been shown K_2, or the rate of disappearance in the cold chamber of silver iodide particles from causes other than nucleation, is about 5.7 by 10^{-3} per second.

Using the diffusion coefficient of 6 by 10^{-5} and Eq. (7), it can be calculated that the smoke concentration should fall at a rate of 1.3 by 10^{-4} per second. This is far less than the observed rate of decrease, K_2, which was found to be 5.7 by 10^{-3}. This calculation, of course, does not take into account the thermal diffusion caused by the vaporizer heater in the cold chamber which would be expected to greatly increase the rate of precipitation on the walls.

Using the diffusion coefficient it is possible to estimate the rate at which the concentration of the smoke decreases because of precipitation on the water drops of the supercooled cloud. The rate of change of concentration due to this cause is given by the relation

$$\frac{-d \ln c}{dt} = -4 \pi D r_O Q \qquad (9)$$

where r_O is the radius of the water drops and Q is the number of them per cubic centimeter.

If we assume the liquid water content to be 1 gm per cubic meter and the drop radius to be 5 microns, the rate of change of concentration from this cause is 3.6 by 10^{-4}.

E. SUMMARY

Measurements have been carried out on the nucleation of supercooled water clouds by silver iodide smokes. The smokes were produced by spraying a solution of silver iodide into a hydrogen flame. The particles of the smokes were found by electron microscope examination to range in diameter from 30 Å to 1400 Å. The number of ice crystals produced per gram of silver iodide was determined as a function of the temperature of the supercooled cloud and the rate of introduction of silver iodide into the flame. Yields of ice nuclei of as high as 10^{16} per gram of silver iodide were obtained when the supercooled cloud was at -20°C. At -10°C, the same smoke produced only $10^{12.7}$ ice crystals per gram.

It has been found that silver iodide particles do not react immediately to form ice crystals when they are put into a supercooled cloud. Ice crystals were found still to be forming at a measurable rate fifty minutes after a silver iodide smoke was introduced into a supercooled cloud. It is believed that fewer ice crystals are produced at higher temperatures than at lower temperatures because the silver iodide particles react more slowly to form ice crystals and most of them precipitate on the walls of the cold chamber before they have time to react.

According to this interpretation of the results, the rate of reaction at -13°C is thirty or forty times that at -10°C.

INFLUENCE OF BUTYL ALCOHOL ON SHAPE OF SNOW CRYSTALS FORMED IN THE LABORATORY

In the course of laboratory measurements on the number of ice-forming nuclei contained in various smokes, a microscope was set up in a refrigerated box for the purpose of counting snowflakes. A supercooled cloud was formed in the refrigerated box at -20°C by the Schaefer technique (1). Smoke containing silver iodide nuclei was introduced into the cloud and the resulting snow crystals which formed were allowed to fall on a slide where they were examined under a microscope. The crystals thus produced were predominantly in the form of flat hexagonal plates.

Without any intentional change in the experimental set up, it was noticed that the type of snowflakes produced had changed from the hexagonal plates to hexagonal prisms having a length of the order of five times their diameter. It was found that hexagonal prisms were produced until the air in the box had been cleaned out by displacing it with air from the compressed air line. When this was done, the flakes formed were once more hexagonal plates. The cause for this change in the shape of the crystals was finally traced to the presence of a small amount of normal butyl alcohol vapor in the laboratory atmosphere which had resulted from accidentally spilling some of this liquid.

The modification of crystal shape caused by traces of butyl alcohol vapor was found to vary considerably with its concentration in the air in the cold chamber. When the partial pressure of the butyl alcohol was of the order of 10^{-6} atmosphere or less, no effect was noticeable. At a partial pressure of the order of 10^{-5} atmosphere, the long prisms were formed. At still higher partial pressures, the effect diminished and hexagonal plates formed once more. The effect of the butyl alcohol vapor on the crystals was found to be similar whether the cloud was seeded by silver iodide smoke or by passing a piece of solid carbon dioxide through it.

The modification of habit produced in the presence of butyl alcohol is similar to the changes which have been reported in the habit of crystals grown from solutions to which various substances have been added. For example, sodium chloride, which usually crystallizes as cubes from aqueous solution, forms octahedra if urea is added to the solution. The suggested explanation for this change of crystal habit is that absorption on the crystal faces changes their relative rates of growth thus modifying their shape.

It seems probable that butyl alcohol alters the shape of the snow crystals in a similar manner. Apparently at very low concentrations of the vapor, the effect on the rate of growth is small on all faces. However, as the vapor concentration is increased, a point is reached at which the rate of growth of the sides of the prisms is greatly reduced relative to the rate of growth of the prisms ends. At higher vapor concentrations, apparently the absorption on the various faces becomes more equal so that the effect on the rate of growth of the faces becomes more nearly equal, and the effect on the shape of the crystal is not very large.

Isobutyl alcohol and allyl alcohol have been found to have an effect similar to butyl alcohol, and it is presumed other higher alcohols would behave in a similar fashion. Ethyl alcohol did not show the effect and, if anything, seemed to favor formation of hexagonal plates.

V. J. Schaefer of this laboratory has extended the scope of these experiments and this work will soon appear in publication.

ACKNOWLEDGEMENTS

The author wishes to thank Dr. Irving Langmuir and Dr. Vincent J. Schaefer for their very helpful counsel and suggestions in this work. He is grateful to Mr. E. Fullam for making the electron microscope examinations and photographs and to Mr. Kiah Maynard and Mr. Duncan Blanchard for invaluable help in testing the smokes.

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VARIATION WITH TEMPERATURE OF THE NUCLEATION RATE OF SUPERCOOLED LIQUID TIN AND WATER DROPS

A. INTRODUCTION

In investigations of the kinetics of the formation of a new phase, it is important to learn at what rate nuclei, or centers of formation for the new phase, make their appearance. It is possible to investigate the rate of nucleation by observing single masses of material during and after a phase transformation. However, in many cases it is difficult to separate the kinetics of nucleation from the kinetics of the growth of the new phase after nuclei have made their appearance. The nucleation of a substance can often be more easily studied by dividing it into a large number of small, mutually independent particles and observing as a function of time the number of particles which have undergone transformation. The time required for a particle to change from one phase to another once a nucleus has formed will, in general, be proportional to the first power of the particle radius. The chance that a nucleus will form will generally be proportional to the second or third power of its radius. Therefore, by making the particle sufficiently small, the time required for the occurrence of a nucleus can be made large in relation to the time required for the particle to transform once a nucleus has appeared. It is advantageous to make nucleation measurements on systems containing a sufficiently large number of particles to be easily treated statistically.

Preliminary investigations have been made on the nucleation of supercooled tin and supercooled water. Observations were made at constant temperatures on the freezing rate of systems composed of large numbers of supercooled drops.

B. EXPERIMENTAL METHODS AND RESULTS

1. Nucleation of Supercooled Liquid Tin

In the experiments on tin, the samples were prepared from a fine tin powder (obtained from Eimer and Amend) consisting of small spheres of tin ranging in diameter from approximately 1 to 10 microns. (The fact that the particles were far from uniform in diameter complicated the interpretation of experimental results. In future work, it will be desirable to perform the experiments on samples containing drops as nearly identical as possible.)

In the first experiments, the sample of tin powder was mixed with a bakelite varnish and spread as a film on a glass slide. The slide was mounted in a small electric furnace built to fit on a Philips x-ray diffraction apparatus. The apparatus was adjusted to give a strong diffraction line of the crystalline tin. The sample was then heated above its melting point (231.89°C) to 240°C. At the melting point, the diffraction line of the solid tin disappeared. Hydrogen gas was run through the furnace to prevent oxidation of the sample. After having been heated above the melting point, the sample was cooled and held at some temperature below its freezing point. The rate at which the supercooled particles crystallized was determined by measuring the rate at which the diffraction line of solid tin reappeared. The results of a typical experiment are shown in Fig. 1. It was soon found that the rate of nucleus formation was greatly increased by a small decrease in temperature and that the temperature control was not sufficiently sensitive to permit measurements with any accuracy.

A different apparatus was then set up in which the rate at which the tin particles solidified could be measured by the rate at which their volume changed. When liquid tin crystallizes, its volume decreases by about five per cent. The tin powder was first heated in air for about half an hour at 150°C to give it a thin coating of oxide to separate the particles. It was sealed into the bulb of a dilatometer (see Fig. 2). The dilatometer was then pumped out and baked at a pressure of less than a micron to remove any gas. "Octoil S" was then distilled into the dilatometer under vacuum. A

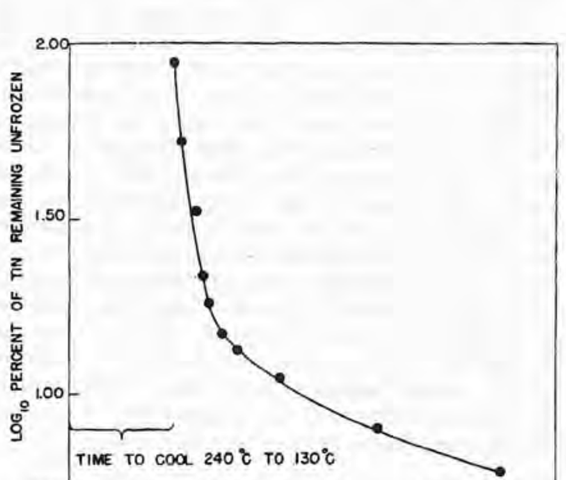

Fig. 1 Fraction of tin drops remaining unfrozen as function of time at 130°C from x-ray data.

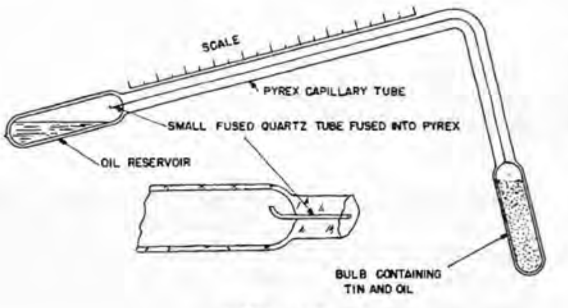

Fig. 2 Dilatometer.

measurement of the rate of nucleation was made by first heating the bulb to a temperature above the melting point of tin (265°C), and then placing it in a silicone oil, constant-temperature bath. The rate of nucleation was determined by observing the rate of volume decrease as measured by the motion of the "Octoil S" along a graduated capillary tube. A long capillary tube was used in the first experiments, but it was found that appreciable error was caused by the slow drainage of the liquid from the walls of the tube. This difficulty was minimized by using the oil reservoir shown in Fig. 2. During the melting of the sample, the tube was held at an angle so that the oil covered the end of the small fused quartz tube sealed into the pyrex capillary. (The small tube was made of fused quartz so that it would not melt while it was being sealed into the pyrex capillary). When the sample had been cooled to almost the desired temperature, the tube was tipped so that the excess liquid ran away from the end of the capillary tube, thus forming the meniscus in a convenient position.

The results of the experiments are shown in Fig. 3. The time has been plotted on a log scale to condense the curves for runs made over a long time interval. If the chances of a nucleus occurring in each tin particle were exactly the same and were independent of the length of time it had been supercooled, one would expect the rate of nucleation to decrease exponentially with time. The curves show clearly that in these experiments this is not the case. The fraction of the sample crystallizing per unit time steadily decreases with time. Some drops nucleate more readily than others, probably because they are either larger than the others or because they contain certain impurities which increase the probability of nucleus formation. The data obtained should be interpreted as the behavior of supercooled tin with whatever impurities were present. It is probable that tin, free of impurities, if it could be obtained, might behave very differently.

One of the most striking features of the data is the very great effect of temperature on the rate of nucleation. A decrease in temperature of seven degrees causes a sixtyfold increase in the nucleation rate. In observations on the rate of nucleation of supercooled water clouds in the presence of silver iodide smoke, the author has observed a similar large negative temperature coefficient(1). For a given smoke, the rate of ice crystal formation was approximately thirty times greater at -13°C than at -10°C.

An approximate value for the activation energy of the nucleation reaction can be computed from the data in Fig. 3. The log of the reciprocal of the time required for one third of the sample to freeze was plotted against the reciprocal of the absolute temperature to give the curve in Fig. 4. This corresponds to an activation energy of -2×10^5 calories. The data taken at 116.7°C has not been used because nucleation at that temperature proceeds so rapidly that most of the sample is frozen by the time its temperature has come to equilibrium with the constant temperature bath.

2. Nucleation of Supercooled Water

The author first attempted to measure the nucleation of supercooled water while conducting experiments at the De-icing Research Laboratory at M.I.T. An emulsion of water drops suspended in lubricating oil was cooled to -29°C with the expectation of measuring the nucleation rate by the rate of volume increase. This method was not successful because the solubility of water in the oil was sufficiently large so that diffusion rapidly took place from the unfrozen to the frozen drops.

Some preliminary studies on water have been made in this laboratory using a variation of the

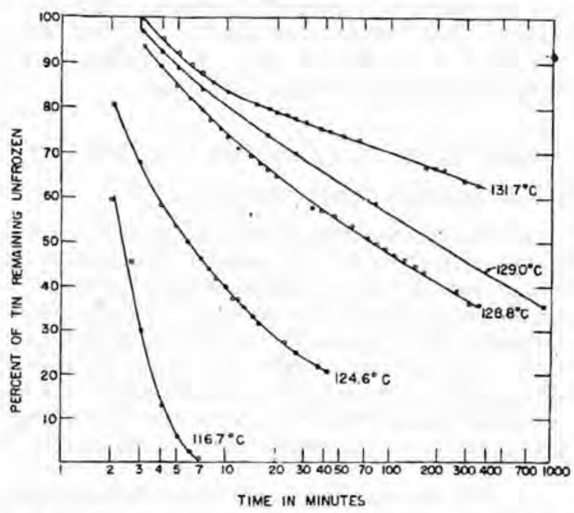

Fig. 3 Fraction of tin drops remaining unfrozen as a function of time from dilatometer data.

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method described above. In these experiments, 64 drops of distilled water weighing approximately three milligrams each were placed in a square pattern on a polished chromium-plated metal plate.

On the recommendation of Dr. V. J. Schaefer of this laboratory, the chromium surface of the metal plate was covered with a thin film of polystyrene by dipping it into a solution. This had been found by Schaefer to lower the temperature to which the water could be supercooled. The plate with the drops on its surface was then placed on a thermostated copper block at some temperature below freezing. To prevent impurities in the air from settling on the water drops, the plate was covered with a piece of plate glass which rested on a raised rim on the copper block. The heat transfer between the block and plate was sufficient to bring the drops on the plate to the temperature of the block in less than one minute. The number of unfrozen water drops was measured as a function of time by visual observation. Figure 5 is a curve showing the nucleation of the drops at various temperatures.

Despite precautions to keep the water drops free from impurities, it is certain that the drops were contaminated by foreign material from the atmosphere and from the surface of the plate, which increased the rate of nucleation. Here again the data would probably be far different for completely pure water. The striking feature of the data is again the large negative temperature coefficient which characterized the results of the experiments on

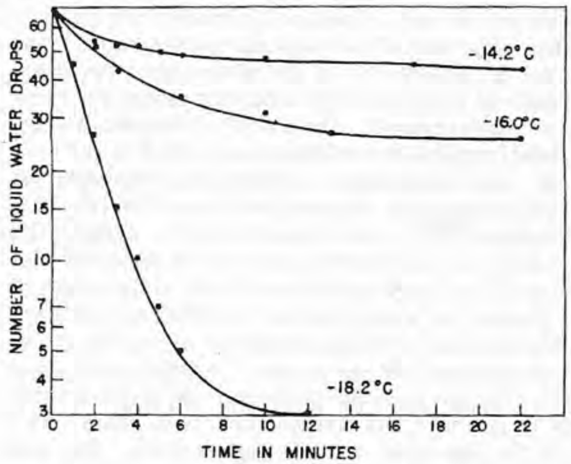

Fig. 5 Fraction of water drops remaining unfrozen as a function of time.

supercooled tin and on a supercooled cloud seeded with silver iodide.

The data for the freezing of water drops given in Fig. 5 can be interpreted in terms of the rate of nucleus formation per gram of water. Figure 6

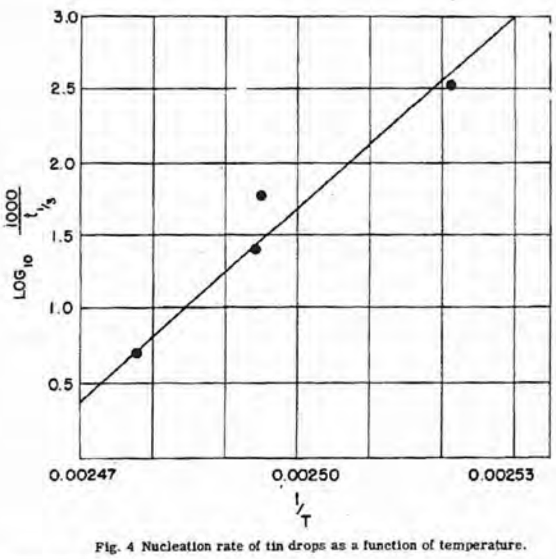

Fig. 4 Nucleation rate of tin drops as a function of temperature.

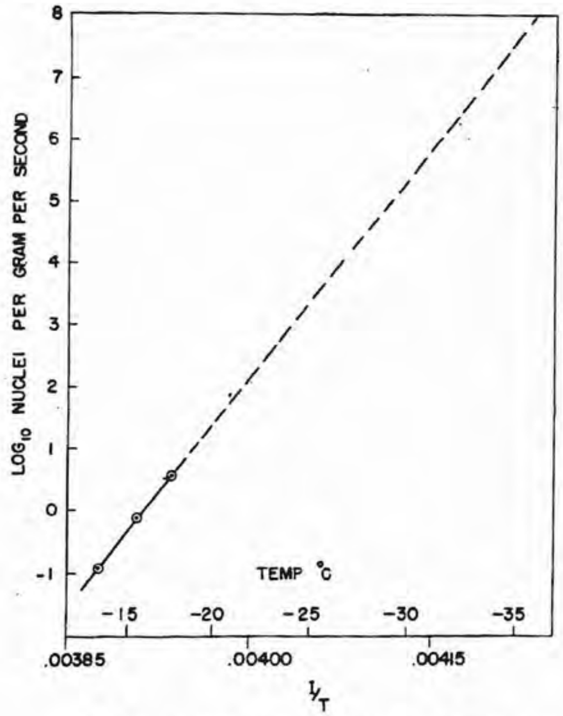

Fig. 6 Nucleation rate of water drops as a function of temperature.

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relates the rate of nucleus formation per gram to the reciprocal of the absolute temperatures. The rate of nucleation was calculated from the times required for the first 22 drops to freeze at the various temperatures. The energy of activation computed from the slope of the curve in Fig. 6 is -1.6×10^5 cal. It is interesting to extrapolate this data for comparison with observations made by Dr. V. J. Schaefer(2)(3) in his experiments on supercooled clouds. If it is assumed that the liquid water content in the cloud in the cold box is of the order of 1 gm/m^3, at a temperature of -25°C, according to this data ice crystals should be appearing at the rate of about 10^4 per second. Actually, with clean air at this temperature, no crystals are observed. It is not until the temperature falls below -39.0 ± 0.1°C that many crystals begin to form. The rate of nucleation in the water drops on the metal plate is much larger than that in the water drops in a cloud, probably because of the nucleating effect of the surface of the plate and chance impurities.

The sudden appearance of large numbers of ice crystals when the temperature is -39°C or lower indicates that in Schaefer's experiments the increase in nucleation rate with decreasing temperature must be even greater than that found in this work.

C. SUMMARY

X-ray diffraction, dilatometric, and visual techniques are described for measuring the extent of crystallization of systems composed of many small mutually independent volumes of supercooled liquid. Preliminary measurements on supercooled liquid tin and supercooled water show their rate of nucleation has a very large negative temperature co-efficient corresponding to an activation energy of the order of -2×10^5 calories.

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OBSERVATIONS ON THE BEHAVIOR OF WATER DROPS
AT TERMINAL VELOCITY IN AIR

The contents of this report deal primarily with some observations and experiments on the behavior of water drops falling at terminal velocity through air. Information was obtained concerning the breakup of drops in non-turbulent and turbulent air streams. The mechanism of breakup under various conditions was observed.

Over seventy stroboscopic photographs were taken of drops of various sizes. The photographs taken were not only of stable drops but also of drops in the process of breaking up. With the information obtained from the photographs and visual observations, graphs were constructed which give a partial picture of what is happening during the fall of a water drop.

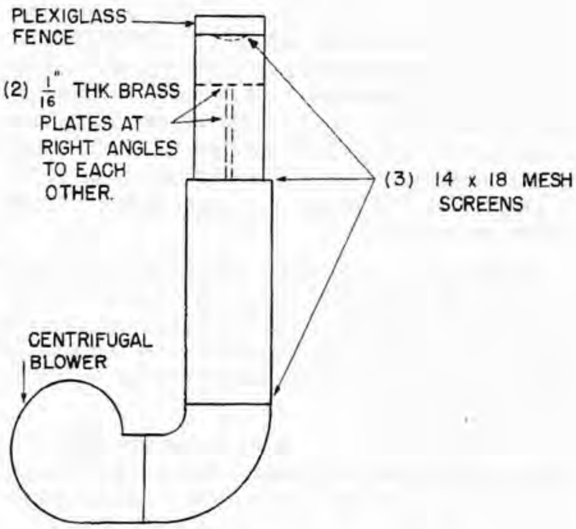
It is hoped that the facts obtained may be used to help construct a clearer picture of the phenomena involved in the fall of natural rain in the atmosphere.

A. Experimental Setup

As a result of the obvious difficulties which would be encountered in the attempt to study water drops falling at their terminal velocity through the atmosphere, a laboratory wind tunnel was constructed. With such a setup, a vertical stream of air was set in motion at a velocity equal to that of the terminal velocity of the drops. In this manner, water drops placed in the air stream would have little relative motion with respect to an outside point. Ample time was thus obtained for the observation and the photographing of the drops.

The construction of the wind tunnel used in the work was quite different from that used by Lenard(1). A centrifugal blower driven by a half horsepower a-c induction motor was used to supply the necessary air stream. (Refer to Fig. 1.) A 90° elbow of 9-inch tubing was attached to the blower outlet to provide a vertically upward air flow. Attached to the elbow was an additional 2-foot section of tubing. A 6-inch square wooden box 15 inches long was placed above the 2-foot section of tubing. A plexiglass fence 2 inches high was added as an extension to the box.

The interior parts of this apparatus consisted of two brass plates 9 inches by 6 inches by 1/16 inch thick, four 9-inch lengths of adhesive tape, and three 14 by 18 mesh screens. The brass plates were placed in the box, as shown in Fig. 1, at right angles to each other. At each 90° junction of one plate with the other, a strip of adhesive tape was used to round off the sharp corners. The use of this tape proved very necessary in successful suspension of water drops. A 14 by 18 mesh screen was placed between the elbow and the straight section of the tunnel, between the box and tubing, and between the box and the fence. The latter screen was found to be much more effective if it was slightly concave upward.



APPARATUS USED TO SUSPEND WATER DROPLETS IN THE AIR STREAM.

FIG. 1

The apparatus was found to be quite sensitive in several respects. If the tunnel was out of the vertical or the brass plates not located exactly as shown in Fig. 1, the drops would not remain suspended for more than a second or so.

The brass plates, as modified by the tape, provided the necessary drag which lowered the center velocity of the air stream as it emerged from the tunnel. This slight decrease in velocity in the central part of the stream, of the order of six per cent,

(1) Met. Z., 249, (1904).

was vital in the successful operation of the wind tunnel.

The placing of water drops within the air stream was accomplished with the use of a simple syringe easily constructed in the laboratory. For obtaining large drops, that is, drops over 8 mm in diameter, a syringe with a bore diameter of 0.568 cm was used. With the aid of an attached millimeter scale, it was possible to obtain the volume of water injected into the air stream. As the diameter of all drops in the air stream was based on volume considerations and not on apparent diameter, the diameter was easily and accurately obtained. All drops were injected into the air stream at the point where they would come to rest; thus it was possible to obtain drops of extremely large size. The equilibrium point for a majority of the drops was approximately 5 cm above the screen.

This method of injecting the drops is different from that used by Lenard in that here the water drop is formed at its point of rest while Lenard allowed the drop to fall into the stream from a stationary injector placed several centimeters above the final equilibrium point.

The injection of drops below 7.5 mm in diameter was accomplished in the same manner with the exception that a syringe of only 0.194 cm bore diameter was used.

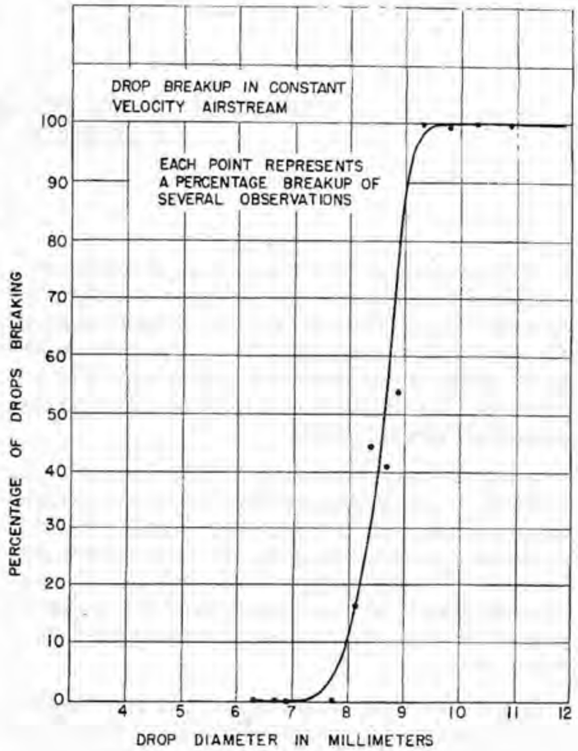


FIG. 11

B. Size of Drops and Suspension Times

The suspension time of all drops observed depended to an extent on the size of the drops. Drops over 8.5 mm diameter were limited in most cases to less than 8 seconds. Within the 8 seconds the drops would break up as a result of oscillations or would be accelerated out of the air stream. The acceleration was caused by the slight increase in the velocity of the central part of the air stream as it left the tunnel.

With the smaller sized drops, the deformation is not as pronounced; thus, they will remain smoothly suspended for 15 seconds or more. Several drops around 7.5 mm in diameter and smaller were observed to remain in suspension for 30 seconds or better, while a few have been suspended for approximately a minute.

In the course of obtaining data over three hundred drops between 3.2 and 10.5 mm in diameter were observed in the air stream.

C. Maximum Drop Diameter Before Breakup

Water drops of small diameter will remain suspended in the air stream without breaking up. However, as the diameter is increased, a point is reached where a few of the drops injected will break up. Breakup then occurs in increasing numbers as the drop size is increased until a point is reached where 100 per cent of the drops are unstable.

In the case of drop breakup in a non-turbulent or laminar flow air stream, it is fortunate that breakup does not occur until the drop size is well in the region where the terminal velocity of all drops is approximately 8.2 m/sec. The value of 8.2 m/sec, the terminal velocity of large drops, does not hold in all cases. There is a slight decrease in terminal velocity of extremely large drops (9.5 mm diameter and above) and drops on the verge of breakup. As a small percentage of the drops observed were in the preceding category, a constant air stream velocity of about 8.2 m/sec was used.

The graph shown in Fig. 2 illustrates the relationship between the size of water drops and the percentage which will break up in the air stream. Observations on over 100 drops were used to plot the curve; therefore, each point on the curve represents the percentage break up of an average of 8 drops within that particular region.

It is apparent from the graph that water drops in an air stream of constant velocity are quite stable up to a diameter of 7.7 mm. At this point, the region of instability is reached. Drops will begin to break up and continue to do so in increasing percentages until diameters of approximately 9.5 mm are reached. At this point, the drops are very unstable and cannot exist without breakup for more than a few seconds. One should not misinterpret the graph in believing that water drops above 9.2 mm diameter are unable to exist at all. Drops of diameters from 10 to 10.4 mm have been observed for four seconds before breakup.

No definite correlation has been observed between the time of drop breakup and drop diameter. In many cases a drop of about 8 mm diameter has had a shorter life than that of a 9 mm diameter drop.

What is shown in Fig. 2 is that out of a large group of drops of a certain size, a certain percentage will break up. As the drop diameters are increased, the percentage of drops breaking in a certain range, say 8 to 8.3 mm, will rise. An analogy can be found in the disintegration of atoms composing a radioactive material. Here, as in the breakup of water drops of a certain size, the atoms are all alike, yet their individual breakup or disintegration times are unpredictable. All that can be said is that a certain percentage will disintegrate within a definite period of time.

D. Drops Subjected to Sudden Change in Air Velocity

Water drops are extremely sensitive to changes in velocity of the supporting air stream. Medium

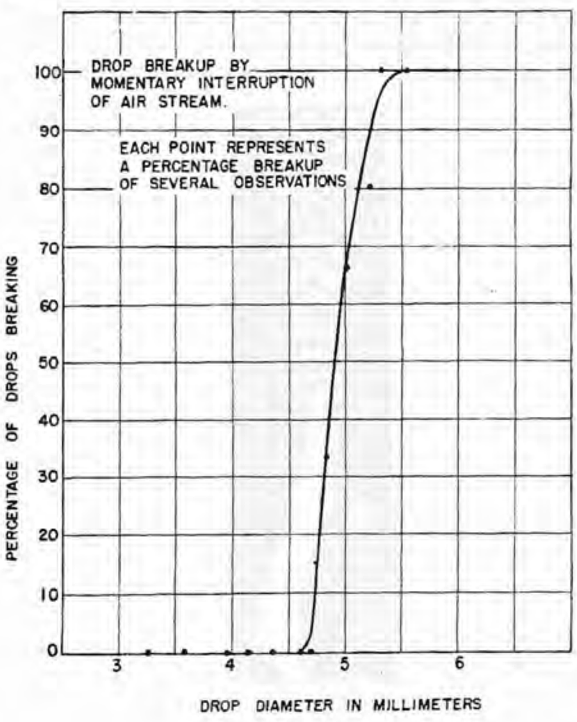


FIG. III

size drops may easily be caused to break up from a momentary interruption of the air stream.

Figure 3 shows the relationship between drop size and percentage breakup. Again, as in Fig. 2, each point represents an average of several observations. In all cases, the drop breakup was caused by passing the hand rapidly through the air stream 10 cm below the drop. This resulted in about a 0.1 second cut off of air flow. The instant the hand passed through the stream, the shock effect of the resumed air flow on the drop produced the breakup.

Drops below 4.6 mm in diameter have been found to be quite stable when subjected to shock as described above. Instability begins to set in at 4.6 mm diameter and increases until at drop sizes of 5.4 mm diameter, all drops subjected to shock will break up. The transition zone is extremely narrow. A difference of 0.8 mm in diameter may determine the stability or instability of a drop.

It can be shown that a small change in the diameter of a drop has a tremendous effect on the sensitivity of a drop in regard to breakup.

By referring to Fig. 3 one can see that at a certain diameter, a certain percentage of drops will break up within a reasonable amount of time. Now there is no reason to believe that drops of the same diameter are physically any different from one another. Therefore, if 10 per cent of the drops will break up at a diameter of 4.7 mm, one would expect the remaining 90 per cent to break at later intervals of time. We thus obtain mathematically

$$dN = -K\,N\,dt \qquad (1)$$

where N is the total number of drops observed. By setting up the integral and placing limits

$$\int_{N_O}^{N} \frac{dN}{N} = -K\int_{O}^{t} dt \qquad (2)$$

where N_O is the number of drops at time O and N the number at time t. By evaluating the definite integral:

$$\ln \frac{No}{N} = Kt. \qquad (3)$$

Now by assuming a definite value of time for t, whether it be one minute or one hour, we obtain

$$K = c \ln \frac{No}{N}. \qquad (4)$$

This shows that the value of K will control the percentage breakup. Now K is going to vary with changing air temperature, barometric pressure, drop diameter, etc., but by assuming a constant at an angle of 45° below the horizontal. This enabled one to determine, to a better degree, whether rotation or oscillation was taking place. By observing the change in position of the major axis with respect to time in Fig. 4-C, the possibility of both rotation and oscillation taking place simultaneously, is realized.

The phenomena of the rotation of large water drops in an air stream can be seen not only from photographs, but by actual observation. Drops above 9.5 mm in diameter often rotate at about 4 revolutions per second and thus are easily followed by eye.

Fig. 4-D shows an 8.4 mm diameter drop taken with the stroboscope setting at 80 cycles/sec. Here again the photograph was taken at 45° below the horizontal. This picture clearly shows the major axis alternating between two positions 90° apart in the horizontal plane. Thus, the predominant mode of deformation in this case is caused by oscillation.

The photograph of Fig. 4-E is another which was taken at the 45° angle. The drop diameter is 6.8 mm and the stroboscope setting was 80 cycles/sec. It is difficult to analyze the photographs of small diameter drops, because the periodic deformation increases rapidly with decreasing drop size. Thus, in Fig. 4-E, only four successive images show the drop going through one cycle. Here, also, the major axis in each image shows no rotation but lies either in the plane of the photograph or 90° to it. Periodic oscillations are evidently taking place.

The photograph of Fig. 4-F is of a 7.9 mm diameter drop taken at a 45° angle. The stroboscopic setting was 80 cycles/sec. The shifting of the major axis to positions 90° apart indicates that oscillations were taking place.

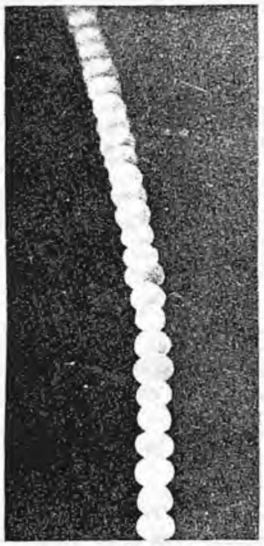


Fig. 4-E

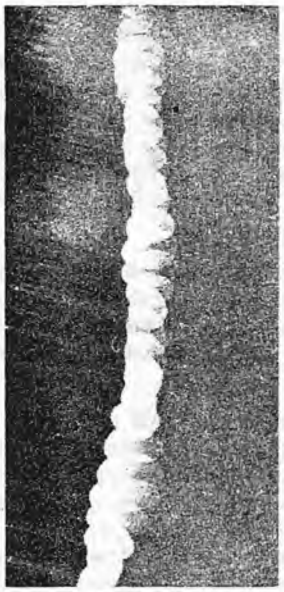


Fig. 4-F

The natural breakup of a drop in a constant velocity air stream (discussed in section F) is shown in Fig. 5-A. The drop diameter was 9.4 mm and the time interval between images was 1/70 second. The formation of the narrow neck of water and its evolution into three small droplets is clearly seen. The small droplets are around 1.2 mm diameter. As a result of their much lower terminal velocity, they are carried upward faster than the two larger drops.

Fig. 5-A

Fig. 5-B

Figure 5-B shows another example of natural breakup. The drop diameter was 8.1 mm and the stroboscopic setting was 60 cycles/sec. The narrow neck of water is easily seen on the top five or six images. The characteristic small drops, which are formed as the neck is ruptured, are not seen. It is probable that the rupturing occurred sometime between the top image and its adjacent image; therefore, the small droplet was carried out of the field of the camera.

Fig. 5-C

The photograph in Fig. 5-C is an example of drop breakup caused by a sudden change in velocity of the air stream. The drop diameter was 8.1 mm. The stroboscopic setting was 90 cycles/sec. Noteworthy in this photograph is the appearance of the drop in the top right image. At this point breakup was just about to occur. The narrow neck had formed and was ready to rupture. However, at that instant, the air stream was diverted and surface tension was able to draw the drop together. As the air stream was again allowed to strike the drop, the shock breakup occurred.

The photograph of Fig. 5-D is another example of breakup by shock or sudden change in velocity of the air stream. The drop diameter was 8.6 mm; the stroboscopic setting was 90 cycles/sec.

The drop is first seen rising in the background of the photograph. As the air stream was suddenly diverted for about 0.1 second, the drop began to fall under the influence of gravity. At this stage, the drop was falling in a manner which, as has been observed in other similar photographs, is characteristic of a drop under such conditions. The drop has rotated a few degrees on its horizontal axis and fallen laterally. When the resumed air stream again struck the drop, extreme flattening occurred. This caused a typical breakup, which resulted in 30 or more drops of various sizes. The majority of fragments were small, 1 mm in diameter or thereabouts.

It is interesting to note the type of oscillation which is occurring on some of the drops resulting from the breakup. These drops are oscillating be-

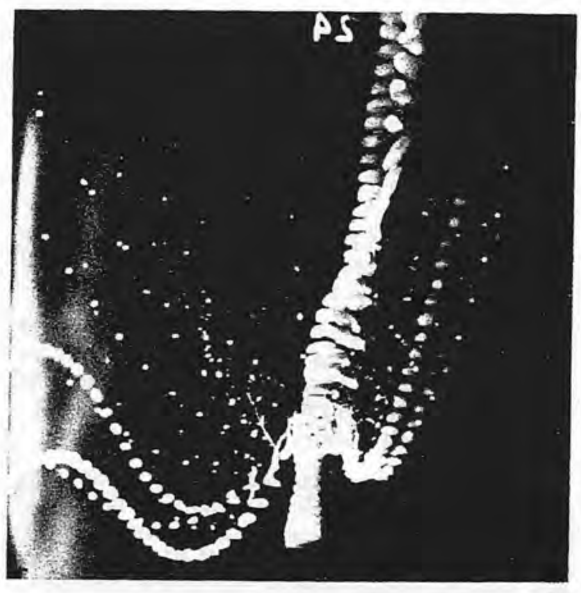


Fig. 5-D

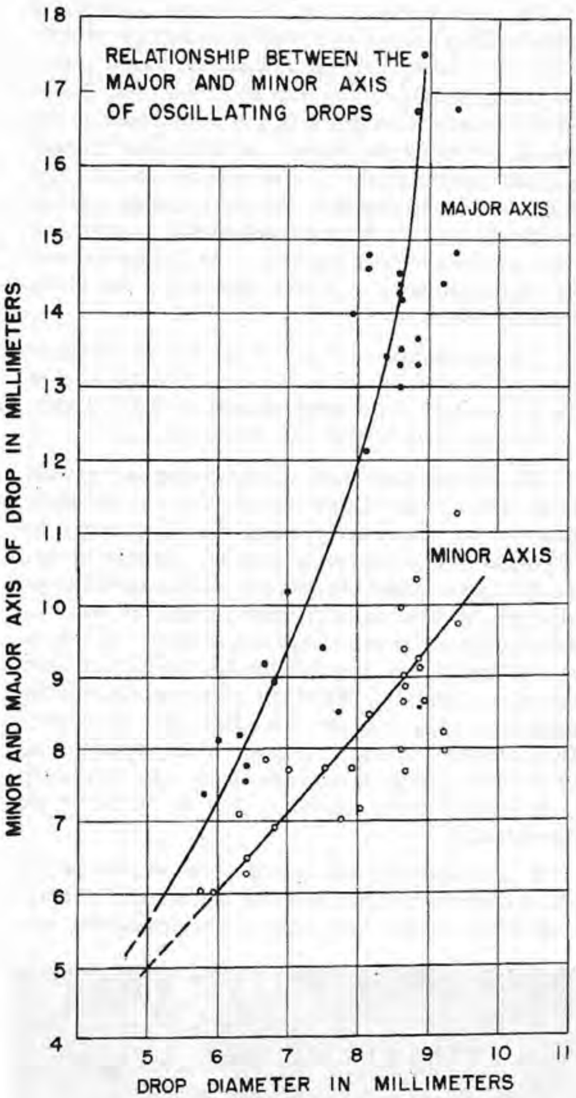


FIG. 6

tween an oblate and prolate form of a spheroid. As will be shown later in this section, this form of deformation is found only with the smaller drops.

The analysis of all the photographs taken in the course of this work has furnished the data for the following topics; (1) the major and minor axes of oscillating drops and (2) the frequency of oscillation as a function of drop diameter.

(1) The Major and Minor Axes of Oscillating Drops. It is evident from examination of the photographs of Figs. 4 and 5 that the maximum and minimum dimensions of each drop will differ considerably from the diameter based on volume consideration. Furthermore, as each drop is undergoing a periodic deformation, these maximum and minimum dimensions will occur periodically.

The graph of Fig. 6 shows the relationship of drop diameter with its maximum and minimum dimensions, which were measured along the major and minor axes of the drops. The major and minor axes were both in the same horizontal plane and at right angles to each other.

It is interesting to note that the drop diameter and the minor axis are nearly identical numerically. The major axis, however, increases rapidly with drop diameter. At drop diameters of 5 mm and lower, the ratio between the major and minor axis is close to 1, while at drop diameter approaching 9 mm, the ratio is close to 2. Thus, it is evident that the deformation is much more pronounced with large drops. While a 6 mm diameter drop may have a major axis of 7 mm, a drop of 9 mm diameter will have a major axis of approximately 17 mm.

(2) Oscillation Frequency as a Function of Drop Diameter. The periodic deformation, which takes place on water drops, will vary as a function of the drop diameter. The types of deformation, as discussed earlier in this section, are oscillation and rotation. It was explained that the rotational effects are noticeable only on drops of extreme size. Thus,

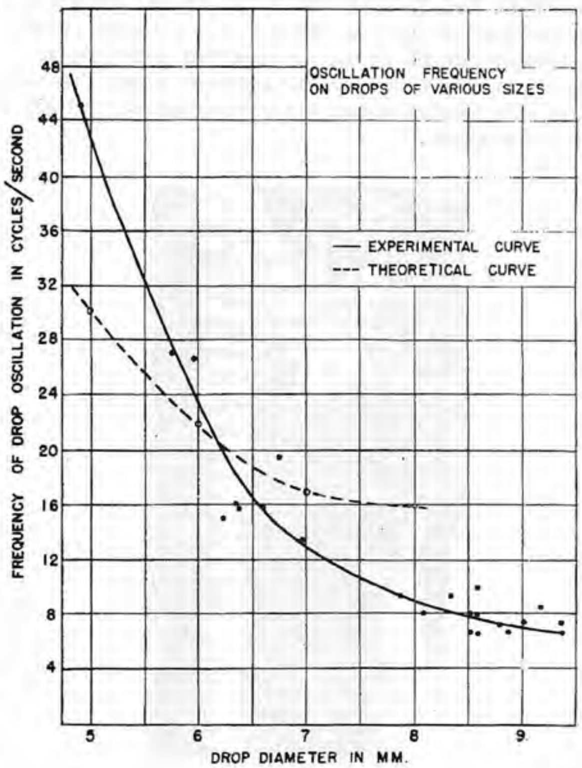


FIG. 7

in the region of drop diameters of 4 - 9 mm, deformation is mainly caused by oscillation.

However, from the analysis of photographs of drops of small diameter, it seems apparent that a third type of deformation can take place. This consists of vibrations on the vertical axis, which cause the drop to alternate between prolate and oblate spheroids.

The graph of Fig. 7, showing the relationship of drop diameter with frequency of oscillation, was constructed with data obtained from photographs of drops of 5 mm to 9.4 mm diameter.

It is interesting to note that at drop diameters around 5 mm, the oscillation frequency is about 44 cycles/second, but falls off rapidly as the diameter is increased to 6.5 mm. At 6.5 mm diameter, the frequency is about 16 cycles/second. This value falls off slowly to around 7 cycles/second at 9 mm diameter.

The dotted line was plotted from values obtained from a theoretical formula(3).

F. Breakup Fragments of Individual Drops

The type and number of particles resulting from the breakup of a water drop apparently depends upon the following three factors. These are drop size, phase and type of drop deformation, and the degree of shock given the drop. In some cases, one factor will heavily outweigh the other in controlling drop breakup.

Drop size alone will not control the method of breakup, but as the drop size determines the deformation and deformation in turn determines the type of breakup, it is a combination of the two factors, which should be considered. Large drops, that is, drops 8 mm and above in diameter, in a constant velocity air stream exhibit very little of the explosive-like tendency to fly apart into a dozen or more smaller drops as is so commonly characteristic of drops subjected to shock breakup.

Seventy-four drops, all between 8 mm and 9.5 mm. diameter, were observed in the process of breaking up in a constant velocity air stream. Eighty-nine per cent of the drops split into two approximately equal drops and a third smaller drop of about 1 mm diameter. In a few cases, two or more of these small drops were seen; 8.3 per cent exhibited characteristics of shock breakup, that is, a dozen or more fragments of various sizes moving at high velocity away from the breakup point. The remaining 2.7 per cent broke into three equal size drops with two small drops of less than 1 mm diameter. The latter case resembled the first, in that the action of breakup was smooth and non-violent.

(3) Handbuch der Physik. Vol., VII, p. 367.

The breakup of a drop into two equal size drops and a much smaller drop or drops is shown in Fig. 5-A. The origin of the small drops is in the neck of water which exists between the two large drops just at the point of rupture. The ratio of the length of the neck to its diameter determines the number of smaller drops into which it will break. As can be seen from the experimental evidence, the number is usually one. The breakup of drops in this manner is very similar to the rupturing of a jet of water as it descends from a circular orifice. Some beautiful experiments which illustrate the formation of these small drops in a falling jet are described by Tyndall.

If sudden velocity changes are applied to the air stream, a drop will break up into fragments which may number from 5 to 20, depending upon the degree of shock. Regardless of the degree of shock, the resulting fragments will have an infinite variety in size. As a majority of these fragments are below 3.5 mm diameter, their terminal velocity is lower than that of the original drop. Immediately after breakup, these fragments are travelling at velocities higher than their respective terminal velocities. Thus the upward force of the air stream is greater than the gravitational pull of each drop. It is undoubtedly this unbalanced force which causes the fragments of breakup to move away from the point of breakup at such high velocities.

G. Aerodynamic Effects as a Cause of Drop Collision

As a drop remains suspended in an air stream, unequal pressures may be found on its surface with the minimum on the top. As a result, the upward velocity of the air in the wake of the drop is lower than the upward velocity of the supporting air stream. Thus, it would be expected that by introducing a drop into the wake of a drop of equal size that the upper drop would fall rapidly toward the lower drop. It seems likely that this mechanism plays an important part in the collision build-up of rain drops in nature. The following experiment was carried out to determine the effectiveness of this mechanism.

The velocity of the air stream was set at 8.3 mm/sec; thus all drops released in the air stream would either rise slowly or eventually slide out. A drop was placed upon the center of the upper 14 by 18 mesh screen. Secondary drops of small diameter were released at heights of 2.5, 5, and 7.5 cm above the lower drop. If the upper drops were of small diameter, no collisions were observed. Instead, these drops would rise rapidly. However, with larger diameter upper drops, their rise in the air stream was less rapid. As a certain diameter drop was reached, it would fall downward and collide

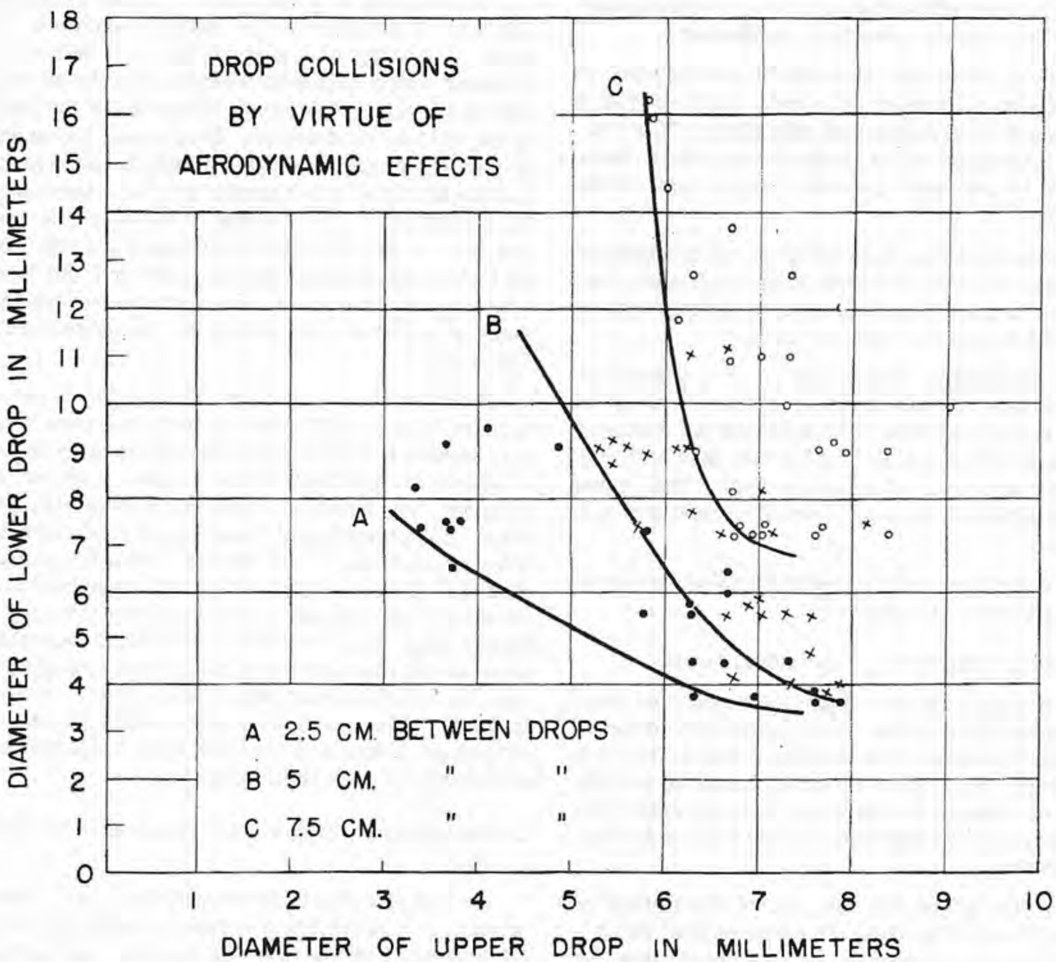


FIG. 8

with the lower drop. All drops larger than this critical size would exhibit the same effect. This experiment was tried many times with different heights between the two drops. Each time, the diameter of the lower drop and minimum diameter of the upper drop necessary for collision was recorded.

The graph of Fig. 8 shows the relationship between the drop diameters necessary for collision by virtue of the aerodynamic effects. Curve A on the graph is for 2.5 cm separation between drops. For example, if a drop of 7 mm diameter is placed in the air stream, a drop placed 2.5 cm above it would have to be at least 3.5 mm diameter to fall towards it. All drops larger than 3.5 mm diameter would be equally as effective. All points to the right of the curves will satisfy the requirements for collision, while points to the left will not. The curves are then merely boundary lines between regions where drop collisions may occur and where they may not.

As the distance between drops increases, the slope of the curve rises which indicates the sharp decrease of the aerodynamic effects with increasing distance. At a separation distance of 7.5 cm a drop must be about 7 mm in diameter to cause a drop above it to fall towards it. Even in this case, the upper drop would have to be of the order of 7 mm diameter to have any effect.

One should not confuse this type of collision with the type which takes place when a larger drop catches and collides with a lower velocity smaller drop. All drop collisions observed were due to the aerodynamic effects of one drop on the other.

It was noticed that drops placed above others and several millimeters off the vertical still exhibited the above mentioned aerodynamic effects, but to a lesser degree.

H. Drop Breakup by Collision Effects

It seems probable that an important factor in the development of rain drops in nature is related to the collisions between drops as they rise and fall in ever changing air currents, especially the development of chain reaction(4) as postulated by Langmuir.

As has been explained, collisions may result from the overtaking of a larger drop upon smaller ones, or by the "attraction" that may exist between drops by virtue of aerodynamic effects.

Previously in this report it was pointed out that drops in non-turbulent air are unstable and will begin to break if they are over 8 mm in diameter. In turbulent air, this value is much lower. The turbulent or shock effect of the air which results in the lowering of the 8 mm diameter value is not the only influencing factor. Shock produced by drop collision plays an important role.

Lenard has concluded that drops above 5.5 mm in diameter cannot exist for more than a few seconds. A later investigator, Weisner(5), concluded that natural rain drops cannot have a diameter larger than 7.2 mm. Undoubtedly, the collision of drops in nature has kept the maximum drop sizes much lower than some values reported earlier in this paper for individual drops not subject to collision.

Drops ranging from 2 - 6.6 mm in diameter have been observed colliding with drops ranging from 6 - 7 mm in diameter. The resulting drops, which varied from 6.5 to 8.3 mm in diameter were relatively stable with the exception of the drops above 7.5 mm in diameter. From the results of several observations, it has been found that it is very seldom that drops above 7.3 mm may be formed as a result of collisions. In some widely scattered cases, it has been noticed that the drops join at impact and almost instantaneously part again into two original drops of about the original size.

(4) Langmuir, I. Occasional Report No. I, PROJECT CIRRUS.

(5) Moore. Descriptive Meteorology, 208, (1910).

A METHOD FOR OBTAINING A CONTINUOUS RECORD OF THE TYPE OF CLOUDS IN THE SKY DURING THE DAY

by

Raymond E. Falconer

In December 1947, it was decided that it would be of interest to investigate the correlation that might exist between variations in sky brightness and the rate and type of snow falling. To do this, a photovoltaic cell (G. E. Type PV-1) connected to a photoelectric recorder was used to automatically record the variations in sky brightness.

The photovoltaic, or light-sensitive, cell employed (similar to those used in exposure meters) was mounted in the lower end of a piece of tubing 7 inches long by 3 inches in diameter, thus limiting the "scope" of the cell to about 15° of the sky. The tube was oriented so that the cell was directed to the north at about 15° from the zenith. The terminals of the cell were then merely connected to a photoelectric recorder having full-scale sensitivity of 75 microamperes.

Because of the high sensitivity of this recorder (on hand at the time), it was found that too much light was getting to the cell; and so two filters in the form of fine mesh wire discs painted a dull black were inserted in the tube in front of the cell to cut down the light. This allowed maximum brightness conditions (high-current values) to remain within full-scale reading of the recording microammeter.

To keep snow from collecting on the cell, provision was made for passing an air stream up through the tube. A flow of air was maintained during times of precipitation or when the instrument was to be unattended for several days. This arrangement worked quite well, especially with snow and light rains.

The original photovoltaic cell mounting is shown in Fig. 1A and 4B.

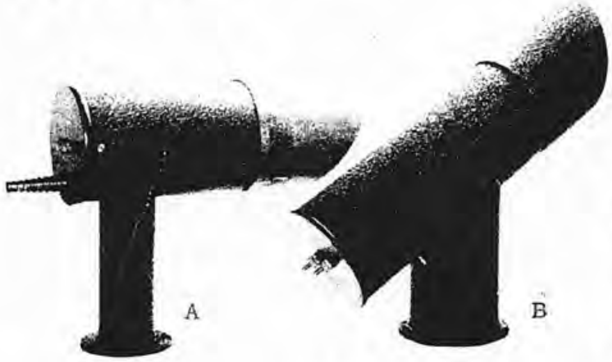


Fig. 1

First records from this sky brightness recorder indicated that although actual visibility during snow storms decreased, the sky brightness during most storms was near a maximum. This was in contrast to a much lower but steady value of brightness obtained on a clear, cloudless day. The presence of clouds and precipitation generally seemed to give brightness values greater than those observed on clear days, although it has since been found that there are exceptions, notably during the presence of dark cumulonimbus and thick nimbostratus.

After watching the record traces for sometime, it soon became evident that the type of trace shown on the sky brightness record was a rather good indicator of the type of cloud cover prevailing during a day. There seemed to be a typical trace for each general cloud type.

Fig. 2 shows actual daily traces of sky brightness recorded at the Research Laboratory in Schenectady. Chart speed was 2 inches per hour

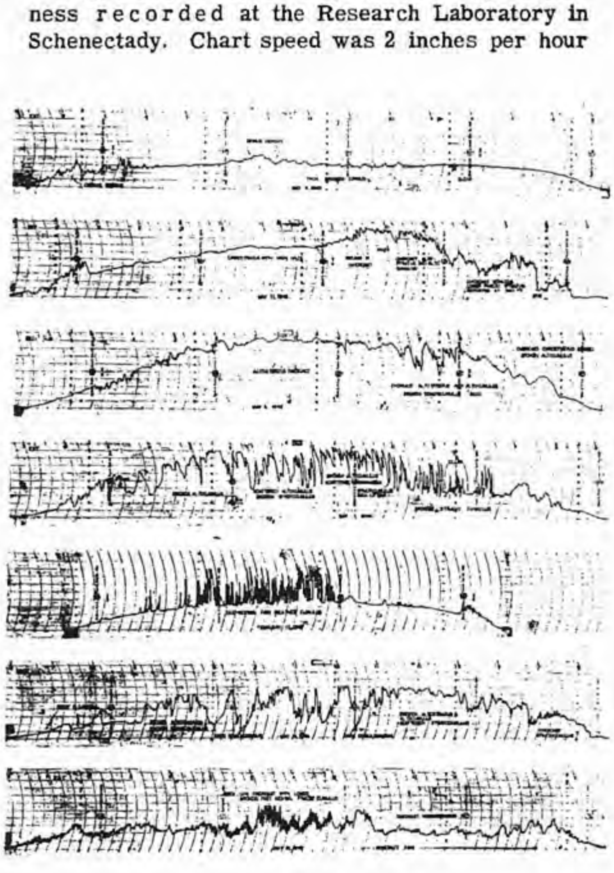


Fig. 2

and notations are from observations of sky conditions at that time.

After studying records obtained over a period of several months, it is believed that the following description of typical traces will generally hold true.

1. Normal or Clear Sky – A steady smooth trace increasing from zero current reading at sunrise, reaching a moderate value (about 1/4 full scale) during the day and returning again to zero at sundown.

2. Thin Cirrus – Small increases in brightness above normal with smooth deflection.

3. Dense Cirrus – Smooth increase in current somewhat greater than for thin cirrus.

4. Altostratus – Maximum brightness with only slight deflection from an average high-current value.

5. Altocumulus – Maximum brightness with small to moderate deflection.

6. Stratocumulus Overcast – An irregular trace mostly above normal but occasionally below if the cloud becomes very thick. The maximum value is usually about half way between normal and the average high altostratus value. Deflections are rather sharp and more definite compared to the cirrus densus condition.

7. Fair Weather Cumulus – Sharp and frequent deflections above the normal current value depending on the number of clouds passing over.

8. A combination of altostratus and/or altocumulus with lower stratocumulus will show an average high-current value with fairly sharp deflections toward normal.

9. Cumulonimbus Clouds are very dark due to their great thickness. With such a cloud, the brightness indication will be down below normal reaching practically zero current indication with a really thick thunderstorm cloud.

10. Nimbostratus Clouds are indicated by a more or less consistent average between zero and the normal clear sky condition.

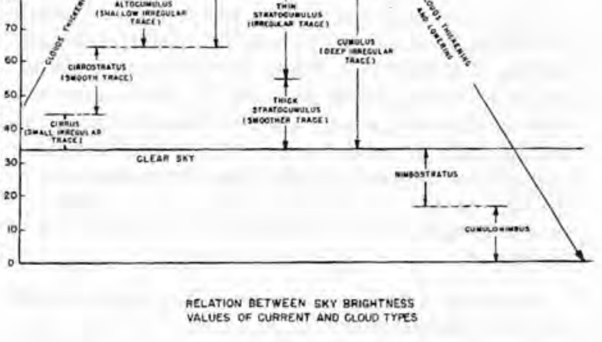
A cloud of uniform thickness will give a smooth trace with few or minor deflections while a broken cloud layer causes larger and sharper deflections from the normal condition. Scattered clouds will, of course, give fewer deflections than broken clouds. Fast moving, low cumulus or fractc cumulus will give the greatest frequency of deflections.

In general, then, high thin clouds (Ci and Cs) give slight increases above the normal clear sky current values. As these clouds thicken somewhat and lower to middle cloud levels (As and Ac), the light reading increases to maximum current values. Apparently, beyond a certain thickness, the reading goes down again from a maximum toward the normal. As thick spots in the Ac-As deck appear or, as a lower deck of Sc may form under the middle cloud layer, deflections of reduced light value are more evident. As the lower and upper clouds merge to become an extremely thick cloud layer, the reading may go below the normal clear sky value. This is particularly true of the very thick cumulonimbus clouds which may cause the light value to drop practically to zero during the passage of a thunderstorm. This sequence is shown graphically in Fig. 3.

It has been noted during apparently clear sky conditions, when a smooth trace should be recorded, that, occasionally, small deflections occur. The deflections are usually not as great as those observed with cirrus clouds. At times, it has been felt that city smoke might cause the deflections but generally there is nothing visible in the sky to which they can be attributed.

It is believed that invisible water vapor in the atmosphere may be responsible for these deflections in many cases.* On one or two occasions, these small deflections appear to have been due to very thin cumulus fumulus clouds that were barely to be seen even with careful observation. The occurrence of deflections seems to be greatest with high winds and turbulence aloft. It has also been noted, in comparing traces of two different clear days, that one trace may have a slightly higher value of current than the other. This perhaps indicates that there was a layer or layers of the atmosphere having higher water vapor content on one day than the next.

Actual values of current in light units have not been used in these preliminary experiments since the interpretation of the trace, in general, depends



RELATION BETWEEN SKY BRIGHTNESS
VALUES OF CURRENT AND CLOUD TYPES

Fig. 3

* See "Weather by Starlight" by Eric Sloane. Weatherwise, p. 32, April, 1948.

on relative, rather than actual, values of current. However, it will be desirable in the future to calibrate the instrument on standard light units.

There are likely to be different combinations of cloud types which will give the same value of brightness, thus making it difficult to interpret the record in terms of the true sky condition. In such a case, intelligent consideration of the trace as a whole and a knowledge of the usual cloud sequences should make it possible to determine cloud conditions with reasonable accuracy. The factors which will tend to confuse the interpretations, of course, are variations in the height of the cloud bases, the thickness of the cloud, and the particle size in the cloud. (In this regard, it would be desirable to correlate readings of the sky brightness meter and actual cloud heights as determined by a ceilometer or radar. The latter might also tell something about the cloud thickness and particle size.) In any event, after examining several months of records, it is believed that the sky brightness recorder as described above will, in general, give a very good picture of the variations in cloud cover during the day.

Such an instrument should be useful in automatic weather stations to give some indication of sky conditions in remote locations. Present developments of remote unmanned stations do not transmit such information, although it would seem to be important to have detailed cloud data if possible.

Some automatic weather stations do transmit solar radiation intensity which might give similar indications to the instrument herein described if the radiation sensitive element did not "scan" such a large portion of the sky. In doing so, the effect of individual clouds is lost since the radiation from them is very small compared to the radiation from the whole sky. However, by confining the area of sky scanned to much smaller dimensions, say a section of sky 15° in diameter, the presence of individual clouds in the field of scope will make large differences in the radiation or reflected light indicated by either type of recorder.

For use in an automatic weather station, a method of storing up the cloud information and then transmitting it at intervals would be necessary. No attempt has been made to work out such a method here in this laboratory, but it is thought that information could be stored up on a tape recorder during a given time interval. At the times for transmission, the tape would be run so as to repeat in a matter of seconds what has been recorded in a matter of a few hours.

Recently a modification has been made on the original photovoltaic cell assembly. Essentially, it is the same sort of construction, but a variable iris has been mounted in the tube in front of the cell, the angle of the tube has been lowered so that

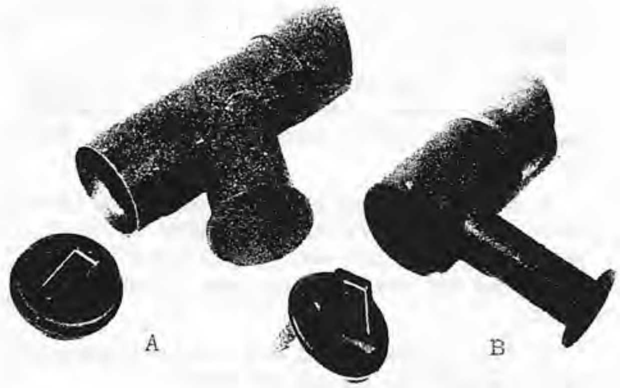


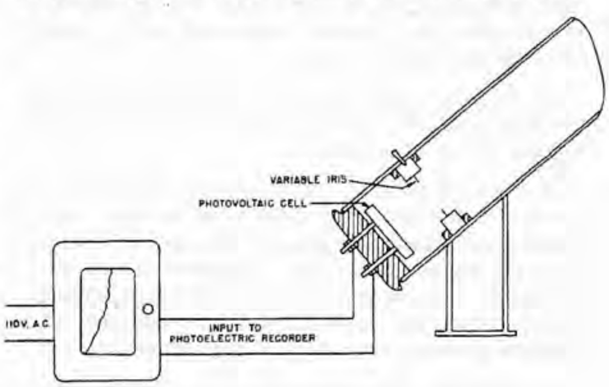
Fig. 4

its long axis is oriented about 60° from vertical and directly north, and a mounting base has been added so that it can be easily screwed down to a platform or shelf.

With this arrangement, shown in Fig. 1B and 4A, the scope of the cell is not directly overhead and thus does not represent cloud conditions right over the station but rather somewhat to the north. However, it has been found in comparing both types of mountings that there is very little difference in the two traces other than a slight lag in peaks on the curve as a cloud passes.

The advantage of using a cell mounted in this way is that it can be mounted out in the open with much less chance of the cell being effected by precipitation. This eliminates the need for blowing compressed air up through the tube. There is also little chance for direct sunlight getting at the cell and with the variable iris, the amount of light can easily be adjusted to any desired microammeter scale reading.

Two of the above units have been built. A schematic design of the arrangement is shown in Fig. 5.



SIMPLE SCHEMATIC OF PHOTOVOLTAIC CELL AND RECORDER

Fig. 5

One is continuously in operation at the Research Laboratory in Schenectady, while the other is continuously operating at the Mt. Washington Observatory, Gorham, New Hampshire.

Owing to the very severe icing and snow conditions on Mt. Washington, the cell necessarily has to be located within the building, being directly behind a special heated window pane. Records from this high altitude station (6288 feet) are essentially the same as at low land stations, except when there is a thin cloud cap over the mountain or when thin clouds are just breaking over the summit. When this occurs, the light intensity increases greatly, the deflections reaching high-current peaks with each passing cloud. Attempts are being made to correlate variations in brightness during "in cloud" conditions with values of liquid water content and drop size measured in the cloud.

For use during the hours of darkness, a box containing a photovoltaic cell unit and a projector spotlight source has been set up on the railway trestle outside the observatory building. In this self-contained unit, the cell and light source are separated by a compartment within the box so that the cell does not normally see the direct light from the source. In the presence of fog, however, light is reflected from the cloud droplets back to the cell. The amount of reflected light varies with the liquid water content and drop sizes within the cloud. This installation has only recently been completed so no comparative data have been obtained.

Another installation of a photovoltaic cell and recorder has been made in the B-17 probing plane used in seeding experiments on Project CIRRUS. The cell is mounted in a tube which is directed straight downward out of the bottom of the ship up near the nose. When the ship goes into a cloud, there is usually a very marked increase in current value. The reverse is true in coming out of the cloud. This should provide accurate means for correlating variations in temperature, humidity, etc., upon sudden entrance or exit from clouds. While the brightness might not always increase upon entering a cloud, it is felt that some abrupt change in the lighting will take place so that the desired information can be obtained.

Considerable time and experimenting could be spent in more accurately correlating continuous records of light-current values with cloud types, heights, drop size, etc., but it is not within the scope of the present contract to do so. The information obtained and presented in this report has required no great amount of time other than routine daily checks on sky conditions and servicing of the recorder. A more elaborate project might be worthwhile.

Research Laboratory
Knolls I
December 9, 1948

THE DETECTION OF ICE NUCLEI IN THE FREE ATMOSPHERE*

by

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There are few things related to weather which cause more difficulty in the temperate zones of the earth than snow storms. This is particularly true as man depends more and more on mechanized equipment. The efficient operation of automobiles and airplanes is difficult when snow covers the roads or runways.

During the winter of 1947-1948 a majority of the important snow storms occurring in the northeastern United States arrived unannounced and apparently unexpected. Among the factors which probably play an important role in the initial development of such storms is the concentration of sublimation nuclei in the atmosphere.

It can be shown in a laboratory cold chamber(1) that a cloud of liquid water droplets may easily be cooled to a temperature of -38°C. In the free atmosphere, such supercooling has also been measured by observers in the polar regions, at mountain observatories, and in aircraft.

The development of ice on aircraft in flights through supercooled clouds is often such a serious operational hazard that planes are grounded rather than risk flying through thick clouds at temperatures below freezing. At temperatures lower than -20°C, the liquid water content of a cloud system is generally so low that relatively little trouble occurs in the temperate zones of the earth even though light icing is commonly experienced.

The frequent occurrence and the physical reasons for the formation of supercooled clouds in the atmosphere must be better understood to improve the predictions related to the persistence of icing clouds or the development of snow storms. Any supercooled cloud in the free atmosphere is a potential snow source, the lack of sufficient ice crystals forming in the cloud being one of the few factors which permits such an unstable condition to exist for more than a few minutes.

During a recent study of certain physical properties of the free atmosphere, several methods were developed to detect the presence of sublimation nuclei in the air. These methods may be used whether the air is saturated with moisture or not. These methods all take advantage of the inherent property of water to exist in a supercooled state. Three different techniques were found to be useful and will be briefly described in this paper.

The Use of a Cold Chamber

The most useful method employs a box insulated on the bottom and sides which may be cooled below 0°C.

While any of the ordinary methods for cooling the chamber may be used, such as a brine solution (one part NaCl to three parts chipped ice) or dry ice (solid carbon dioxide), the most convenient equipment consists of a small commercial home freezer of two or four cubic foot capacity, although a much smaller unit may be used in field tests. Whatever the cooling method used, it is desirable, if possible, to be able to lower the temperature to at least -20°C.

To permit easy observation of nuclei in the cold chamber, the walls and bottom should be painted black or lined with black velvet. If hung loosely on the walls, very little, if any, frost will form on a velvet liner. Excellent observation of the developments which occur in the chamber may be obtained if it is illuminated with a powerful flashlight or similar light source.

To make a count of nuclei, the following procedure is recommended. A sample of air is introduced into the chamber. This may be accomplished with a blower or any similar method. A fog is then formed in the chamber by permitting water to evaporate from moistened paper, cloth, or other absorbent material placed in the cold air of the

* This paper has been submitted for publication to the Journal of the American Meteorological Society. It represents, in the main, the subject matter presented before the joint session of the American Meteorological Society and the Institute of the Aeronautical Sciences held at the Hotel Astor, New York City, January 28, 1948.

(1) Schaefer, V. J. The Production of Ice Crystals in a Cloud of Supercooled Water Droplets. SCIENCE, 104, pp. 457-459, (November 15, 1946).

Schaefer, V. J. The Production of Clouds Containing Supercooled Water Droplets or Ice Crystals under Laboratory Conditions. BULLETIN OF AMERICAN METEOROLOGICAL SOCIETY, 29, No. 4, pp. 175-182, (April, 1948).

chamber. After the cold air becomes saturated, a visible cloud forms consisting of tiny water droplets. These cool to the temperature of the surrounding air within a few seconds.

If any active sublimation nuclei are present in this air sample, they immediately start growing at the expense of the supercooled water droplets since the vapor pressure of water is higher than ice at all temperatures below 0°C.

If this happens, the particle immediately becomes visible in the light beam among the supercooled water droplets. This occurs because the flat, angular surfaces of the crystal gleam and twinkle as light is specularly reflected from the prismatic faces of the crystal.

If crystals appear in the light, their number may be estimated semi-quantitatively by counting the number visible in a given volume of the chamber. Thus, if the concentration is low, the number in the entire beam may be estimated; while if it is high, the number per cubic centimeter is noted. If the number is very low, the number of crystals seen during several minutes of observation is noted.

It is desirable, if possible, to make successive determinations of the presence of active nuclei as the box is slowly cooled. In this way, the threshold temperature may be determined for sublimation nuclei of different types and degrees of effectiveness.

Since the operation of an insulated cold chamber is practically unaffected by the temperature of the outside air, it is possible to detect potential sublimation nuclei no matter what the temperature of the outside air may be. The cold air in the chamber is stabilized due to the strong inversion which is an inherent property of such units as recommended. For this reason, it is possible to make the observations without covering the top of the chamber.

If ice crystals appear in the chamber, their crystal form may be determined (1) by direct observation under a microscope placed in the chamber (2) by preparation of plastic replicas[2] (3) by permitting the crystals to fall into a supercooled soap film and watching the form of the crystal that grows and (4) by letting the crystals seed a thin film of a dilute, water-soluble plastic. The last two methods may be used independently whenever the temperature of the outdoor air is below freezing.

Since January 1, 1948, regular observations using the cold chamber method for detecting sublimation nuclei have been conducted at the Mt. Washington Observatory as part of the fundamental weather research studies under way by our research group in Project CIRRUS . At the present writing, a total of

TABLE I
VARIATION IN NUMBER OF SUBLIMATION NUCLEI
AS A FUNCTION OF TEMPERATURE OF FREE AIR – (COLD CHAMBER METHOD)

Temp	Ca. $1 \times 10^6/M^3$	Ca. $1 \times 10^3/M^3$	$1 \times 10^2/M^3$	None
-30°C	4	5	1	1
-26°C	3	3	1	4
-22°C	5	4	0	1
-18°C	6	4	0	1
-14°C	3	5	0	3
-10°C	5	4	0	3
-6°C	1	2	5	4
-2°C	0	1	3	7
+2°C	0	3	3	6
+6°C	2	0	6	3
+10°C	0	2	3	6
+14°C	0	1	9	1

(2) Schaefer, V. J. A Method for Making Snowflake Replicas. SCIENCE, 93, 239-240, (March, 1941).

Schaefer, V. J. Use of Snowflake Replicas for Studying Winter Storms. NATURE, 149, p. 81, (January 17, 1942).

more than 1300 observations have been made at three-hourly intervals. Table I presents a typical sample of the variations which have been observed at different temperatures. The results listed represent nearly all of the observations made at the air temperatures shown when the summit was free of clouds. When supercooled clouds cover the summit of the mountain, the air often contains a concentration of ice crystals as high as five per cubic centimeter. This concentration is not high enough, however, to use up the supercooled water droplets in the air since orographic lifting condenses the water faster than the ice crystals can use it up. Many of these ice particles consist of rime fragments broken off by the erosion of blowing snow.

More data of the kind shown in the table is needed and a considerable amount of study must be conducted before any significant conclusions may be drawn from these interesting observations. The wide variations in number of sublimation nuclei observed at specific temperatures is of significance. It is this type of variation which may account for the seemingly haphazard occurrence of supercooled clouds in the atmosphere.

Plans call for a continuation of these observations for at least another year at the Mt. Washington observatory. These will be supplemented by lowland observations near sea level at Schenectady.

Use of Soap Films and Bubbles as Nuclei Detectors

There are certain film forming solutions* which may be easily supercooled. These may be used to detect ice crystal nuclei.

Films may be formed on a ring one to four inches in diameter or bubbles may be produced. This latter method affords interesting and, sometimes, spectacular results. For example, if a film is formed on a three-inch ring and then suddenly moved upward, a bubble six to ten inches in diameter may be formed. When the air temperature is about -8°C (17.6°F) from one to ten ice crystals are often observed growing in the film. These crystals assume four basic forms. They are (1) symmetrical hexagons (2) symmetrical crosses or x-shaped crystals (3) asymmetric 4-rayed crystals and (4) asymmetric crystals having more than four rays. Table II and III show typical observations made in the Mohawk Valley near Schenectady. The variations observed suggest differences in concentration of active nuclei in the air coming into contact with the supercooled bubble. When ice crystals form in large free floating supercooled bubbles, it is a common observation to see single crystals growing to a size greater than six inches. If the bubble breaks before it freezes solid, this large crystal flutters down to the earth. If no crystals form before the bubble breaks, no residue is visible except a faint mist of water droplets. If, however, a considerable number of crystals form, the number may be determined (if not more than about ten) by counting the individual fragments which fall to earth when the bubble breaks. Figure 1 shows an eight-inch diameter bubble in which crystals are growing.

Instead of using bubbles, it is also useful at times to form a film on a circular ring. Figure 2 shows such a film which has been seeded by tiny snow particles which have fallen from the sky.

TABLE II

EXTREMES IN NUMBER OF SUBLIMATION NUCLEI AS A FUNCTION OF AIR TEMPERATURE

Date	Time	Temp(°C)	No. of Nuclei	Type	Comments
2/11/48	0800	-18	50	Hex.	Alt. st. clouds
2/24/48	0700	-18	20 - 30	x	Supercooled fog in lowlands
12/25/48	0730	-14	30 - 40	Hex.	Clear
1/23/48	0800	-14	10 - 15	Hex.	Stratus overcast
1/22/48	0815	-10	10 - 20	Hex. x	Stratus overcast
2/13/48	0745	-10	3 - 5	Hex. x	Cirrus haze
1/25/48	1200	-7.8	20 - 30	Hex. x	"Frosty" air
2/19/48	0730	-7.8	1 - 5	x	Cirrus haze
2/15/48	0800	-6.6	5 - 10	Hex. x	0.8 St. cu.
3/1/48	2200	-6.6	none	--	Cirrus haze
2/24/48	2300	-6.1	none	--	Clear, 22° halo
3/15/48	0645	-6.1	none	--	Cirrus haze

* Circus Bubbles. Bombay Distributors, New York City.
Aladdin Bubbles. Aladdin Sales Company, New York City.
King Size Bubbles. Mecklenburg Specialties, Inc., Charlotte, North Carolina.

TABLE III

VARIATION IN NUMBER OF ICE NUCLEI UNDER NEARLY ISOTHERMAL CONDITIONS

Date	Time	Temp(^{o}C)	No. of Nuclei	Type	Comments
2/11/48	1300	-9.5	20 - 30	Hex. x	Alt. cumulus
1/22/48	0815	-10	10 - 20	Hex. x	Thin cu. hum.
1/23/48	0745	-9	10 - 20	Hex.	Cu. humilus
2/23/48	0800	-9.5	5 - 10	Hex. x	Scat. fr. cu., hazy
2/13/48	0745	-10	3 - 5	Hex. x	Cirrus haze
3/11/48	0645	-9.5	2 - 5	Hex.	0.8 st. cu. sun pillar
2/22/48	2200	-9.5	1 - 3	Hex. x	Clear
3/6/48	2130	-9	1 - 2	Hex. asym.	Cirrus haze
3/13/48	2200	-9	1 - 2	x	Thin haze
2/20/48	0745	-9.5	0.1 - 1.0	Hex.	Clear

When larger numbers of crystals develop in the bubble, a rough estimate of the number may be made by direct observation. This is most easily accomplished during the day by forming the bubble so that it is viewed in the general direction of the sun. At night or with an overcast in the sky, a projection floodlight may be used. The best effects may be seen if the observer looks toward the light at an angle a few degrees from its direct beam.

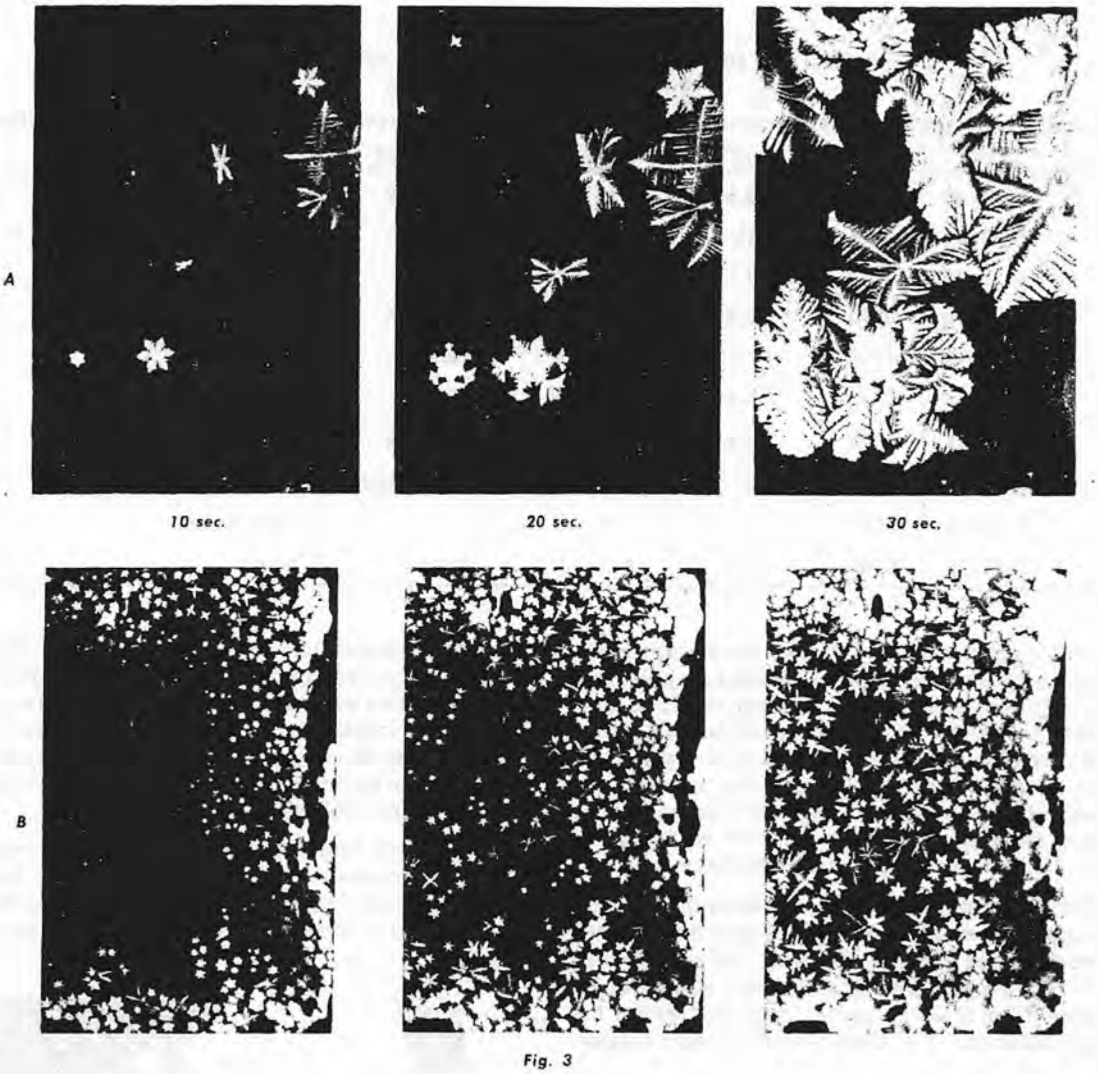
Careful study must be made to establish the difference between the effects which may be produced by sublimation nuclei contacting the supercooled film from the surrounding air and the effects which develop from freezing nuclei contained within the bubble solution. The observations to date suggest that the symmetrical six- and four-rayed crystals and the asymmetric forms having five or nine rays are produced by active sublimation nuclei from the air. The crystal forms having curved rays which are suggestive of the fern-like forms of frost are believed to be caused by the presence of freezing nuclei in the bubble solution.

An effect similar to that observed in the flat films and round bubbles may be obtained by mounting a thin film of a plastic, such as cellulose acetate*, on a frame. This is then coated with a slightly

Fig. 1

Fig. 2

* Kodapak cellulose acetate.



A, B — 10 sec. 20 sec. 30 sec.

Fig. 3

viscous layer of polyvinyl alcohol dissolved in water. A three percent solution of this water soluble plastic works quite satisfactorily. The water in the solution readily supercools. When contacted by an active ice nucleus, a large single crystal of ice grows rapidly from the point where it contacts the supercooled plastic film. As the crystal grows, it drives much of the polyvinyl alcohol ahead of it. When more than one crystal forms, this precipitated material is trapped at the interfaces between the crystals. The resulting structure, if kept in the cold chamber close to the wall, will remain unaltered as the frozen water slowly sublimes leaving a negative replica of polyvinyl alcohol. The residue thus forms a permanent record of the crystallization forms. Figure 3 shows several stages in the formation of such a replica. The successive pictures were taken ten seconds apart, 3a showing a replica produced when only ten active nuclei contacted the supercooled film, 3b showing the effect observed when many were present.

Significance of Results

It is believed that the methods described in this paper may provide data which eventually will serve to give a better understanding of the erratic occurrence of supercooled clouds in the free atmosphere. A considerable amount of data must be collected before definite correlations can be attempted to establish the relationships which probably exist between the number of sublimation nuclei in the atmosphere and the frequency of supercooled clouds or snow.

STUDIES OF THE EFFECTS PRODUCED BY DRY ICE SEEDING OF STRATUS CLOUDS

by

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An Analysis of Flight No. 23, April 29, 1948

In Flight No. 4 on April 7, 1947 (First Quarterly Report, Project CIRRUS, July 15, 1947, pages 9-11, 15, and 27-30) dry ice was dropped on the top surface of a continuous stratus cloud deck at the rate of about one pound per mile along an L-shaped seeding line having a total length of about 14 miles. Within 45 minutes, an area of about 50 square miles, still retaining the shape of the L, was observed and was photographed from a plane about 8,000 feet above the top of the stratus clouds. At the time, the sun was only 10° - 15° above the western horizon and thus, because of the difference in the directions of the sunlight scattered from the supercooled water droplets and from ice crystals, the seeded area sometimes appeared as a dark area on a light background and from other directions appeared as a light area on a dark background.

Measurements of photographs showed that the width of the seeded pattern increased at the rate of 5 or 6 miles per hour, that is, the velocity of propagation was about 2.7 miles per hour on each side of the original line of seeding. This spreading of the ice nuclei and larger ice crystals through a quiescent stratus cloud at the rate of about 1.2 meters per second was presumably due to local convection and turbulence produced within the cloud layer near the edges of the seeded area because of the heat generated by the transformation of the cloud from one consisting of supercooled water droplets to one containing small ice crystals.

Flight No. 4 demonstrated that it was possible to remove the supercooling in about 50 square miles of stratus clouds having an average temperature of about -7°C by using only 12 pounds of dry ice distributed along a 14 mile line in a period of about six minutes. The snow crystals thus produced undoubtedly settled out of the top of the cloud layer which was roughly 4,000 feet thick, but the total liquid water content of the cloud was so small that only an insignificant amount of snow was produced. In Flight No. 4 only one plane was involved and, because of regulations, this plane could not fly down through the cloud layer to observe what was occurring beneath the clouds. In future flights, it was hoped to have at least two planes and to get better photographic data of the rate of growth of the seeded area.

Studies of this kind give fundamental data on the production of snow within supercooled clouds and the elimination of icing hazard in stratus clouds. It was considered to be desirable to work with seeded areas of such size that they could be readily photographed and analyzed. We have, therefore, up to the present avoided carrying on experiments with continuous seeding over areas as large as 100 or 1,000 square miles, although it is with just such large areas that results of the greatest practical importance should be obtained.

In winter there are often extensive layers of stratus clouds of great thickness from which no snow falls, but which presumably might be made to yield snow or rain in substantial amounts if ice crystals could be generated near the top of the cloud. If the lower part of the cloud is warm, that is, if it has a temperature above 0°C, the melting snowflakes would presumably grow by accretion in accord with the Bergeron-Findeisen theory of precipitation. Small-scale experiments, such as that performed in Flight No. 4, would presumably give a valuable basis for planning for future research in the control of precipitation from stratus and even from cumulus clouds.

Flight No. 23.

It is the object of this report to describe the results obtained in Flight No. 23 made on April 29, 1948. It was hoped to obtain information as to the rate of propagation of the ice crystal cloud and to attempt to correlate this rate with the meteorological conditions which prevailed at the time. By several studies of this kind with clouds having different temperatures, thicknesses and stabilities, it should be possible to get enough knowledge of the mechanisms involved to forecast with reasonable accuracy the results of seeding operations.

This flight was arranged to be carried out over Cape Cod Bay about 50 miles southeast of Boston within range of the Weather Radar Research Project in the Department of Meteorology of Massachusetts Institute of Technology (Signal Corps Contract No. W-36-039-SC-32038). We hoped that by radar it might be possible to detect precipitation produced by seeding and that the positions of the planes could be checked. From these results, we could decide whether in future flights we should use radar and radio communication to control the flight from the ground.

Two planes from Project CIRRUS at Schenectady took part in Flight No. 23. One was a B-17 G 43-37746 and the other a B-25 J 44-86893. The planes took off from Bedford Airport at about noon and the flight was completed about 3:00 p.m. (EST), when the planes started back to Schenectady.

The B-25 carried out the seeding operations with dry ice, flew down through the seeded area, studied the precipitation seen below the clouds, and flew up through the hole produced by seeding. No photographs were taken from this plane, but some meteorological data were obtained, especially air temperatures.

The B-17 flew over the clouds in counter-clockwise circles of large diameter (22 to 33 miles) so as to keep the seeded area approximately in the center of the circle. Sequences of two to three photographs were taken at intervals of one to two minutes while the plane was flying on a straight course. Then, in response to directions given by the photographer, the course was changed so that the photographer could keep the seeded area about abeam on the left side of the plane. During most of the flight, the plane was at an altitude of 13,000 feet to 16,300 feet.

A photopanel having a camera with 35 mm film which took a photograph about every 45 seconds of the instruments on the panel and an ML-313 were installed in the B-17. There were also push buttons arranged at several points on the plane so that the pilot, the photographer, or the meteorologist could operate the photopanel at the time of taking a photograph or recording any observations. For example, when the plane was changing its altitude, readings of wet and dry bulb thermometers were taken at about every thousand-foot level during the ascent as well as the descent. The photopanel data thus included:

1. Time -- hours, minutes, and seconds.
2. Photopanel frame number.
3. Rate of climb -- feet per minute.
4. Indicated air speed -- miles per hour.
5. Indicated altitude -- feet.
6. True heading of the plane.
7. Turn and bank indicator.
8. The panel indicator which showed whether that particular frame was taken in response to the "timer", photographer on the left side of the ship, navigator, or meteorological instruments. (Indicated dry bulb, indicated wet bulb for the free air.)
9. Panel temperature (used for making corrections of the instrument readings).

At the time of Flight No. 23, there was a very extensive area of smooth topped stratus clouds that extended from Boston out over Cape Cod Bay a little beyond Cape Cod. East of Cape Cod over the Atlantic the sky was cloudless. Detailed consideration of the meteorological conditions will be contained in a later section of this report. The cloud base was at approximately 4,800 feet, and at the time of the first seeding the top averaged about 8,100 feet. At the cloud base, the free air temperature corrected for dynamic heating was -2.8°C. Below the cloud base down to the surface of the sea, the lapse rate checked well with the dry adiabatic lapse rate. Just above the cloud top there was a temperature inversion of one or two degrees centigrade and between 9,000 and 9,600 feet altitude, the temperature was constant at -11.2°C. In the clear air above that, the lapse rate up to 16,000 feet was quite constant with the value of 2.28°C per 1,000 feet as compared with the dry adiabatic lapse rate of 2.96°C.

Photographic Data - Data obtained during the flight consisted of 68 photographs which were taken between 1306 and 1446 EST. These were taken with a Speed Graphic camera on 4-inch x 5-inch negatives with a 5-inch focal length. From these pictures, enlargements were made with a two-fold enlargement ratio giving 8-inch x 10-inch photographs corresponding to a focal length of 10 inches. It was desired to use these photographs for the measurement of vertical and horizontal angles.

If the top of the stratus deck is flat and at a constant known altitude and the horizon is clean cut, then, according to the methods described in the First Quarterly Report, it is possible by measurement of a single picture to determine the shape and size of the pattern outlining the seeded area. To locate these modified areas and detect horizontal and vertical movements, it is desirable to know accurately the position of the plane at all times and the direction of the camera axis at the time the photographs are taken. If these data are available, however, it becomes possible to make an independent determination of the size and shape of the seeded area by comparing horizontal angles in two or more successive photographs without the use of vertical angles and without accurate knowledge of the position of the horizon line. This procedure is particularly useful when the top of the stratus cloud is not flat or where the cloud altitude changes with time. In this case, one determines horizontal distances and positions by photographic triangulation using as a base line the length and direction of the line connecting consecutive air stations at which pictures are taken. The flight directions are obtained from the photopanel data and the lengths of the lines are calculated from the air speeds and the time intervals between the photographs.

The Flight Path of the Plane - During the flight a few "fixes" were obtained by Loran and by radio compass, and in a few cases, by rough observations of points on Cape Cod seen through holes in the cloud. These data. however, were found to be rather unreliable and the positions so determined were incompatible to such a degree that average errors of the order of several miles were evident. The procedure adopted was to calculate the flight path of the plane with reference to a set of co-ordinates fixed with respect to the air through which the plane was flying at the altitude of the plane; that is, the flight path was determined by dead reckoning from the photopanel data including heading, time, and the air speed but without allowing for wind drift. The air speed was, of course, corrected using the altimeter pressure, the air temperature from the meteorological data, and the instrumental errors. Figure 1 gives the flight path calculated in this way between 1252 and 1447 EST. The numbers placed along the line in Fig. 1 are the running numbers of the photographs. The scale giving distances in miles is placed at the lower part of the figure, and the direction in which each photograph was taken is indicated by the directional arrows.

The method of constructing the flight path from the photopanel data will be described in more detail in a later section of this report. An examination of Fig. 1 will show that after some original maneuvers for the purpose of getting into position, the B-17 described a path consisting of a 3/4-circle about 15 miles in diameter from which photos 1 to 5 were obtained. The first seeding was done about the time

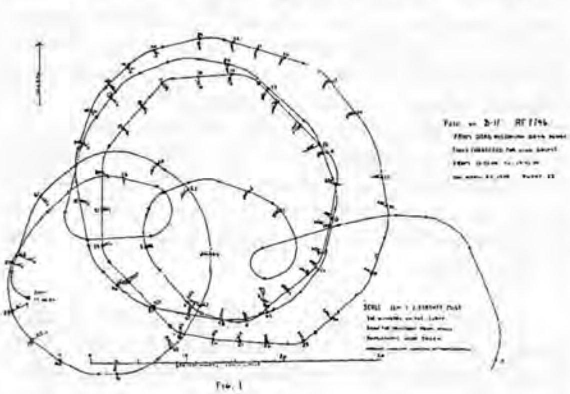


Fig. 1

that photo No. 2 was taken. The fact that the plane then described 2 3/4-circles having a common center (which was not far from the place at which photo No. 2 was taken) proves that the photographer, who was directing the course of the plane, was observing a definite point in the cloud deck which was moving with respect to the ground at a rate about the same as that of the air through which the plane was flying. In our first analysis of these data, plots were made of the flight path of the plane with respect to the ground taking into account the drift due to a wind velocity of about 30 miles per hour from 300° true north. The flight path in that case resembled a cycloid rather than a series of circles because the plane was circling about a moving point.

In Fig. 1 it was seen that after 2 1/2 turns, roughly 30 miles in diameter, the plane made a small loop, took photo No. 56, and then made 1 1/4 turns of another circle about 22 miles in diameter while photos No. 56 and 68 were taken. Again, it is significant that the path described is quite accurately a circle.

As a matter of fact, the three large circles up to photo No. 55 represent circling about the first seeded area, while the small circle from photos No. 56 to 68 represents the path flown while the second seeded area was being photographed.

Seeding Operations During Flight No. 23

Seeding No. 1 - This consisted of an L-shaped figure forming two sides of a square with two "point drops" at the fourth corner of the square. The seeding started at 13:07:30 on the course of 254°. After flying on this course at a true air speed of 187 miles per hour for 45 seconds (a distance of 2.1 miles), a sharp left turn was made so that within 30 seconds the course had changed 90° to a course of 159° true north. The radius of the turn was 0.9 miles. The straight flight along the 159° continued for 45 seconds (a distance of 2.1 miles). At this point, the dispensing of the dry ice, which had been going on at about two pounds per mile for a distance of 5.6 miles along the seeding path, was stopped. Then a second 90° left turn was made in 30 seconds to a course of 74° and at about 20 seconds later, 1 1/2 pounds of dry ice were dumped at one point and about 20 seconds later, a similar amount was dumped. The times of these "point drops" were not accurately recorded.

The effects produced by the first seeding will be described in detail later but the photographs show the beginning of effects in about photo No. 8, and photographs of this area were taken regularly up to photo No. 55 at 1414 EST.

Seeding No. 2 - At 1418 the decision was made to seed a new area southwest of the original one using six "point drops" along a straight line on a course of 240° which would give a seeding line along the length of a band of cloud still remaining. The clouds near the original seeded area were gradually beginning to dissipate as they moved out to the sea past Cape Cod, but the six "point drops" were made over a strip of cloud about ten miles wide and twenty miles long, which was still unbroken. Unfortunately, the course flown by the seeding plane, instead of being 240°, was 204°. According to the records taken on the B-25 plane this second seeding started at 1426 on a heading of 204° true north and was completed at 1428 at the same heading. The six "point drops" of 1 1/2 pound each were spaced about 20 seconds apart, corresponding to a distance of one mile since the air speed was 180 miles per hour.

The Position of the Plane - During the time in which photographs were being taken it was planned, as far as possible, to fly the plane on a straight course at constant altitude so that two or more consecutive pictures could be taken until the photographer found that the seeded area was falling so far behind that it was obscured by the elevator surface. Then by interphone he notified the pilot that a lef turn should be made until such time as the photographer found that the seeded area could be photographed just back of the wing tip. At the beginning and end of each turn, the pilot caused a photopanel record to be made by pressing a button. During the turns a nearly constant rate of turn was maintained, and an analysis of data shows that, in general, the radius of curvature during these turns was about four miles.

A rather large scale plot was made from the air speed data, the time, and the heading of the plane as recorded by the photopanel. All necessary corrections were applied to the indicated air speed and the indicated heading. All the points shown by small circles on the track given in Fig. 1 show the positions of the plane at which photopanel data were recorded. Table I gives photopanel data only for the air stations at which the photographs were taken.

An analysis of the plot showed that the flight path could be broken down into straight sections, during which photographs were taken, and circular arcs in which the heading of the plane, φ, varied linearly with time. The length of the line S along these straight or curved sections of the flight path was obtained by multiplying the air speed by the time interval. In order to plot the flight path as shown in Fig. 1, it was found convenient to calculate the radius of curvature R of the curved flight sections. Let S be the distance traversed by the plane during one section of the flight having a duration of t seconds. Then we have

$$S = Vt. \qquad (1)$$

When the plane during the time t describes a circular arc of length S, the radius of curvature is given by

$$R = S/\theta, \qquad (2)$$

where θ is the angle (in radians) through which the plane has turned in time t.

The plotting of the points shown in Fig. 1 in small circles is done most conveniently by calculating the length of the chord C which corresponds to any given circular arc θ. The relation between C and R is given by

$$C = 2R \sin (\theta/2). \qquad (3)$$

When the angle θ is less than about 90°, C may be calculated by a series expansion based on Eq. (3).

$$S - C = (R\theta^3/24)\,(1 - \theta^2/80 + \ldots). \qquad (4)$$

The whole flight path as shown in Fig. 1 can be constructed graphically by laying out the straight lines corresponding to the straight parts of the flight path, each line having the direction φ as given by the corrected photopanel data. For the circular arcs, the difference in the values of φ between the beginning and end of the curved arc gives θ for use in Eq. (2) and (3). The length of the chord C is then calculated by Eq. (3) or (4) and the direction of this line is the arithmetical mean of the initial and the final value of φ. It was found, however, to be more convenient to calculate the co-ordinates x and y of the successive air stations by multiplying the length of the chord C by $\cos\varphi$ or $\sin\varphi$ to get the increments of x and y.

All the points shown by small circles in Fig. 1 were plotted from the corresponding value of x and y and were checked graphically by observing the lengths of the sections and the azimuths φ of the straight sections and the chords.

Table I gives the locations of the points at which photographs were taken. The table contains data for the time, the heading of the plane, φ, the true air speed, the co-ordinates x and y from an arbitrary origin, and the azimuth of the camera axis.

Analysis of the Photographic Data - In order to determine the position and the shape of the seeded area during the course of its development after seeding, it is important to know the direction φ_c in which the photograph is taken, that is, the azimuth of the camera axis or the principal plane of the photograph. The tip of the left wing or the left elevator showed in nearly all the photographs. Since the photographs were taken from a fixed position in the ship and the angle to the wing tip or the elevator tip was known with respect to the ship's head, it was possible to determine φ_c.

An independent check of the correctness of these angles was obtained in an examination of the photographs by picking out in pairs of consecutive photographs two or more points that were seen in both.

Table I

DATA FOR THE FLIGHT PATH

Flight No. 23

Photo No.	Time E. S. T.	True Heading φ	True Airspeed mi/hr	True Altitude + 1000 ft	Co-ordinates (miles) x	y	True Camera Axis
1	13 0632	322	225	13.3	28.15	46.08	237
2	0733	292	220	13.3	24.95	47.98	216
3	1145	162	223	13.3	14.16	42.56	76
4	1342	136	229	13.3	18.49	36.79	48
5	1523	78	228	13.3	24.48	34.97	44
6	1604	52	221	13.3	26.68	36.24	349
7	1645	52	226	13.3	28.66	37.79	323
8	1727	52	216	13.3	30.74	39.41	316
9	1814	14	199	13.3	32.25	41.73	305
10	1905	16	196	14.8	33.01	44.45	282
11	2021	10	205	14.8	33.80	48.50	267
12	2121	316	216	14.8	32.84	51.66	240
13	2222	314	221	14.8	30.23	54.22	227
14	2317	312	222	14.8	27.73	56.51	206
15	2448	268	224	14.8	22.95	59.16	181
16	2544	266	226	14.8	19.46	58.98	158
17	2645	230	223	14.8	15.75	58.35	139
18	2733	222	228	14.8	13.65	56.22	135
19	2818	224	229	14.8	11.70	54.13	124
20	2935	178	218	15.1	9.54	49.86	99
21	3035	182	203	15.1	9.54	46.22	81
22	3139	178	201	15.1	9.54	42.56	67
23	3301	136	223	16.1	12.25	38.79	52
24	3357	136	227	16.1	14.66	36.29	37
25	3459	108	226	16.1	17.57	33.71	15
26	3554	92	225	16.1	20.98	33.11	9
27	3638	96	228	16.1	23.73	32.92	2
28	3721	92	229	16.1	26.45	32.73	354
29	3822	62	227	16.1	30.28	32.90	336
30	3919	50	229	16.1	33.14	35.09	323
31	4053	20	230	16.1	37.29	39.31	297
32	4246	350	227	16.1	38.93	46.27	268
33	4331	350	227	16.1	38.44	49.07	258
34	4504	320	230	16.1	36.12	54.44	241
35	4607	320	230	16.1	33.54	57.51	225
36	4730	286	230	16.1	28.88	59.83	208
37	4816	286	231	16.1	26.05	60.64	195
38	4856	286	231	16.1	23.58	61.35	186
39	4951	258	235	16.1	20.09	61.71	173
40	5106	252	234	16.1	15.30	60.65	159
41	5156	228	235	16.1	12.54	58.98	140
42	5235	230	240	16.1	10.62	57.32	130
43	5322	200	235	16.1	8.77	54.86	118
44	5410	200	236	16.1	7.70	51.92	104
45	5536	168	234	16.1	7.69	46.36	84
46	5804	132	234	16.1	11.47	37.84	53
47	14 0010	102	232	16.1	18.93	34.98	26
48	0103	102	232	16.1	22.26	34.27	8

Table I (Cont'd)

DATA FOR THE FLIGHT PATH

Flight No. 23

Photo No.	Time E. S. T.	True Heading φ	True Airspeed mi/hr	True Altitude + 1000 ft	Co-ordinates (miles)		True Camera Axis
49	14 0219	74	228	16.1	27.01	35.00	350
50	0406	32	229	16.1	32.19	39.26	309
51	0529	12	232	16.1	33.71	44.27	---
52	0730	338	230	16.1	32.37	51.54	289
53	0929	310	231	16.1	27.04	56.89	251
54	1049	280	232	16.1	22.60	59.32	209
55	1411	220	235	16.1	10.71	56.09	183
56	2444	284	224	16.1	12.03	48.57	119
57	2846	202	232	16.1	0.46	40.35	90
58	3002	160	240	16.1	0.38	35.55	66
59	3055	132	241	16.1	2.32	32.67	48
60	3148	120	241	16.1	5.18	30.60	34
61	3320	90	237	16.1	11.04	29.26	01
62	3456	52	236	16.1	16.68	31.79	321
63	3615	32	234	16.1	19.65	35.93	288
64	3739	0	229	16.1	20.63	41.22	264
65	3926	318	232	16.1	18.38	47.56	222
66	4029	302	234	16.1	15.16	50.00	203
67	4354	224	235	16.1	3.23	47.08	148
68	4530	200	239	16.1	0.84	41.29	100

By connecting these points in one photograph by straight lines and extending these to the horizon, the direction of the line could be calculated from the position of this horizon point on the photograph. In spite of the fact that two consecutive photographs might be taken from points 2 or 3 miles apart, the directions of the points where these lines meet the horizon in successive pictures are identical since parallel horizontal lines on a photograph converge towards a single point on the horizon. Actually to get high accuracy by this method, it was necessary to apply corrections because of the curvature of earth and the depression of the horizon. These methods will be described later.

A comparison of these two methods indicated that, in general, the accuracy of the camera azimuth φ_c was such that the average error was about $\pm 2^{\circ}$. There were a few photographs taken in which neither the wing tip nor the elevator showed and it was, therefore, necessary to depend on the photographic method to determine φ_c. In flights made subsequently to Flight No. 23, a wire was stretched from the wing tip to the elevator which carried near its center an insulator which showed in all the photographs. From the known position of this insulator, it was then possible to determine φ_c.

During the course of Flight No. 23 a series of sixty-eight photographs were taken from the photo plane. Only eight of these have been selected to illustrate particular phases of the operation.

Photo No. 1 (1-23-746) illustrates the stratus deck existing before the initial seeding run.

Photo No. 2 (25-23-746) shows the L-shaped seeded area 27.5 minutes after seeding and also the location of the spot drop beyond.

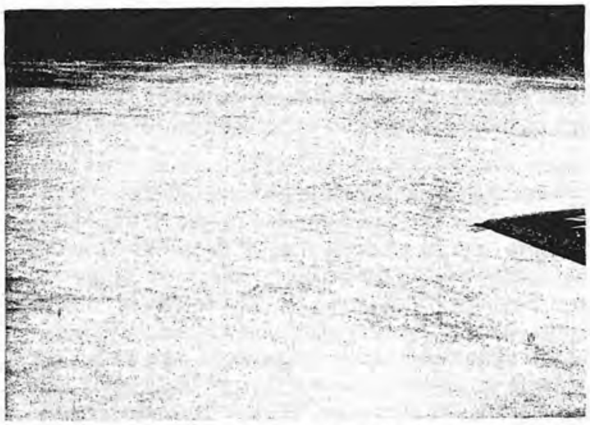
Photo No. 3 (27-23-746) shows the modified region after 29.1 minutes at which time the spot drop is difficult to see.

Photo No. 4 (46-23-746) shows the area 50.5 minutes after seeding with a considerable depression visible.

Photo No. 5 (57-23-746) was taken just as the seeding plane was finishing its run during which six "point drops" of 1 1/2 pounds were made at one mile intervals. On the original photo, the seeding plane may be seen as indicated by the circle, and the third modified area is already 0.33 miles in diameter 113 seconds after seeding.

Photo No. 6 (59-23-746) shows the six areas 4.3 minutes after completing the seeding run. At this point the second area, indicated by the arrow, has grown to a diameter of 0.40 miles.

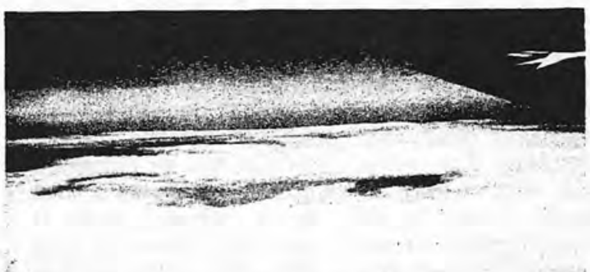
Photo No. 7 (65-23-746) shows the six areas as ellipsoids approximately one mile in diameter 12.5



PHOTOGRAPH NO. 1

PHOTOGRAPH NO. 2

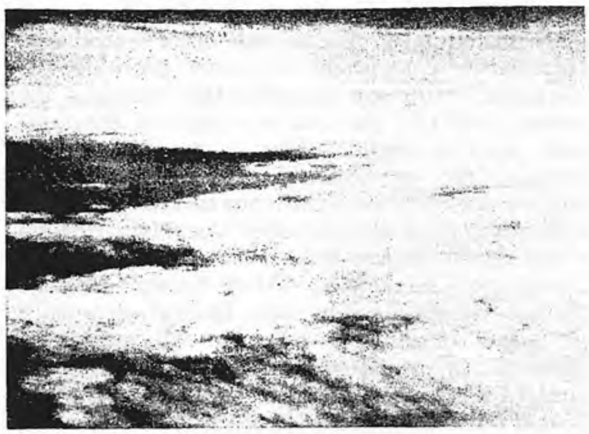
PHOTOGRAPH NO. 3



PHOTOGRAPH NO. 4

PHOTOGRAPH NO. 5

PHOTOGRAPH NO. 6



PHOTOGRAPH NO. 7

PHOTOGRAPH NO. 8

minutes after seeding. A careful analysis shows that they are nearly exact circles.

Photo No. 8 (68-23-746) shows the last photo taken after 19.5 minutes at which time most of the supercooled clouds had dissipated leaving the six circular clouds of ice crystals as persistent snow areas. This is an excellent example of overseeding.

General Effects Produced by Seeding

The observers on the B-17 plane noticed the effects within less than 5 minutes after seeding, but the effects are only clearly recognizable in the photographs beginning with photo No. 13. The distance and position of the seeded area with respect to the sun in these first photographs were such that the contrast was not sufficiently good for reproduction in this report. The original photographs, however, beginning with photo No. 12, show the seeded area unmistakably, and it is even possible to go back and detect the early effects of the seeding beginning in photo No. 6 taken about 9 minutes after seeding. The plane was at a distance of about 10 miles. By photo No. 16, however, the L-shaped pattern was clearly recognized, and it could be seen that the width of the seeded area had already increased to more than one mile. The far edge of the seeded area appeared in some places as a very sharp line illuminated by the sun indicating that the top of the seeded area had subsided to a depth of about 400 feet. Another portion of the L (the northeast leg) showed a type of cumulus development indicating that some snow crystals had been carried upward to a height of about 500 feet above the original height of the stratus deck so as to hide the far edge of the seeded area. In photo No. 18 both the near edge and the far edge are clean cut and definite along most of the length. The "point drop" is also separately recognizable. In photo No. 19 the subsidence of the topmost surface of the seeded area has progressed further. The width of the NE leg of the L was about two miles. In photo No. 21 the whole L is becoming much more distinct, and the top surface now appears quite uniform about 600 feet below the original level without any appreciable indication of snow having been carried aloft. Photo No. 22 shows a further development of the same type. In photo No. 23 the width of the L at the bend is about 3.7 miles, and the diameter of the "point drop" is 1.5 miles.

Photos Nos. 24 to 27 show an apparently dark area developing just to the west of the bend of the L just outside of the rather sharp boundary of the seeded area. Gradually this seems to move into the seeded area or the boundary extends out past the dark area. It is believed that the dark appearance is caused by the thinness of the cloud at this point so that much light, instead of being reflected back into the sky, is transmitted down to the surface of the sea. The width of the seeded area along its whole length gradually increased, but the inner edge of the bend appears to rise along the original level with some cumulus activity coming from below. The outer edge of the seeded area, however, near the edge of the bend appears to be depressed and thin.

Photos Nos. 28, 29, 30, and 31 show somewhat less contrast and are not suitable for reproduction. During this time the southern leg of the L gradually seems to merge with the "point drop" so that the whole pattern takes the form of a large U. However, later, beginning with photo No. 33, the southern part of this pattern seems to become rather indefinite, and the pattern becomes again more like an L; but the angle at the bend is then greater than 90°. The seeded area, at all times, retains its individuality and remains separate from other areas in the stratus clouds which were gradually dissipating. The northern leg of the L shows a considerable cumulus development from photo No. 30 on to No. 34 with clouds that finally rose to nearly 1,000 feet above the original stratus deck. Beginning with photo No. 34, the edge of the L, especially at the northern end, becomes very clear cut and dark edges form to make it look as through the cloud in some places had wholly cleared away but with snow falling from the edge. Photo No. 36 shows that the seeded area has a total length of 9.5 miles and a maximum width of 5.2 miles. In photos Nos. 36 to 39 the whole seeded area appears dark in color with complete breakthrough in about 20 percent of the area, but new and presumably supercooled cloud layers are slowly forming across a part of the seeded area. These, however, are relatively thin and are, in general, considerably lower in elevation than the top of the undisturbed stratus. Photos No. 41 to 46 show a gradual increase in the area from which the clouds have been removed. Photo No. 46 shows this very clearly. The total area within the seeded area which is now devoid of clouds covers about 30 square miles. It is seen particularly well from this photograph that out over the sea at a distance of about 35 miles there are no clouds. A long strip of cloud running approximately north to northeast at a minimum distance of about 25 miles from the photo station is seen in photo No. 46. In the north, there is a partly cloudy area to within a distance of about 17 miles. The seeded region is now an elongated area only slightly resembling an L having a total length of about 10 miles and a maximum width of about 7 miles. Photos Nos. 47 to 51 have been analyzed in great detail. About 20 to 30 points that are identifiable in the upper surface of the clouds have been used to determine horizontal and vertical angles, and the comparison of horizontal angles in successive photographs has been used to determine the shape and size of the seeded area. Then by measuring the vertical angles below the horizon, the altitudes of the cloud top and the various cloud formations within the seeded area have been determined. Photo No. 57 was taken just after the completion of the second seeding in which the B-25 flew on a course of 204° and made six "point drops" about a mile apart along a straight line. An examination of the photographs shows very clearly four "point drops" and it shows the B-25 (about 0.3 millimeters in size on an 8-inch x 10-inch photograph) just in front of the nearer of the two cumulus clouds that lie at the right hand side of the photograph. From the known speed of the plane, it is possible to calculate the exact time of seeding and the time that has lapsed between the first four "point drops" and the time at which photo No. 57 was taken.

end on and now the circular form of the separate seeded areas is very apparent and the diameter can be measured accurately. It has been found that the diameter of the second seeded area was 1.04 miles and the others lie very close to the same value. A reference to Table II shows that the age of the spot at this time is 775 seconds, thus indicating that the diameter increased at the average rate of 4.8 miles per hour during these first 13 minutes. In photo No. 66 the line of the six seeded spots is seen almost end on, but there is poor contrast. The seeded areas appear as six circular areas which have already begun to overlap so that the circles are now considerably over a mile in diameter. The seeded areas are very close to the edge of the stratus clouds.

Point Drop Number	Time	Diameter (miles)	Age (sec)	Rate of increase in Diameter (miles per hour)
1	14:26:10	0.32	156 sec	7.4
2	14:26:31	----	135 sec	---
3	14:26:53	0.33	113 sec	10.6
4	14:27:08	0.27	98 sec	9.9

It is remarkable that within two minutes each seeded area appears as a circle of diameter 0.3 miles, having increased in diameter at a rate of nearly 10 miles an hour. In the photograph, the seeded area appears as a line rather than as a circle. Calculations show, however, that at a distance of 6.6 miles, the seeded area should appear as an ellipse of high eccentricity not appreciably different from that shown in the photographs.

In successive photographs, the diameters of the circles increase regularly although as the plane circles the seeded areas, the line of seeding is sometimes seen end on and sometimes from the side. In photo No. 59, all six of the points are clearly recognizable, and we can see that they are now definitely ellipsoidal in shape and that they are increasing rapidly in size.

In the next photograph, No. 60, the azimuth of the picture is 34° so that the line is seen nearly end on. The contrast, however, is rather poor and not good for reproduction. It should be noted in photo No. 58 that the dark area at the upper left near the point at which the six point seeding commenced, there is a large area nearly free from clouds. This is the southern end of the original seeded area, seeded 43 minutes previously. This can also be recognized in all succeeding photographs up to photo No. 62. An analysis of photo No. 61 shows that the width of the seeded area is now about 8 miles, but the northern end has merged into the dissipating cloud areas that lie to the NE. The six seeded points are recognizable in photos Nos. 61 to 63, but the contrast is very poor so that they cannot be reproduced. In photo No. 65, however, the line is again seen nearly

The last two pictures, Photos. Nos. 67 and 68, show the line of six seeded areas running across the picture nearly at the edge of the clear sky. They appear in the photographs as cigar-shaped clouds, but they are probably truly circular lenticular clouds. They have a very different texture from the unseeded clouds, appearing slightly darker in color and seeming to persist although all the rest of the clouds around them are dissipating. This is presumably due to the fact that ice crystals have a lower vapor pressure than supercooled water droplets so that when the cloud dissipates, the ice crystals persist longer than the cloud of water droplets.

Effects Produced on the Temperature and Turbulence within a Stratus Cloud by Seeding

Wet and dry bulb free air temperature readings were taken on the B-17 plane while climbing to 16,200 feet and again when descending. The dry bulb temperatures were corrected for the effect of dynamic heating by subtracting from the observed reading 0.85° multiplied by the square of true air speed in hundreds of miles per hour. The water vapor pressure was calculated from the difference between the indicated dry and wet bulb temperatures and the ambient pressure at that altitude (not the stagnation pressure). From this vapor pressure, the mixing ratio x was calculated.

The results showed that from the ground level up to the base of the cloud at 4,800 feet the lapse rate was constant and equal to the dry adiabatic lapse rate of 3.0°C per thousand feet. In these calculations, the relation between the altitude and the pressure was determined by integration taking into account the temperatures as they varied with altitude. The mixing ratio x between 980 feet and 3,900 feet was constant at 3.0 ± 0.05 g per Kg of dry air, indicating that vertical convection was probably occurring or at least that there was neutral stability. The free air temperature at the cloud base, 4,800 feet, was -2.8°C and the pressure was 836 mb. Calculations show, however, that if the mixing ratio throughout the air mass were constant at 3.00, the cloud base, according to Weather Bureau charts, should be at 785 mb and at a temperature of -7.0°C corresponding to 6,520 feet altitude. If this mixing ratio continued up to the top of the cloud at 8,100 feet where the pressure was 737 mb, the water vapor content (x) at the top of the cloud would be 2.4 so that the liquid water content would be 0.6 g/Kg.

$$\lambda = C(1 + B)/(1 + A/T), \qquad (5)$$

where C is the dry adiabatic lapse rate;

$$C = 0.986 \times 10^{-4}\ ^{\circ}C/cm \qquad (6)$$

or

$$C = 3.00^{\circ}C \text{ per 1000 foot rise}; \qquad (7)$$

$$B = 9.059\ Le/T(T - e) \qquad (8)$$

and

$$A = 2.574\ (L/T)p/(p - e). \qquad (9)$$

In these equations, L is the latent heat of evaporation of the water or ice, and e is the corresponding vapor pressure for saturated water or ice. For water, we put $L_W = 608$ and for snow or ice $L_S = 678$. We thus have for supercooled water,

Table II

		Before Seeding			After Seeding		
Altitude feet	Pressure mb	Temp °C	Mixing Ratio x Kg/m³	Liquid Water Content g/m³	Temp °C	ΔT	Snow Content g/m³
4710	839	-2.5	3.70	0	-2.5	+0	0
4800	836	-2.8	3.70	0	-2.64	+0.16	0.04
5800	807	-4.8	3.28	0.44	-4.51	0.29	0.50
6800	777	-6.86	2.91	0.80	-6.38	0.48	0.86
7800	746	-8.97	2.58	1.00	-8.36	0.61	1.18
8100	737	-9.63	2.48	1.19	-8.96	0.67	1.26
Averages		-6.05		0.63	-6.45	0.40	0.69

On the other hand, at the base of the cloud, 4,800 feet, the air was saturated and, therefore, must have had a mixing ratio of 3.70 g/Kg. Table II contains data for the temperature distribution and the liquid water content within the cloud on the assumption that the cloud originally contained supercooled water droplets and that the total water content, vapor and liquid, x + y was constant at a value 3.70 g/Kg. It is also assumed that the temperature distribution corresponds to the saturated adiabatic for liquid water. It is desired to then calculate the changes in temperature that would result when this cloud is seeded with dry ice. When these enormous numbers of ice nuclei are produced, the water droplets evaporate giving vapor which condenses on the ice nuclei and the temperature of the cloud rises because of freezing of the water, and the increase in the snow content above that of the original water because of the vapor pressure of the ice is less than that of the water. Equations have been derived for calculating the saturated adiabatic lapse rate for a cloud containing supercooled water and for one containing ice crystals. The lapse rate λ is given by

$$B_W = 5509\ e_w/T(p - e_w) \qquad (10)$$

and

$$A_W = 8.62 \times 10^6\ e_w/T^2(p - 2e_w) \qquad (11)$$

and for snow

$$B_S = 6142\ e_S/T(p - e_S) \qquad (12)$$

$$A_S = 1.072 \times 10^7 e_S/T^2(p - 2e_S). \qquad (13)$$

The lapse rates for the 1000-foot intervals centering about 5,300 feet, 6,300 feet, and 7,300 feet were calculated from these equations with the results given in Table III. From the data of the second column of Table III, the temperature changes per thousand feet were calculated giving the results shown in column 3 of Table II.

In the B-17 one measurement was taken of the temperature within the cloud. At 7,630 feet with a pressure of 750 mb, the dry bulb temperature was -7.2°C. If we apply the usual correction for dyanmic heating, the temperature should be -9.9°C whereas according to Table III, it should have been -8.62°C.

Table III

LAPSE RATES FOR THE STRATUS CLOUD, FLIGHT 23

Altitude	Saturated Adiabatic Lapse Rates in °C per 1000 feet	
	Water	Snow
5,300	2.00	1.84
6,300	2.06	1.93
7,300	2.11	2.00

The discrepancy of about 1.3° is undoubtedly due to partial neutralization of the dynamic heating by the cooling effect of the liquid water. The temperature of -9.9°C at that altitude would obviously be impossible for it would correspond to a highly super-adiabatic lapse rate.

Table II also gives the mixing ratio calculated from the e_w and p. Multiplying this by the density, which ranges from 1.078 Kg/m^3 at 4,800 feet to 0.975 Kg/m^3 at 8,100 feet, we obtain the liquid water content in column 5 expressed in g/m^3. The average liquid water content within the cloud thus comes out to be 0.63 g/m^3.

An equation has been obtained (whose derivation will be presented in a later report) by which the rise in temperature, ΔT, produced by seeding can be calculated. The equation is

$$\Delta T = \left[333.\ y_1(p - 2e) + D\right] / \left[(p - 2e) + E\right] \quad (14)$$

Here ΔT is in °C, y in grams of liquid water per gram of dry air, and p and e are in mb. The quantities D and E are given by

$$D = -16.95\ t_1(1 - 0.0067 t_1)\ e_{s1} \quad (15)$$

and

$$E = 144.2\ (1 - 0.0073\ t_1)\ e_s 1, \quad (16)$$

where t_1 is the initial temperature in °C at any point before seeding and t_{s1} is the vapor pressure of ice at that temperature.

Using this equation, the temperature rises produced by seeding are given in column 7 of Table II. The final temperature, t_2, is given in column 6. The last column shows the snow content in g/m^3. It is seen that it is greater than the water content before seeding.

Observations from the B-25 Plane

The following is a log of operations following the completion of seeding.

13:11 The B-25 circled over the seeded area to observe the effects which were produced.

13:18 The seeded area was first noticed at this time.

13:20 The seeded area was very apparent.

13:28 to 13:32 The plane descended through the seeded area following the same path as originally seeded with headings of 279° and 106° and noted that the base of the cloud was at 4,700 feet.

13:35 Precipitation was seen falling from the seeded area.

13:36 It was noted that precipitation was in the form of light snow. As seen from below small holes appeared within the seeded area.

13:38 The precipitation area was very pronounced at this time and it had descended to an altitude of 3,000 feet.

13:41 to 13:43 While descending from 2,900 feet to 2,600 feet, turbulence was noted although previously there had been no turbulence.

13:51 Flew at an altitude of 2,500 feet directly through the precipitation area, which was apparently caused by the seeding. The visibility in this cloud was less than 1/8 mile. The precipitation was falling in the form of rather large snowflakes.

13:53 At an altitude of 2,600 feet.

13:54 Altitude 1,800 feet. The precipitation was still descending and reached this altitude. The plane gradually descended keeping pace with the bottom of the precipitation.

13:56 Altitude 1,500 feet.

13:58 Altitude 1,200 feet.

13:59 It was noted that the precipitation was dissipating, probably melting and evaporating.

14:06 The plane climbed up to the hole and reached the top of the seeded area at 14:18. This was the time that photos No. 52 and 55 were taken.

14:26 Seeding No. 2 was made.

An analysis of these data show that snow was falling at the rate of about 50 to 60 centimeters per second. Within 20 minutes after seeding at 8,100 feet snow had already fallen to the 2,000 foot level, and in 20 minutes more the lower part of the precipitation had reached the 1,200 foot level at the rate of about 90 cm per second, assuming that the precipitation started from the base of the cloud at 4,800 feet. However, much of the precipitation started at a higher level which corresponds to speeds greater than this. No observations have been made of how long the precipitation lasted after 13:59 when it was observed that the precipitation at 1,200 feet was dissipating. Presumably, precipitation at a higher level was continuing from the edges of the seeded area. This at least was what we had observed in the flight of March 7, 1947 when a seeded area passed over Schenectady.

From the observation that the mixing ratios for water vapor in the air below the clouds are practically constant at 3.0 Kg/m^3 and the fact that the free air temperature corresponds with the dry adiabatic lapse rate, we can calculate the relative humidity and the wet bulb temperatures at each altitude. Snowflakes which fall from clouds into relatively dry air below cannot begin to melt until they reach a place where the wet bulb temperature is above freezing. According to these calculations, this altitude is 3,200 feet. The snowflakes would naturally fall several hundred feet below this level before showing any appreciable melting. This agrees well with the observation. The visibility is only 1/8 mile at 2,600 feet where presumably the visibility was a minimum, and at 1,200 feet the precipitation had dissipated.

We have estimated that the average liquid water content in the cloud was about 0.7 g/m^3 and that the thickness was about 1,000 meters. Thus if all the liquid water in the cloud was precipitated without loss to the ground, it would give 700 g/m^2 or a depth of 0.07 cm of water or roughly 0.7 cm of snow. In December 1946, in analyzing the flight data in which Dr. Schaefer seeded his first cloud on November 13, 1946, a theory was developed for the rate of growth of snowflakes after ice nuclei are introduced into a cloud of supercooled water droplets. The rate of growth of the snow crystals under these conditions can be calculated by the equation

$$r^2 = 2\ MD(p_w - p_s)t/\sigma RT. \qquad (17)$$

In this equation, M is the molecular weight of water (18), D is the diffusion coefficient of water vapor in air, p_w is the saturated vapor pressure of water, p_s is the saturated vapor pressure for snow or ice, t is the time in seconds, is the effective density of the snowflake, T is the absolute temperature, and R is the gas constant 8.37×10^7 ergs per degree. This equation is derived for the case of a sphere. It can be applied to the growth of a snowflake by choosing appropriate values of radius r and the density . Schaefer has found that at temperatures of -5 to -10°C, such as prevailed in Flight 23, the primary crystals that form at the introduction of ice nuclei produced by dry ice are in the form of small hexagonal plates having a thickness about 1/10 of the maximum diameter. We may, therefore, let r in Eq. 17 be the diameter of the hexagonal plate, and we can choose the density p by assuming it to be that of a sphere which has a total surface equal to that of the hexagonal plate. If we take the thickness of the snow crystals 1/10 of its diameter, we find that the value of is 0.27 g/cm^3. It is evident from Eq. 17 that the diameter of the primary snowflake increases in proportion to the square root of the time. Table IV enables us to see how the rate of growth depends on the temperature.

Table IV

THE RATE OF GROWTH OF SNOW CRYSTALS IN AIR SATURATED WITH RESPECT TO WATER

Temperature	Diameter after 1 sec
0°	0
-5°C	1.35×10^{-3} cm
-10°C	1.55
-15°C	1.50
-20°C	1.40
-30°C	1.07
-40°C	0.75

To determine the size of the crystal at any other time, one simply multiplies the values given in the second column of Table IV by the square root of the time in seconds.

While the snowflake grows in size, it falls at an increasing speed. When the particles are small during the first five minutes of their growth, their velocity of fall is given by Stokes' Law. We may again use the equation for spheres and take the effective density to be 0.27 for hexagonal plates having a thickness 1/10 of their diameter. The velocity of fall thus becomes

$$v = 3.7 \times 10^5\ r^2, \qquad (18)$$

where r is in centimeters and v is in centimeters per second. By combining this with Eq. 17, we find that the velocity increases in proportion to time or, in other words, they move with uniform acceleration. If we use the data in Table IV for the temperature range from -5 to -10°C, we thus find approximately that the distance which the growing snowflakes fall with time is

$$x = 0.05\ t^2, \qquad (19)$$

with the distance measured in centimeters.

These calculations show that primary hexagonal snowflakes which fall at a rate of 60 centimeters per second would have a diameter of 0.06 cm, would have a thickness of 0.006 cm, and would weigh 25×10^{-6}g. According to Eq. 17, it would take about 10 minutes for the crystals to grow to this size.

From the weight of these flakes, we may then estimate the number of flakes that would have to fall per cm^2 to give the total precipitation of 0.07 cm depth of precipitation at the base of the cloud. We find in this way that there will be about 3,000 snowflakes per square centimeter, and if we assume that the whole cloud covered 45 square miles about 25 minutes after seeding, it would mean that about 3×10^{15} snowflakes fell from the cloud. Let us suppose that if crystals fall in any one place, they form a column 1,000 feet high which is the thickness of the cloud. Then we find that the average concentration of the snowflakes is 0.03 flakes per cm^3, so that the snowflakes were on an average of about 3 centimeters apart while falling through the air. On this basis, we can estimate the visibility. The area of the hexagonal face of each snowflake would be about 0.003 cm^3, or since the snowflakes are in more or less random directions, the effect of a light beam that can be intercepted can be taken to be about 0.002 cm. With a concentration of 0.003 flakes per cm^3, we thus find that the amount of light intercepted is 6×10^{-5} per cm. The reciprocal of this, or 170 meters, gives the effective free path of the light rays in reasonable agreement with the observation that the visibility was 1/8 mile (200 meters).

It is also interesting to know whether snowflakes of this character would collide with one another and form clusters as they fall onto the ground. The effect can be estimated roughly by assuming that half the snowflakes are falling with a velocity of 40 meters per second while the other half fall at 70 meters per second. We find then that the change of any particular snowflake colliding with another is 0.005, and during this time, it travels an average distance of 60 centimeters. Thus we see that on average, one of these primary snowflakes will fall only about 120 meters before it collides with another one. At the height of 2,600 feet we will, therefore, have most of the flakes scattered in clusters. It is a common observation that the clustering of small snowflakes has almost no effect on the velocity of fall, and we see small clusters, large clusters, and hexagonal flakes falling side by side at a velocity of 150 centimeters per second.

It thus seems that the seeding experiments of Flight 23 precipitated all of the condensed moisture from an area of roughly 50 square miles in the form of falling snow. Even if all the snow had fallen to the ground without melting or evaporating, it would not have given more than 5 to 7 millimeters depth of snow. Actually, however, the humidity below the cloud was far too low to permit any snow or rain to reach the ground.

It has been mentioned before that in planning these seeding tests, we have deliberately chosen to work with relatively thin clouds and small area seedings. From such experiments, however, we can draw very definite conclusions as to what would have happened if a similar seeding run had been made at the top of a stratus cloud 3,000 or 4,000 meters thick. Since the liquid water content of most stratus clouds is nearly zero at the base and often increases to a maximum at the top, the total precipitable water is roughly in proportion to the square of the thickness. In such a case, the seeding, like that of Flight 23 which gave 3×10^{15} snowflakes, could have given a precipitation of, say, five millimeters; and over an area of 50 square miles ($1.3 \times 10^{12} cm^2$), the weight of rainfall produced would have been of the order of 10^6 tons.

The data from Flight 23 may also be used to estimate effects that might be expected by the seeding of very large cumulus clouds. Consider, for example, a cloud which gives a total rainfall of one inch of water within half an hour. If the raindrops are of the diameter of 4 millimeters, each drop will weigh about 0.003 g, and it will only take about 85 rain drops per square centimeter to give this rain, whereas in Flight 23 there were about 3,000 snow crystals per cm^2. Consider, also, a large cumulus cloud in which the active part covers an area about 20 square miles and the cloud top is 25,000 feet high and the base is at 5,000 feet. With the dry adiabatic lapse rate below the cloud, the temperature would be 30°C at sea level, 16°C at the cloud base, 0°C at 15,000 feet, and -20°C at the top of the cloud. The liquid water content would increase from zero at the base to 3 g/m^3 at 10,000 feet, 5.2 at 15,000 feet, and 6.2 at 25,000 feet, the average liquid water content being 4.3. The total precipitable water would then be 2.6 centimeters. Of course, these figures may be reduced by the effect of entrainment of drier air into the cloud. On the other hand, in extensive cloud systems such effects are often not important. The number of ice nuclei which were actually found and introduced into stratus clouds in Flight 23 would appear to give snowflakes in the freezing level which could, in accord with the Bergeron-Findeisen theory, give heavy rain on the ground even without any increase in the number of nuclei originally present.

There is conclusive evidence that in naturally occurring storms a small number of nuclei originally present can produce snowflakes which by various processes can then be multiplied, probably by fragmentation. Such effects should occur under favorable conditions with clouds which have been seeded. It is very important to conduct experiments so as to realize these conditions of self-propagating snow or rain storms. It has been pointed out elsewhere* that the snow crystals falling below the freezing level and melting can, in the case of a thick cumulus cloud with high internal vertical velocities, set up a chain reaction causing heavy rain to form from relatively few nuclei at the top. Seeding with dry ice, however, which produces enormous numbers of such nuclei could speed up the beginning of such reactions and, therefore, should sometimes give rain of exceeding severity. I believe such storms would be produced in tropical areas and more will be reported about these at a later time.

The Propagation of Ice Nuclei in Stratus Clouds and the Effect of Stability in Cloud Layers

In Table III it has been shown that in Flight 23 the seeding produced an increase in temperature at the base of the cloud of 0.1°C and 0.6°C at the top. If the seeding is done along a single line, and the dry ice pellets fall through the whole cloud layer, the seeding actually takes place over a vertical plane surface which is, at first, of very limited thickness. The dry ice pellets do not fall strictly vertically but move laterally, probably to several meters, because of the irregular shapes of the falling particles. It is very important to study the mechanism by which these nuclei may be carried out as much as three miles from the original line of seeding within one hour in a cloud that has no appreciable internal turbulence. The spreading is, of course, produced by new turbulence set up due to the local temperature rise in the seeded portion of the cloud.

Consider, for example, a vertical sheet of cloud having a thickness B but extending vertically through the whole height of the cloud and horizontally with the plane of seeding. If we had only to consider a volume of air having a temperature ΔT above its surroundings, we would find that the warm air would rise and mix with the surrounding air and the temperature would thus be lowered. In the case of a seeded cloud, however, the conditions are very different. The number of nuclei is almost inexhaustible, and thus as the warmed part of the cloud which contains ice crystals and nuclei mixes with the supercooled cloud surrounding it, the temperature of the whole mass that is involved rises and stays at the temperature, ΔT, above the surrounding cloud. Thus as the seeded layer gets thicker, the forces capable of producing and maintaining turbulence increase in magnitude.

If we consider a sheet of cloud filled with ice nuclei where the temperature is ΔT, this parcel of air would seem to have a vertical acceleration equal to $g\Delta T/\Delta T/T$. This acceleration sets up velocities which increase with time, but frictional losses are also beginning to increase so that finally the velocity reaches a limiting value.

In a large air mass, once a parcel of air is heated it tends to rise, but its movement involves the neighboring air masses. Thus the acceleration of the air and the terminal velocity are not as high as they would be if these surrounding air masses did not exist. These effects can be taken roughly into account by dividing the acceleration by 2. We can thus calculate the order of magnitude of the velocities of seeded clouds by the following two equations:†

$$v = (1/2)\,g\,(\Delta T/T)t \qquad (20)$$

and

$$v = \sqrt{g(\Delta T/T)S}. \qquad (21)$$

The first equation gives the increase in velocity during the period of acceleration, and the second equation gives the limit of terminal velocity after a circulation has been set. With a thin sheet of seeded cloud of thickness B, we may put S = 2B, for the vertical currents that are set up rise up to a distance of only twice the thickness of the layer before turbulence mixes them with surrounding air. The result is that the thickness of the layer, B, increases in proportion to the square root of time roughly according to the following equation.

$$B = (1/8)gt^2(\Delta T/T). \qquad (22)$$

Taking this change in thickness into account, one can then calculate that the velocity of the updraft of the seeded sheet is

$$v = (1/2)gt(\Delta T/T). \qquad (23)$$

With the rise of temperature of only 0.5°, it can be calculated that within three minutes, terminal velocities of 1.5 meters can be set up in the seeded area and that the thickness by that time will have reached about 100 meters. The above calculations are, of course, based on the assumption that there is no inherent stability within the cloud, that is, before the seeding the lapse rate corresponds to the saturated moist adiabatic.

It is evident that when the thickness B of the seeded layer becomes half the thickness of the cloud, S_c, the foregoing equations no longer apply. You can, however, use Equation 21, replacing S with S_c. If we use the data of Flight 23 using $S_c = 10^5$ cm, putting ΔT as 0.40°, the average temperature rise produced by seeding, we find that the terminal velocity of the vertical currents would be about 4 meters per second or about 9 miles per hour. This vertical velocity would occur, of course, in a region a few hundred meters thick near the edge of the seeded pattern. Within the interior of the pattern, temperature is uniform and vertical currents

† Occasional Report No. 1, page 26.

* I. Langmuir. "The Production of Rain by a Chain Reaction in Cumulus Clouds at Temperatures Above Freezing." Occasional Report Number 1, Contract No. W-36-039-SC-32427, (15 April 1948).

would die out. These vertical updrafts from the inside of the pattern near this boundary will carry the ice nuclei upwards and spread them out over the surrounding area. The fact that the horizontal propagation velocities of about 1.5 meters per second are observed is not surprising.

Let us consider what would happen if the air mass S_c is stable, that is, it has a temperature lapse rate λ less than λ_0 which we take to be the saturated adiabatic lapse rate. Under these conditions, it is easy to see that a temperature rise, ΔT, at any given place in the cloud will cause that air parcel to rise only to a height S above its original position given by

$$S = \Delta T/(\lambda_0 - \lambda). \quad (24)$$

Since according to Eq. 21, the velocity v varies only in proportion to the square root of S, we still have considerable vertical velocities at the boundary of the seeded area even though there is very marked stability. Under the conditions of Flight 23, it was seen that the saturated adiabatic lapse rate of a cloud layer would be 2.0°C per 1,000 feet, which corresponds to $\lambda_0 = 0.67 \times 10^{-4}$ deg/cm. If now we assume that the lapse rate in the cloud is only half as great, viz., 1.0°C per 1,000 feet or $\lambda = 0.33 \times 10^{-4}$ as in the above case, then v=1.5 meters per second instead of 4.0 meters per second. So, even in these stable clouds there could still be a reasonable rate of propagation. As each parcel of air containing ice nuclei rises to a new level, it spreads out to that level coming into contact with the seeded cloud and causes a rise in temperature in the new parcel so that again we have a new propagation in a higher layer.

If there is already turbulence within the cloud, then it would appear that the effects of seeding may propagate much more rapidly. In large cold cumulus clouds, for example, the effects may be expected to propagate very rapidly throughout the cloud.

The Effects of Overseeding

In the foregoing analysis of Flight No. 23, the rate of growth of snowflakes as given, for example, in Table IV has been calculated on the assumption that the snow nuclei are so far separated that each is surrounded by water vapor saturated with respect to water. If a limited volume of cloud is seeded with relatively large amounts of dry ice, enormous numbers of minute ice nuclei are formed, the water drops evaporate, and cause these minute nuclei to grow. However, there is not enough water vapor to allow them all to grow to very large size. The original cloud may have had, for example, 200 to 500 water droplets per cm^3, whereas the number of new ice crystals formed may be 10 or 100 times greater. If there are too many, the smaller ones will evaporate to give vapor which condenses on the larger ones. In any case, the number of ice crystals will be larger than the number of water droplets originally present. Such an ice cloud may be more stable than one which grew from a cloud of liquid water drops and the velocity of fall of the particles may remain negligible. Along the lines of seeding, an L shaped pattern, there frequently remains a cloudy area which persists long after the surrounding clouds have dissipated. An excellent example of such an effect is seen in photos Nos. 67 and 68 where the six ice crystal clouds have persisted long after most of the other clouds have disappeared.

In the seeding of small cumulus clouds, one usually finds just this effect -- the seeding produces no visible snow fall, and no one but a skilled observer detects the change from a supercooled cloud to one consisting of ice crystals. It is only by looking for halos and brightness at different angles that one sees the ice in the cloud.

In the case of an unbroken deck of stratus clouds, however, the seeded area is always surrounded by one in which there are no ice crystals. In this region of low concentration of ice cyrstals, snowflakes grow rapidly so that as they accumulate, they fall out of the cloud. It is, therefore, near the edges of the seeded area that one finds the broken edges. The seeded area frequently remains filled with ice crystals which cut down the visibility.

It is planned in future flights to study the seeding of stratus clouds with particular emphasis on the production of large cleared areas suitable for landing of aircraft. We, therefore, plan to fly a flight pattern as follows: Fly the plane first in a direction approximating that of the wind movement about 10° to the left of the wind. Fly a straight line for about 20 miles seeding at the rate of about one pound per mile. Then make a sharp left turn for a radius of one mile, continuing seeding. After turning through an angle of 155°, straighten out, cross the original seeded line, and on the new course fly 20 miles while continuing seeding. We thus have a seeded pattern which consists of a huge V with an ellipse on the upwind vertex and with two huge arms 20 miles long. On the inside of the V near the apex and in the ellipse, the effects of overseeding will be apparent, but as the effects propagate from both seeded lines towards the axis of symmetry, the concentration of ice nuclei decreases and, therefore, the size of snowflakes increases in size and a long clear line should be left along this axis which is free even from snowflakes. I believe that experiments conducted in this way will be particularly valuable in studying the feasibility of clearing large areas for use of aircraft.

Under favorable conditions, the converging seeded areas near the axis may give self-propagating effects which we desire to know more about.

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