INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
34100 TRIESTE (ITALY) - P.O.B. 586 - MIRAMARE - STRADA COSTIERA 11 - TELEPHONES: 224281/2/3/4/5/6
CABLE: CENTRATOM - TELEX 460392 - I

SMR/164-2

AUTUMN WORKSHOP

IN

CLOUD PHYSICS AND CLIMATE

25 NOVEMBER - 20 DECEMBER 1985

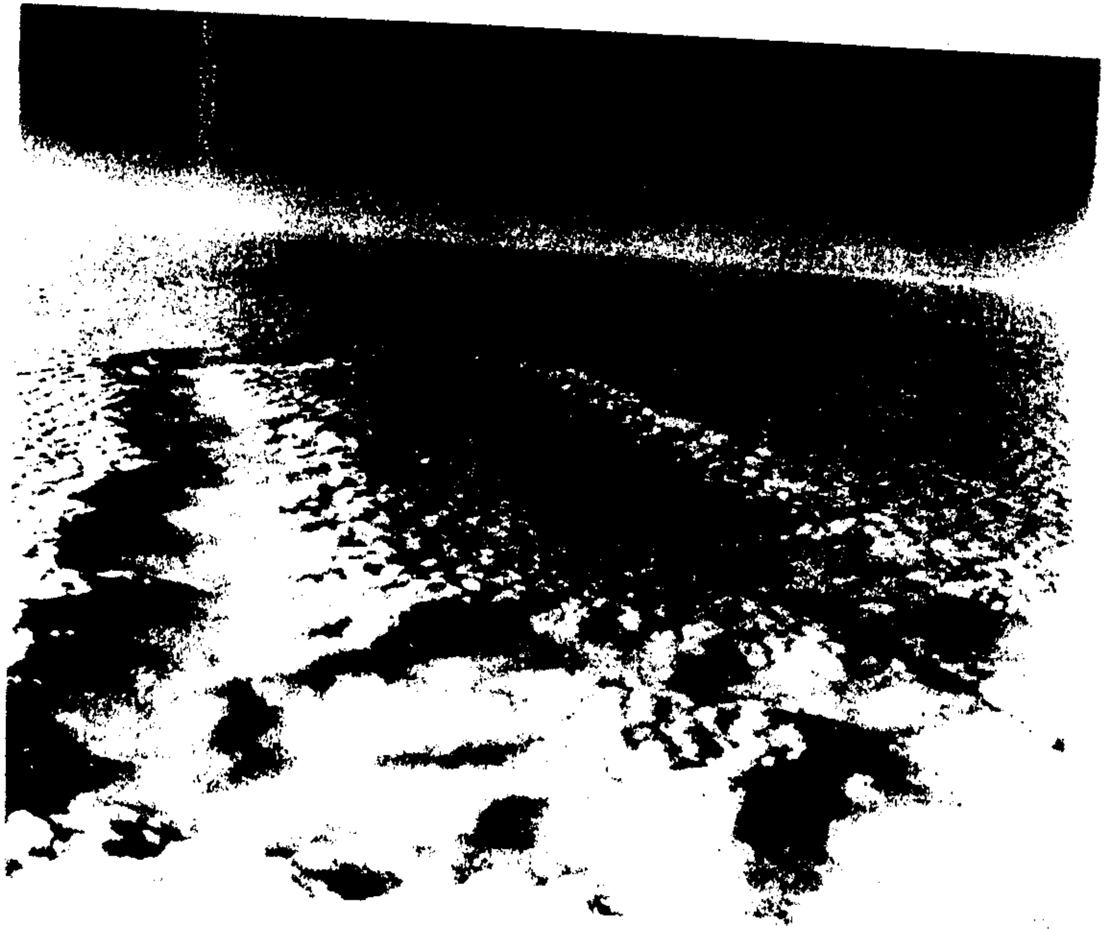
EARLY HISTORY OF CLOUD SEEDING

B. VONNEGUT

Atmospheric Sciences Research Center
ES 323
State University of New York at Albany
1400 Washington Avenue
Albany
New York 12222
U.S.A.

Barrington S. Havens
James E. Jiusto
Bernard Vonnegut

EARLY HISTORY OF CLOUD SEEDING



EARLY HISTORY OF CLOUD SEEDING

BY

BARRINGTON S. HAVENS

WITH ITALICIZED ANNOTATIONS

BY

JAMES E. JIUSTO

AND

BERNARD VONNEGUT

PUBLISHED BY

LANGMUIR LABORATORY
NEW MEXICO INSTITUTE OF MINING AND TECHNOLOGY
SOCORRO, NEW MEXICO

ATMOSPHERIC SCIENCES RESEARCH CENTER
STATE UNIVERSITY OF NEW YORK AT ALBANY
ALBANY, NEW YORK

RESEARCH AND DEVELOPMENT CENTER
GENERAL ELECTRIC COMPANY
SCHENECTADY, NEW YORK

1978

PREFACE

One of the pleasantest writing assignments of my professional General Electric career was that of preparing the history of Project Cirrus. Not only was the subject itself of great interest to me, providing as it did an opportunity to learn something about weather and meteorology, but the work involved made it possible for me to enter into an exciting atmosphere of scientific inquiry and to make the acquaintance of a number of splendid people, with some of whom I was privileged to form lasting friendships. Perhaps the greatest privilege of all was the opportunity to know and work with, however peripherally, that astonishing genius, Irving Langmuir.

Consequently, when Dr. Vonnegut asked me for my cooperation in bringing this 25-year-old history down to date, I was delighted to agree. In the course of that undertaking, I found that the subject had lost none of its fascination and the associations none of their appeal. For the reader's benefit, in order that the revisions may not interfere with the unity of the original narrative, the updating material has been inserted throughout the text in the form of italicized indented paragraphs.

As an entirely personal side light on the matter of the periodic cloud seeding in New Mexico in 1949, and 1950, I found it interesting to recall that at that time I was spending winter weekends at my camp in the foothills of the Adirondacks. I quickly became conscious there of a recurring pattern of weather behavior over a period of many weeks, with periods of clear weather and snowfall alternating with a regularity difficult to reconcile with the random behavior with which I was familiar. It was not until I was later engaged in compiling this history that I learned of some of the debate concerning this complex issue.

Finally, I feel it is necessary to point out that my role in preparing the original account was and has been strictly that of a chronicler, contributing nothing but the services of a professional writer, and taking advantage of every opportunity to rewrite or lift verbatim the original material of others where it served the purpose. After all, this is one of the necessary functions of a conscientious historian.

Barrington S. Havens

Following the discovery of cloud seeding by Vincent J. Schaefer in 1946, an extensive cloud physics research program known as Project Cirrus was carried out at the General Electric Research Laboratory under U. S. government sponsorship. When this work drew to a close in 1952, a history of its activities was prepared in accordance with the Laboratory policy initiated several years earlier by Dr. C. G. Suits, its director. Barrington S. Havens, a member of the Public Relations Services Division, who had wide experience as a professional writer on the General Electric Monogram and the General Electric Review (no longer published), was given this assignment. He began by collecting existing material and conducting informal interviews with the various participants. From these, with the help of the staff, he was able to prepare the final version (History of Project Cirrus, Report No. RL-756, General Electric Research Laboratory) appearing here, which met with everyone's approval. This, therefore, represents as nearly an accurate account as could have been prepared.

During the period of years since Project Cirrus ended, I (B.V.) have encountered a number of books and magazine articles dealing with cloud seeding in which statements have been made about the early history that are clearly at variance with my own recollections and the facts as related in this history. When I attempted to set matters straight by communicating with the authors, I discovered that almost invariably they were unfamiliar with this accurate account. This is not surprising, for it was never made available to the general public and appeared only in a greatly abbreviated form in the General Electric Review (1952). In view of the continuing widespread activity and interest in cloud seeding, I think it is desirable that this careful history of its beginning be published and made generally available.

It seems worthwhile at the outset to emphasize important and often unrecognized facts concerning the history of cloud seeding. The initial discoveries, that clouds could be seeded with dry ice and with silver iodide, were made not on a government-sponsored research project, but were the result instead of an in-house research project in the General Electric Company Research Laboratory. It is worth stressing that the investigations that led to both discoveries were not conducted with a view of learning how to modify clouds or weather, but as basic research to learn how nature operates. Not until after the basic discoveries had been made was it recognized that they provided the foundation for techniques that could be used to modify clouds in the natural atmosphere.

I (J.J.) began to teach a course titled, "The Principles of Weather Modification". Because there was no text available, I found myself resorting to papers in the literature, technical reports and several other collected articles gathering dust in my files. In order to present a reasonably coherent picture of the evolution of the subject, an attempt was made to track weather modification concepts back to their early origins. It was surprising how often the route led to the Project Cirrus program.

Bernard Vonnegut called to my attention a report titled, "History of Project Cirrus". When he suggested that this document might be worth publishing in the open literature, my time-consuming searches prompted me to agree. Furthermore, the feeling of excitement and discovery that accompanied that prolific period is everywhere evident in the report; that too seemed worth exposing to students and researchers.

We decided to add illustrations and to trim the report to manageable size but in no way to alter the tone or scientific content of the original manuscript. In order to link the past with the present, and to reappraise certain ideas in the light of a quarter-century of progress, the report was appropriately annotated. We hope these comments, and the epilogue will prove as durable over the coming years as most of the original Project Cirrus findings.

Bernard Vonnegut
James E. Jiusto

Acknowledgement:
We are all indebted to Sally Marsh who, except for this, organized and typed this entire manuscript.

Bernard Vonnegut
James E. Jiusto

March 22, 1979

TABLE OF CONTENTS

I. INTRODUCTION

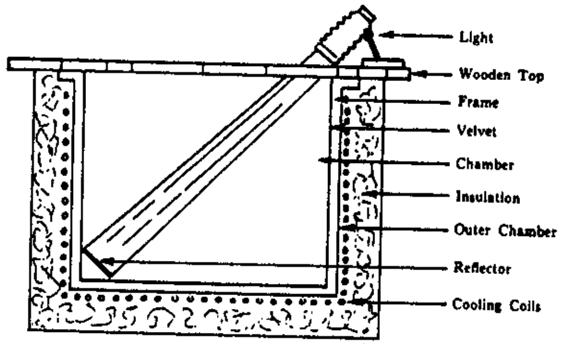
This history of Project Cirrus was prepared at the request of the General Electric Research Laboratory for three reasons. First of all, the project has been --and still is, at this writing--of such unusual interest and significance, that the telling of the story is merited for its own sake. Secondly, the termination of the project is bound to result in an eventual dispersal of the various members of its personnel.† Already Dr. Langmuir has retired from active General Electric employ, and the other members of the project are, and will be, more and more engaged in new and completely different activities. And finally, the broad aspects of the project have such wide implications that it is particularly important that the story be committed to paper "for the record".

It has not been easy to organize the raw material in any simple, logical fashion. As is so often the case, the project was very complex, with a number of subdivisions associated with the main activity. Some of these subdivisions ran consecutively, some operated in parallel, and others intertwined or branched off in variously divergent directions.

Where it was possible the material has been arranged in chronological or otherwise logical order. Where it was not possible, the various subordinate topics have been taken up in as nearly a logical order as possible. As a result, cases will be found where the story "gets ahead of itself," and later it becomes necessary to retrace one's steps to pick up the thread.

The history, with the exception of the Introduction and Conclusion, consists of two main parts. The first is the story of the early activities which led to the formation of Project Cirrus. The second is the story of Project Cirrus itself.

†Although most of the various members of the Cirrus personnel did indeed disperse, it is interesting to note that Vincent Schaefer, Duncan Blanchard, Raymond Falconer, and Bernard Vonnegut are currently on the staff of the Atmospheric Sciences Research Center at the State University of New York at Albany.



Schematic Diagram of Cold Chamber

U. S. Army, Navy, and Air Force personnel of Project Cirrus with G. E.'s Langmuir, Schaefer, and Maynard (4th, 3rd, and 1st from right standing in the rear). Various instruments used in the research can be seen installed on the nose of the B-17 airplane.

II. EARLY HISTORY

It would be difficult, if not impossible, to trace the complete lineage of everything leading up to Project Cirrus. General Electric scientists were not the only ones who studied many of the problems involved. And even when restricting consideration to General Electric research projects, the situation is complicated. The following material, however, is confined as much as possible to work that has a relatively direct bearing on Project Cirrus research.

GAS MASKS AND SMOKE FILTERS

The earliest activity leading directly to Project Cirrus was the study, beginning in 1940, of the fundamental nature of filtration in gas masks. This work was undertaken by Dr. Irving Langmuir and Dr. Vincent J. Schaefer at the request of the U. S. Chemical Warfare Service (1).

Gas masks normally use charcoal to adsorb poison gases, but even in World War I the possibility arose that the enemy might use toxic smokes which could not be adsorbed by charcoal and thus would have to be removed by a filter.

The first step in attacking the problem was to make some smokes of the type for which the filters would be used. In doing so, the scientists studied the particles which composed the smokes. They investigated such things as particle stability, concentration, and measurement. They obtained fairly successful theoretical results and a better understanding of how to build a good filter. And incidentally, they acquired a great deal of detailed knowledge of how to make a smoke which would be non-volatile and would consist of particles far smaller than those of ordinary smokes, and they learned much about their optical properties.

This work was done under a National Defense Research Committee contract. As Langmuir and Schaefer neared the end of the work, a form letter was received in August, 1941, asking if anyone could think of a way to make a white screening smoke that could be used over large areas to cut down the hazard from aerial bombardment. Langmuir and Schaefer wondered whether they couldn't do this by using the methods they had adopted for making smokes for testing filters. They decided to try.

SMOKE GENERATORS

It was found that the easiest way to make smokes and control the particle size was to take some oil and put it into a volatile condition. They heated oleic acid and similar substances up to about 200°C and passed a stream of air over them to get the vapor mixed with air. Then they quenched the mixture suddenly by blowing in a large amount of cold air. The particles grew in size, and by sudden quenching they found they could stop the growth at any desired point and also make particles of very small size. They were surprised to find that, under certain conditions, the particles were of extraordinarily uniform size.

Further work and experimentation showed that the same thing could be done on a large scale. Larger generators were built, tests were made, and the design was adopted by the Army and used successfully on a large scale during the war (1).

Several years later this technique for producing aerosols by vaporization and subsequent quenching and condensation was applied in modified form by Vonnegut (2) in the design of various cloud seeding generators. It was thereby possible to disperse silver iodide as enormous numbers of submicron particles.

PRECIPITATION STATIC

Quite independently of this work, the Secretary of War asked in 1943 for research into the problems of precipitation static (1). It was believed that the invasion by Japan would have to come very largely from air attacks through the Aleutian Islands, across Alaska, and from the North.

The difficulty in flying aircraft in the Aleutians was very serious. One of the big problems was icing of the aircraft, but even more baffling was the complete loss of radio contact when the planes flew through snowstorms. The planes might become electrically charged, sometimes to a potential of 250,000 volts or more, producing corona discharges from all parts of the plane and causing such electrical disturbances that radio sets could not receive messages. Pilots had particular difficulty in finding their bases and getting down through foggy bad weather. What could be done about it?

Langmuir and Schaefer were interested. They had no particular ideas on the subject, except that it had to do with weather. In their opinion, the best place to investigate similar conditions was the well-equipped laboratory of the Mount Washington Observatory on top of Mount Washington in New Hampshire. Mount Washington in winter has an average temperature of minus twenty degrees C, the wind averages about 27 meters per second, and most of the time clouds sweep over the summit. It seemed to offer the proper conditions for research of this kind.

So equipment was installed at the summit, and Schaefer went there several times during the winter of 1943 to conduct experiments. But he discovered that anything exposed there during the winter immediately became covered with ice, because the air was full of supercooled water droplets. He and Langmuir became so interested that they hoped they would not have to continue a long study of precipitation static.

AIRCRAFT ICING

It so happened that the Army Air Force was just as much interested in problems of aircraft icing as in precipitation static. This fitted in so well with the new interest of Langmuir and Schaefer that in 1944 they started a study of that project (3). They had much assistance from Victor Clark, Raymond E. Falconer, and others of the observatory personnel, who were already working on riming and icing. Langmuir and Schaefer, however, were able to introduce some new and very productive ideas.

Extensive mathematical calculations were necessary. The first work of this nature was done by Langmuir, and his results were used in connection with cloud studies at Mount Washington. During the later stages of the Mount Washington studies, Langmuir decided to make use of a differential analyzer for these calculations, and in preparing the material for that purpose, he was assisted by Dr. Katharine Blodgett. Thus it was possible to calculate the percentage of water droplets which would be deposited on a given surface under specific conditions. The information was used on data obtained on Mount Washington to determine the number and size of water droplets involved in the formation of rime ice.

Langmuir and Blodgett (4) computed the collection efficiencies of cylinders, ribbons and spheres for impinging droplets. This pioneering work, while published only as an Army Technical Report, is used extensively and described in virtually all current cloud physics texts. The sphere values were also employed by others in early calculations of droplet collision-coalescence processes, although the original theory applied best to the collection of small droplets by large drops. The importance of raindrop coalescence as an effective precipitation mechanism has resulted in continued work on the collection efficiencies of spheres with theoretical refinements still being made (5)(6)(7)(8)(9).

The theoretical studies carried out by Langmuir on drop trajectories represented one of the early uses of a computer to solve a complex scientific problem. It involved the use of the differential analyzer at General Electric, a version of the original one at MIT.

CLOUD STUDIES AT MOUNT WASHINGTON

The theoretical calculations worked beautifully in practice. Langmuir and Schaefer began to acquire a very satisfactory understanding of some features of cloud structure and the growth of cloud particles. They became absorbed in this new interest. Langmuir found he could apply to his smoke generator work the same evaporation-condensation theory he had used to calculate the growth of smoke particles (10).

Although Langmuir and Schaefer felt they had a fundamental theory for some of the factors that caused particles to grow in clouds to the proper size, they didn't believe conditions were right for further study on Mount Washington. It would be far better to study cloud particle growth with airplane penetration of clouds. That would require the development of new instruments.

It was late in 1945. They took the question up with the Army Air Force and the Signal Corps. They were led to think that perhaps somebody might furnish aircraft for experimental purposes of this sort; it seemed that it would be desirable to know something about clouds from a standpoint of national defense. Unfortunately, the research was done on their own to a large extent, testing instruments on Mount Washington; they never got approval for tests in aircraft.

By this time the pair were deeply interested in their cloud study. The thing that struck them most was that, if there are any snow crystals in a supercooled cloud, they must grow rapidly and should tend to fall out. They concluded that in winter, if there are supercooled stratus clouds from which no snow is falling, even though the temperatures in the clouds are below freezing, there simply are no appreciable numbers of effective snow nuclei. Such clouds could apparently be supercooled to very low temperatures.

They thought this presented a problem that should be investigated. Why was it that sometimes snow forms quite readily, with apparently no lack of nuclei on which crystals can grow, and at other times there seem to be no nuclei at all? They concluded there must be something in the atmosphere that causes water droplets to change to ice only at certain times and under various conditions. They decided to make some careful experiments in the laboratory in an attempt to duplicate those conditions.

SCHAEFER'S COLD BOX

During Langmuir's absence in California for three or four months in 1946, Schaefer made what Langmuir described as "some beautiful experiments" (1). During the previous winter he had been studying the behavior of droplets on cold surfaces to see how they supercooled or

froze as the temperature dropped. He had found he could supercool water drops to as low as -20°C on surfaces coated with polystyrene and similar materials. He had realized, however, that such experiments were not simulating supercooled clouds and had sought a better method of experimentation.

He decided to try a home freezing unit of the type used for food storage. He lined it with black velvet so as to get a good view of what happened inside when a beam of light was directed down into the box. He then breathed into the box, and the moisture condensed and formed fog particles which were just like ordinary cloud particles, although the temperature was about -23°C. No ice crystals formed. He tried many different substances dusted into the box to get ice crystals to form, but almost never got any. He got just enough to convince him that, if they were present, he could easily see them.

Schaefer's cold box, an elegantly simple piece of apparatus, was a cornerstone in the developments of Project Cirrus, not only in the discovery of seeding by dry ice, but also of silver iodide and in the evaluation of various aerosol generators used in seeding. In contrast to many important innovations made in research, which are often the result of technological innovations that have become available, this beautiful experiment was really the result of Schaefer's insight alone. The simple technology necessary for making the cold box had been available for several hundred years before Schaefer did the "obvious".

Finally, on July 13, 1946, when the temperature of the chamber was not low enough, he put a big piece of dry ice into it to lower the temperature. In an instant the air was full of ice crystals. The crystals persisted for some moments after he took the dry ice out.

Following this discovery, Schaefer conducted a number of experiments which showed that even a tiny grain of dry ice would transform the supercooled cloud in the cold box to ice crystals. Quantitative experiments were conducted which showed that many millions of crystals could be produced in this manner.

In order to find out if there was something peculiar to dry ice which produced this effect, he worked with other cold materials. For example, he showed that, by dipping a common sewing needle into liquid air and then passing it momentarily through the supercooled cloud in the cold box, similar spectacular effects occurred. This demonstrated that the presence of a sufficiently cold substance was all that was required to produce the effect. Schaefer devised methods and equipment for determining, with considerable accuracy, the critical temperature at which the supercooled cloud changed to ice crystals (11).

The freezing of supercooled water has been shown to be actually a stochastic process governed by the size (volume) of the drop and rate of cooling as well as the degree of supercooling. However, the probability of freezing and generation rate of ice embryos within a drop becomes so large at approximately -40°C that this temperature is customarily referred to as the spontaneous freezing point of water drops.

VONNEGUT'S EARLY WORK--CLOUD STUDIES AT M.I.T.

Meanwhile the stage had been set for another important contribution to this pioneering work in meteorology. Before Dr. Bernard Vonnegut became associated with the General Electric Research Laboratory, he was employed at the Massachusetts Institute of Technology, where he had been engaged in various studies during the early years of World War II. In the laboratory of the Chemical Engineering Department he worked on smokes for the Government's Chemical Warfare Service. He measured smokes, smoke penetration, and the effectiveness of smoke filters. Then he became interested in the problem of icing of airplanes and went to work on that in the Meteorology Department, for the Air Force.

Meanwhile he had been doing some work on the side in supercooling. He found that, by making an emulsion of water drops suspended in oil, he could cool water far below the normal freezing point; it would not freeze until a temperature of -20°C or lower was reached, whereupon the whole mass froze very rapidly (12).

Vonnegut joined the staff of the General Electric Research Laboratory in the Fall of 1945, and he continued his supercooling investigations there. In various contacts with Langmuir and Schaefer, he learned of the work they were doing. Knowing that Schaefer was already working on the supercooling of water, he switched his activity to the supercooling of metals, in order to avoid duplication. He found he could supercool Woods metal by subdividing it into many small, independent particles, and he developed a technique of studying the effect with x-rays. He also worked with tin (12).

Vonnegut had been interested in the work being done by Langmuir and Schaefer and had kept in rather close touch with it. In the fall of 1946, Langmuir asked if he would be interested in helping with the quantitative work being done on the number of ice crystals produced by dry ice. As a result, Vonnegut applied himself to this and other problems in the general study of nucleation.

SILVER IODIDE

It occurred to Vonnegut that some substance very similar to ice in its crystal structure might serve as the nucleus for the formation of ice crystals in Schaefer's cold box. He went through all the known tables of crystal structure and, from over a thousand compounds, selected three substances that he thought might have possibilities: lead iodide, antimony and silver iodide ([illegible]).

He dropped samples of each of these three substances into the cold box. The results were almost negligible, although he produced enough effect with the lead iodide to warrant further experiments. He and Schaefer tried iodoform and iodine and obtained ice crystals in small numbers with them, too, but nowhere near as many as with dry ice seeding. The problem continued to intrigue Vonnegut, and on November 14, 1946, he decided to try a metal smoke instead of the powder. He introduced some silver smoke into the box by drawing an electric spark from a piece of silver, and it produced a swarm of ice crystals in the cold box.

The results were so spectacular that he decided to try silver iodide again, but this time as a smoke, for the effect with silver did not persist. First he vaporized silver iodide and then he introduced into the cold box the smoke resulting from the rapid condensation of this vapor. It was a complete success. Further investigation showed that his earlier negative results with silver iodide had been caused by the fact that the silver iodide used was contaminated with sodium nitrate. Powdered silver iodide worked very well when it was reasonably pure. He also found that the reason for the successful use of iodine was again impurity--favorable contamination with silver.

It has come to light recently (15) that the ability of silver iodide to nucleate ice formation in supercooled water had been discovered earlier by Bloch. In 1936 he employed this substance to initiate freezing of supercooled water in a temperature controlling device for a cryostat.

Tor Bergeron, the late Norwegian meteorologist, enunciated a theory to explain the formation of precipitation that now bears his name. He suggested that snow, and rain if the snow melted, could originate by the growth of ice crystals in supercooled clouds. In reminiscences concerning the development of his ideas, he stated, "I knew not enough physics and hadn't read Vollmer's 'Phasenlehre'. Irving Langmuir, V. Schaefer and/or B. Vonnegut evidently had, and it was really a treat when, thanks to Carl Rossby, my wife and I visited Langmuir in Schenectady on the 20th of April 1947, and he devoted half a day to us" (16).

However, the General Electric scientists did not become aware of Vollmer's important work on the theory of nucleation until sometime after the discovery of dry ice and silver iodide seeding.

The problem then became one of finding out how silver iodide worked and of finding methods of generating silver-iodide smoke of small particle size on a large scale. So many nuclei could be produced with silver-iodide smoke that calculations indicated all the air of the United States could be nucleated at one time with a few kilograms of silver iodide, so that the air would contain 100 particles of silver iodide per liter--far more than the number of ice nuclei occurring normally under natural conditions (14).

If one assumes 10^{15} particles of effective silver iodide per gram, a cloud airspace 10 km high, and the area of the United States to be eight million square kilometers, approximately 4 tons of silver iodide would be required to yield 100 particles per liter. In certain rainmaking concepts, it is estimated that the addition of only 1 nucleus per liter of air will stimulate precipitation; under these circumstances, the hypothetical quantity required would reduce to approximately 40 kilograms. Thus, while Langmuir considerably overestimated the effectiveness of silver iodide, the general argument that reasonable quantities are involved is valid.

LANGMUIR'S EARLY SEEDING CALCULATIONS

Meanwhile Schaefer and Langmuir had continued their study of the effects of dry ice. In August of 1946 Langmuir made a theoretical study of the rate of growth of the nuclei produced by dropping pellets of dry ice through clouds of supercooled water (17). He calculated the velocity of fall and time of dissipation of the dry ice, the amount of ice particles that would be formed, their size, the amount of snow which would result, etc. With a reasonable number of pellets dropped along a flight path into the top of a cloud, the limiting factor would not be the number of nuclei but the rate at which they could be distributed throughout the cloud.

He also showed that such a formation of ice and snow particles would raise the temperature of the cloud, and he calculated the amount of temperature change. Thus the air in the cloud would be caused to rise, increasing its upward velocity because of the seeding. The resulting turbulence would spread the ice nuclei throughout the cloud. He anticipated that it would only be necessary to seed a stratus cloud along lines two or three kilometers apart in order to give

complete nucleation of the cloud within a period of 30 minutes or so.

Langmuir recognized that heating would be produced not only from the freezing of the supercooled cloud droplets, but also from the freezing of supersaturated water vapor that is contained in the air between the droplets. For many years the importance of the additional heat released by seeding received little attention, and then Joanne Malkus (18) began her classic studies on the almost explosive growth that sometimes results when cumulus clouds are seeded.

FIRST MAN-MADE SNOWSTORM

Thus the stage was set for an actual experiment with an airplane in real clouds. On November 13, 1946, a Fairchild airplane was rented at the Schenectady airport, piloted by Curtis Talbot, and Schaefer went aloft in search of a suitable cloud (19). It was found over Pittsfield, about 50 kilometers east of Schenectady, at an altitude of 4.3 kilometers and a temperature of -20°C. What happened next is best described by the following extract from Schaefer's laboratory notebook entry for that day:

"Curt flew into the cloud and I started the dispenser in operation. I dropped about three pounds (1.4 kilograms) [of dry ice] and then swung around and headed south.

"About this time I looked toward the rear and was thrilled to see long streamers of snow falling from the base of the cloud through which we had just passed. I shouted to Curt to swing around, and as we did so we passed through a mass of glistening snow crystals!.....We made another run through a dense portion of the unseeded cloud, during which time I dispensed about three more pounds of crushed dry ice.....This was done by opening the window and letting the suction of the passing air remove it. We then swung west of the cloud and observed draperies of snow which seemed to hang for 2-3000 feet (0.6-1.0 kilometers) below us and noted the cloud drying up rapidly, very similar to what we observe in the cold box in the laboratory..... While still in the cloud as we saw the glinting crystals all over, I turned to Curt and we shook hands as I said 'We did it!' Needless to say, we were quite excited.

"The rapidity with which the CO_2 dispensed from the window seemed to affect the cloud was amazing. It seemed as though it almost exploded, the effect was so widespread and rapid.....

"When we arrived at the port, Dr. Langmuir rushed out, enthusiastically exclaiming over the remarkable view they had of it in the control tower of the General Electric Lab. He said that in less than two minutes after we radioed that we were starting our run, long draperies appeared from the cloud vicinity".

The first seeding flight was of tremendous significance. Not only did it show that the laboratory experiments and calculations were justified, but it also contributed new material to the rapidly accumulating store of seeding knowledge. For example, it suggested that the veil of snow that first appeared immediately below the cloud could not have been produced by snow falling from the cloud but rather was produced directly by the action of the dry ice pellets falling into a layer of air below the cloud which was supersaturated with respect to ice but not with respect to water.†

Subsequent experiments proved that it was also frequently possible to seed a supercooled cloud by flying just below it and dropping dry ice. The thickness of the layer in which such seeding is possible is about 10 meters for each degree C below the freezing point at the cloud base. The ice crystals thus formed may be carried up into the cloud if the cloud is actively growing by convection.

On November 21 Schaefer seeded a supercooled valley fog with dry ice. He found that it was possible to reduce visibility by generating more ice crystals than fog droplets and also to dissipate the fog by dispensing just enough ice crystals to use up the fog droplets, each crystal growing large enough to fall to the ground.

OTHER EARLY FLIGHTS

There were two other seeding flights made by Schaefer with a rented plane that month, one on the 23d of November, and the other on the 29th (20). These tests were made on isolated cumulus-type clouds. The whole of each cloud was changed into ice within five minutes and snow began falling from the base of the cloud. Photographs were taken from the ground every 10 seconds, and these were developed and projected as movies. They showed that with orographic clouds, the air moves into one part and leaves another part; 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 usually of little interest, for the effects last but a few minutes.

---

†At that time I was editor of the General Electric Monogram. The late Thurse Sigman, an assistant editor, was on a newsgathering call at the General Electric News Bureau offices on the day in question. When he returned to the Monogram offices, he announced dramatically: "Well, Schaefer made it snow this afternoon over Pittsfield! Next week he walks on the water". (B.H.)

Another flight test was made on December 20 (20). This time the sky was completely overcast, and by 9 o'clock in the morning the Weather Bureau in Albany reported that it expected snow by 7 o'clock that evening. At about noontime, Schaefer dropped about 11 kilograms of granulated dry ice in the lower part of the cloud at a rate of .3 to .6 kilograms per kilometer, about 300 meters above the irregular and ragged base of the overcast, at altitudes ranging from 2.1 to 2.6 kilometers. A 1 kilogram bottle of liquid carbon dioxide was also discharged into the cloud during this period.

Before and during the seeding flight, a light drizzle of supercooled rain had been encountered, which seemed to evaporate before it reached the ground. Flying back along the line of seeding, after seeding was completed, it was found that the drizzling rain had stopped and that it was snowing. But on reaching the point where the seeding had stopped, drizzle conditions were again encountered. Three more seeding runs were made along the same line.

The plane then descended to 1.3 kilometers, where the visibility was better, and made a reconnoitering flight, checking the places where snow was falling. By this method and through reports received, it was found that snow started to fall in many places in the region. At 2:15 p.m. it started snowing in Schenectady and at many other places within 160 kilometers. It snowed at the rate of about 25 millimeters per hour for eight hours, bringing the heaviest snowfall of the winter. While the seeding group did not assume it had caused this snowstorm, it did believe that, with weather conditions as they were, they could have started a general snowstorm two to four hours before it actually occurred, if they had been able to seed above the clouds during the early morning.

ESTABLISHMENT OF PROJECT CIRRUS

This, then, was the situation in which the research workers found themselves by the end of the year: their work on precipitation static, and then on aircraft icing, had developed through cloud studies into meteorological work of profound significance. But, while their work on precipitation static and aircraft icing had been done under government contract, the work they were now doing on weather research was not. Their last contract had expired at the end of June, 1946, six months earlier.

At this point Dr. C. G. Suits, Director of the General Electric Research Laboratory, reported some of the results of cloud seeding to company officials. While it was clear that weather modification and experimental meteorology were remote from the research which had been the traditional interest of the Laboratory and the Company, it was equally clear that these new results were possibly of very great significance to the country. It was, therefore, decided that the work should be encouraged and pushed forward.

Because the results might have such wide application to the country generally and because much government assistance would be needed in the form of weather data, airplanes, and flight equipment, it was decided a government contract for the continuation of the work should be sought. While the government agency which had sponsored the previous research was not interested in the new work, other government agencies were. Normal contacts with the Signal Corps, for example, had kept that organization in touch with the new research, and Colonel Yates, chief of the Air Weather Service, had asked the Company to submit a bid covering this work in the latter part of September. A formal proposal covering cloud modification and cloud particle studies was submitted to the Evans Signal Laboratory at Belmar, New Jersey (a Signal Corps unit) on September 20. Meanwhile the weather studies were being conducted at General Electric expense, although General Electric anticipated no benefit resulting to the Company from the meteorological work.

The flight test of December 20 added a powerful stimulus to the Company's negotiations with the government. Although the General Electric press release covering it did not claim that the general snowstorm was caused by the seeding, the coincidence of the two events did cause some independent speculation over the possibility of cause and effect.

This question was brought by Suits to the attention of Vice President R. E. Luebbe, general counsel of the Company. It was recognized that the possibility of liability for damage from cloud-seeding experiments was a very worrisome hazard in this new form of cloud experimentation. Since such a threat to the share owners' money would not be balanced by any known gain to the Company's products or business, there was great reluctance to incur risks of uncertain but potentially great magnitude.

This was another--and particularly important--reason that any seeding experiments be conducted under government sponsorship. No further seeding flights were made until such sponsorship was provided. A contract was, however, received from the Signal Corps covering "research study of cloud particles and cloud modifications" beginning February 28, 1947. It included cloud modification by seeding, plus investigations of liquid water content, particle size, particle distribution, and "vertical rise of the cloud with respect to the base".

An important part of this contract was a subparagraph stating that "the entire flight program shall be conducted by the government, using exclusively government personnel and equipment, and shall be under the exclusive direction and control of such government personnel". The Research Laboratory immediately notified all those involved in the research "that it is essential that all of the General Electric employees who are working on this project refrain from asserting any control or direction over the flight program. The General Electric Research Laboratory responsibility is confined strictly to laboratory work and reports". The project had joint sponsorship by the U. S. Army Signal Corps and the Office of Naval Research, with the close cooperation of the U. S. Air Force, which furnished airplanes and the associated personnel.

The title of Project Cirrus was not applied immediately. It went into effect officially on August 25 of that year.

The name of "Project Cirrus" given to the government-sponsored research on cloud seeding was conceived by Vincent Schaefer. The act of cloud seeding causes the transformation of a cloud made of supercooled water drops into a cloud of ice crystals. Since such clouds, consisting of minute ice crystals, are known to meteorologists as cirrus, he conceived that this would be an appropriate name. He told Daniel Rex of this, who shortly thereafter proposed this designation at a meeting of the Steering Committee, which accepted it as the official title.

Vincent Schaefer experimenting with a rather elaborate version of his cold box experiment.

Vincent Schaefer, Irving Langmuir, and Bernard Vonnegut in Schaefer's laboratory where cloud seeding was discovered. (Eric Schaal - Fortune Magazine 1947-1978, © Time, Inc.)

III. GETTING ORGANIZED

As described in the preceding chapter, the work done on Project Cirrus and the activities leading up to it were covered by several contracts with the government, as listed in Appendix 1. The first of three Signal Corps contracts was signed in February, 1947; the last of these remained in force until the end of September, 1952.

The total funding over a five-year period resulting from these grants amounted to $790,116. By contrast, a contemporary project, such as the U. S. National Hail Research Experiment, had a budget for 1972 alone of approximately $2.5 million.

The over-all direction of the project and the formation of broad matters of policy were entrusted to a Steering Committee consisting of representatives of the three military branches of the government cooperating in the project. Dr. Irving Langmuir and Dr. Vincent J. Schaefer of the Research Laboratory served as consultants on the committee. The governmental personnel were as follows [alternates and succeeding personnel assigned to the project are listed in Appendix 2]:

Signal Corps	Dr. Michael J. Ference, Jr.† Chief, Meteorological Branch Evans Signal Laboratory Belmar, New Jersey
Navy	E. G. Droessler Geophysical Branch Office of Naval Research Department of the Navy Washington, D. C.
Air Force	Major P. J. Keating Chief, Weather Equipment Flight Test Facility Middletown, Pennsylvania

The activities of Drs. Langmuir, Schaefer, Vonnegut and others of the General Electric Company's Research Laboratory staff were limited by the Steering Committee to laboratory work and analysis. The General Electric scientific group came to be known to the personnel of the project as the Research Group. In addition to Langmuir, Schaefer and Vonnegut, this group included Messrs. Kiah Maynard, Raymond Falconer, Raymond Neubauer, Robert Smith-Johannsen, Duncan Blanchard, George Blair, Myer Geller, Victor Fraenckel, and Charles Woodman.

An Operations Group was established by the Steering Committee early in the life of the project to plan, coordinate, and control all project air operations, assist in the assembly and analysis of all technical data obtained, provide all necessary meteorological information and service required for the efficient conduct of the project, and take whatever action necessary to fulfill those requirements. This group would include all military and civilian personnel necessary to fulfill those functions and act under the direction of an Operations Committee set up to "assume full responsibility for, and, therefore, exercise complete freedom of action in the initiation of plans for, and the control of, all project air operations to be conducted in the vicinity of Schenectady".

The Operations Committee, like the Steering Committee, included representatives of the three services, plus Kiah Maynard of the Research Laboratory of General Electric as consultant. It went through numerous changes of personnel. The initial membership was as follows:

Lt. Comm. Daniel F. Rex, USN, chairman;
Capt. C. N. Chamberlain, USAF;
Roger Wight, Signal Corps;
Kiah Maynard.

The initial personnel of the Operations Group consisted of six representatives of the Signal Corps, six of the Air Force, and six of the Navy.† Although the number of General Electric people working on the project remained fairly constant at a figure of six or seven, the government representatives varied widely in number. As a consequence, the total personnel of the project varied also, running as high as 40 persons at various times when activities were at their peak. These included crewmen for the planes, weather technicians, and civilian employees for such services as photography. A total of 33 persons went on the Puerto Rico operation (p. 28), and 37 went on the second trip to New Mexico (p. 29).

---

†Dr. Ference tells the story that later in the project when he realized that Langmuir was approaching retirement age, he asked how this would affect his activity. He received the curt and rather gruff response, "You'll know when I'm retired; I'll be dead."

†If ever there was an impossible assignment, it was the one given to a government scientist in the early days of Project Cirrus. He was told, "Go to Schenectady, spend all the time you can talking to Langmuir; milk him dry." The unfortunate man's eyes took on a glazed appearance after only a brief exposure to the prodigious and inexhaustible torrent of Langmuir's ideas.

FLIGHT PROGRAM

At the outset, and until June 1, 1947, Project Cirrus test flights were made by a Weather Squadron assigned to the Signal Corps. A plane visited Schenectady six times, and a total of five seeding flights were made. Olmsted Field at Middletown, Pennsylvania, was the base of its operations.

It was soon discovered, however, that any 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 flight operations were transferred to Schenectady. Headquarters for the Operations Group was established at the General Electric hangar at the Schenectady County Airport.

This massive cast concrete structure was built by General Electric for use in developing and installing special electronic gear for the B-29 aircraft. On the platform of its control tower Langmuir witnessed and photographed the first cloud seeding conducted by his assistant, V. J. Schaefer, on November 13, 1946. With the establishment of Project Cirrus in early 1947, it was arranged for the Project Cirrus flight operations to utilize this nearly new facility built by General Electric, and during the next five years (until 1952), it was headquarters of its flight activities headed by Lt. Comm. Daniel Rex.

In later years, as the General Electric Company transferred its airplane engine development to Cincinnati, the flight facility was abandoned and thus reverted to the County of Schenectady.

Early in 1967 after the hangar and its associated offices had been abandoned for several years, the State University of New York at Albany obtained a lease from Schenectady County and converted it to a major field station and research facility for ten years to 1977. Here Schaefer, Vonnegut, Blanchard and Falconer continued some of their atmospheric studies which had been initiated 25 years earlier!

The facilities expanded until, at the end of 1948, they consisted of a total of [illegible] square meters of office, operations, and storage space, including a control tower, weather office, administrative office, photographic dark room, film storage, Recordak room, operations and analysis room, and a parachute-[illegible] room. In addition to this, [illegible] square meters of conference room was available whenever required. [illegible] room in the hangar served for aircraft installation work and repairs. To facilitate flight operations, two Weather Bureau teletype circuits were installed, as well as a Teletalk system connecting all offices. This could also operate a public-address system in the hangar and the ramp. In addition, connections were made through two leased wires to the Boston CAA control center and the Army Airways control center at Middletown, Pennsylvania.

At first the number of aircraft assigned to the project was disappointingly meager, but eventually this situation was corrected. At one time as many as six planes were available--three from the Army and three from the Navy. Active flight operations began with the establishment of the project in March, 1947, and then continued until August, 1950, when the Operations Group was disbanded at the suggestion of the Research Group. (This move was made in the interests of economy, for most of the objectives of the flight program had by that time been accomplished.)

A list of all the flights made by Project Cirrus is attached as Appendix 3. This list includes the flights made in rented planes before the establishment of the project and the carefully numbered and documented flights thereafter.

GROUND OPERATIONS

In addition to the flight program, the Operations Group had the responsibility for conducting numerous operations on the ground. These operations were of two kinds: photography and silver iodide seeding. When it became apparent that such operations would be necessary as part of the project from time to time, a system of numbering each operation was established. A record of all 84 ground operations conducted was maintained by the Operations Group (see Appendix 4).

Weather observation being essential to operations of the type carried on by Project Cirrus, one of the first steps taken by the Operations Group was to set up a complete weather-observing station as part of the facilities at the General Electric hangar. Daily radio contact was established with the Weather Equipment Flight Test Facility at Middletown, Pennsylvania, and circuits for weather teletype services were installed.

The primary requirements of the weather station were as follows:

1. Preparation of aerological flight data prior to take-off on flight tests.
2. Gathering of data after the flight to supplement that obtained in the air on seeding missions, for the area concerned during the time of test.
3. Cooperating with the Research Group in its study of weather analyzing instruments and test flights, and supplying it with such special weather reports as needed for analysis purposes.

In order to meet these requirements, the Weather Station performed the following functions:

1. Daily small-cloud maps were prepared of conditions during the last hour before take-off on test flights, covering an area having a radius of 300 kilometers from the Schenectady County Airport.
2. Daily flights were made to record the air conditions up to 2.4 kilometers above the airport.
3. Radiosonde data above freezing level were obtained daily from the U. S. Weather Bureau at Albany.
4. Daily surface weather maps were prepared of the complete eastern United States.
5. Data were obtained daily of the winds aloft for the eastern United States.
6. Local weather observations were made hourly.
7. After each test flight, cross-sections of the areas seeded were prepared, based on reports of flight personnel and teletype weather reports.

When the Operations Group was disbanded in 1950 and the facilities at the General Electric hangar were abandoned, the Weather Station was transferred to the penthouse of the General Electric Research Laboratory at the Knolls.

Through the Office of Naval Research, two Navy men had a lengthy assignment to the project as aerologists, and as such they contributed much valuable assistance to the study of general and specific problems encountered in the various research studies. These men were Lt. (jg) W. E. Hubert and H. J. Wells, AGC.

PHOTOGRAPHY

Another very important activity essential to the success of the project was photography of various kinds. From the outset it was found that complete evaluation of the results of the various seeding experiments could not be made without documentary pictures.

Both still and motion-picture types of photography were used. In addition, special techniques were adopted. For example, by means of time-lapse photographs it was possible to speed up movie projection in order to obtain a better grasp of the changes taking place in a cloud. Also, by the use of stereoscopic equipment, it was possible to produce three-dimensional views of cloud systems.

So important was photography considered in the active phase of the project, when the Operations Group was functioning and regular test flights were being conducted, that many civilian professional photographers were employed in addition to those provided by the Signal Corps. On the second New Mexico test operation (p. 29), six photographers made the trip from Schenectady to Albuquerque. During the Puerto Rican test operation (p. 28) over 100,000 frames of time-lapse pictures were taken in color. The load on the darkroom at the General Electric hangar in Schenectady became so great that a photographic trailer was obtained from the Signal Corps Engineering Laboratories to relieve the congestion.

One print of each photograph was, at the time of the preparation of this report, on file in the Knolls penthouse weather station, plus virtually all motion picture film. All negatives are filed in the photographic vaults of the Signal Corps Laboratory at Belmar, New Jersey.

INSTRUMENTATION

A considerable portion of the time and activity of Project Cirrus personnel was spent on the development of special instruments, tools, and equipment essential to the project. As in any new undertaking in which there is little or no previous experience, many new devices of this type had to be designed, or old ones had to be adapted to special requirements. In addition to Schaefer's simple cold chamber, which became a standard item of meteorological research in the field of cloud physics, the more important equipment developed was as follows:

Dry Ice Dispenser. One of the first instruments which had to be developed was an automatic dry ice dispenser (20). This was devised for use in an airplane, to allow a continuous release of dry-ice pellets during seeding operations.

Dry Ice Crusher. This was a device for reducing blocks of dry ice to usable fragments for seeding purposes (21). It greatly reduced the time required for preparing this material for a seeding run.

Silver-Iodide Generators. A number of different methods for the generation of silver-iodide smokes were studied by Vonnegut early in the history of the project. One method vaporized silver iodide from a hot filament (13). Another involved the use of a small electric furnace (22). A third method vaporized silver iodide from a string in a flame and then caused a very fine smoke by rapidly quenching the flame with a blast of compressed air (13). A fourth introduced silver iodide into flares of the standard fireworks type (22). A fifth technique produced silver-iodide smokes by first producing a silver smoke with an electric arc and then converting the silver particles to silver iodide by the addition of iodine vapor to the smoke (13).

In addition, two other techniques were devised which were well suited to large-scale seeding. In one, a solid fuel, such as charcoal impregnated with a silver-iodide solution, was burned (22) (23). The silver iodide vaporized and then condensed in the form of a fine smoke. In the other technique, a solution of silver iodide and acetone was atomized in a spray nozzle and burned, vaporizing the silver iodide (22,23,24).

The silver-iodide vapor rapidly condensed when it mixed with the cool air of the atmosphere, to form a smoke of very small particles, the size of which could be varied over a wide range. A later design of this generator, adapted for use in flight, was found to be simple and reliable.

Spray-nozzle burners o silver-iodide-acetone solution . e still the most common type of generators in use. As was found then (25), in order to enhance solubility, some soluble iodide had to be mixed with the silver iodide and then acetone added to yield a 1-2% AgI concentration.

Camera Clinometer. It became evident in early flights that it would be necessary, when photographing seeded areas, to know the vertical angle at which the camera was pointed. A very simple camera attachment was made to indicate this angle (20).

Flight Instruments. Standard instruments often had to be modified, and new ones were occasionally developed. For example, a device was evolved to record the movement of the airplane "stick" for correlation and measurement of vertical acceleration (20).

Weather Instruments. It was in the field of weather observation and atmosphere studies that most of the instrument development occurred. Some of the early devices were special rods to be mounted on the airplanes to determine the rate of icing (20); an air decelerator to assist in sorting out rain, snow, dust, or cloud particles from the atmosphere as the plane passes through (20, 21); and a cloud-particle gun for sampling the cloud-droplet size distribution in clouds (20, 21). An attempt was made to develop a cloud-particle ranging instrument for airplane use to provide a continuous record of the distribution of particle sizes in a cloud, but without success.

Cloud Drop Meter. An important early development was a cloud meter, designed to provide a measurement of the average effective particle sizes in the various portions of a cloud (26, 20, 21, 27). This device, embodying a continuously moving tape impregnated with a water-sensitive dye, gave a satisfactory indication of the amount of cloud particles collected.

Condensation Nuclei Detector. Another important instrument was developed by Vonnegut for obtaining a continuous record of the concentration of condensation nuclei in a given air sample (28). This involved a simple adaptation of the cloud-chamber technique. Also a very simple pocket-size unit was devised for making spot checks of the relative numbers of such nuclei in a given sample.

Experiments carried out by the Navy showed that the recording condensation nuclei (CN) meter could be used successfully to track ships and submarines by detecting and following the plume of condensation nuclei released by the operation of their internal combustion engines. Development of the original recording condensation nucleus meter devised during Project Cirrus was continued at General Electric under a later classified Navy contract for use in antisubmarine warfare. Subsequent versions of the CN meter proved useful as a research and monitoring tool for air pollution studies. They have since been produced commercially by General Electric and several other companies.

Vortex Thermometer. A development of much significance was the design by Vonnegut of a vortex thermometer for use by airplanes in measuring true air temperature (29). The usual type of thermometer is unsatisfactory for this purpose because of aerodynamic heating caused by the rapid movement of the airplane through the air. The vortex thermometer reduced these aerodynamic effects to a negligible amount. Also, for the first time, it made possible a quite accurate measurement of the temperature in a cloud. Furthermore, an indication of true air speed can be provided by measuring the difference in readings given by a vortex thermometer and one exposed in the normal manner, because the deviation from true temperature of a normal thermometer varies with the speed of the plane. But it was found that the vortex whistle (next paragraph) showed greater possibilities for this application.

Vortex Speed Indicator. An outgrowth of the development of the vortex thermometer was the adaptation of the principles involved to the production of a musical note. As the pitch of the note thus produced varies with pressure, such a whistle could be used as the basis for measurement of true air speed and air mileage for airplanes (30).

Rain Catcher. A tool found very useful in rain studies aloft was a rain catcher, developed to give the average value of the precipitation in the air for approximately each thousand feet of flight. The device involves the use of a rain scoop, a tube whose exit velocity can be controlled, and a group of storage containers (31).

Portable Cold Chamber. A simple but effective cold chamber was designed by Schaefer, which could be carried about for field studies. It consisted of a small rectangular wooden box lined with copper sheeting and having a copper inner chamber. A charge of five pounds of crushed dry ice was found to hold the temperature below -10°C for three hours (32, 33, 34).

Ice Nuclei and Crystal Detectors. Since one of the important properties of the atmosphere as related to the persistence of supercooled clouds is the presence of ice-forming nuclei, considerable effort was expended in the development of an instrument which would provide a continuous, automatic record of the quantity of such nuclei in the air at any given time. Two developmental instruments were devised, but difficulties were experienced with both of them, and neither was brought to a satisfactory degree of perfection. One made use of the tendency of a thin water-soluble film of polyvinyl alcohol to supercool. The latter determined the concentration of ice forming nuclei by counting the ice crystals formed in a cold box (35). Air from the cold box was drawn rapidly past an electrically heated wire. When an ice crystal collided with the wire, it created a sudden cooling and a decrease in electrical resistance, which could be readily detected electrically.

Uniform Particle Generator. A useful tool in the study of cloud physics was an apparatus for producing particles of uniform size, developed during the work on one of the ice nuclei detectors (35). With it, extremely uniform particles were produced in sizes down to about 10 microns diameter by feeding water through a fine glass capillary set into oscillation by a jet of compressed air.

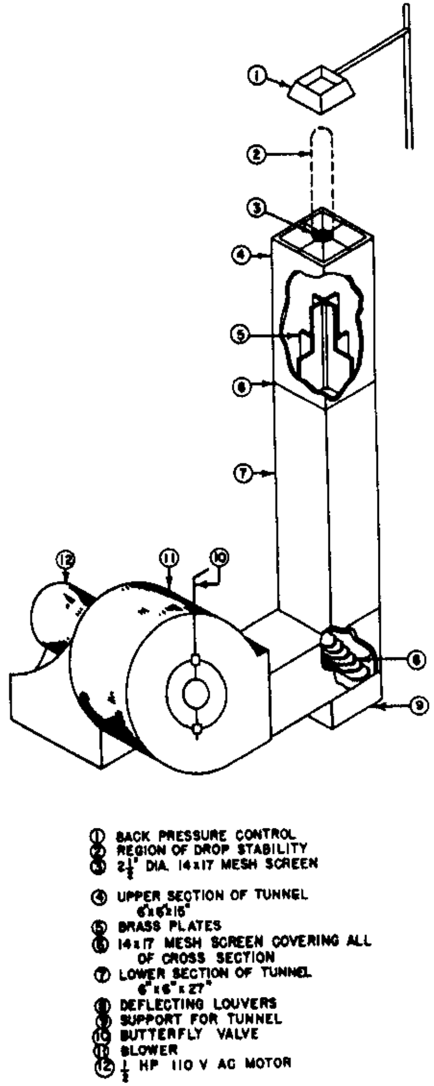
Salt Particle Detector. An apparatus was constructed that detects and counts aerosol particles, such as salt particles, by the pulses of light they produce when they enter a hydrogen flame. Observations showed that the concentration of large sodium-containing particles in the atmosphere is subject to considerable fluctuation (36).

Cloud Chamber. A very simple but effective adaptation of the continuous cloud chamber was developed by Schaefer, using water instead of alcohol (37, 38). It gave promise of considerable value in conducting quantitative experiments with a controlled atmosphere. It consisted of a closed, vertical, glass cylinder in which a constant moisture and temperature gradient was obtained by humidifying the top with a moist piece of blotting paper and cooling the lower part with dry ice. This device produced regions of supersaturated vapor under conditions of extreme cleanliness and provided a valuable tool for the study of nucleation.

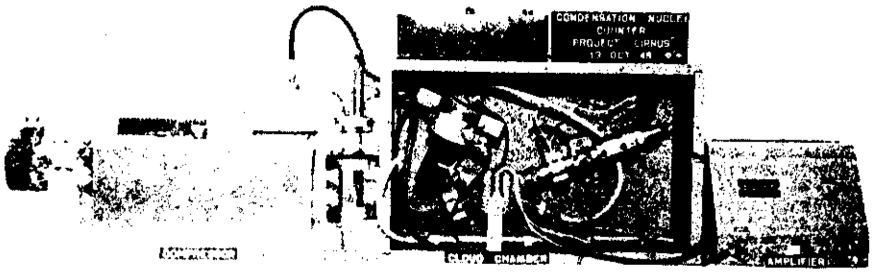
Aerosol Precipitator. A very simple apparatus was constructed to precipitate aerosol particles from the atmosphere on a strip of paper. It was found useful in the study of condensation nuclei in the atmosphere.

Snowflake Recorder. This device was developed to record the type and concentration of snow crystals reaching the ground during the storm period of the winter season. It utilized a strip of paper on which was rubbed a water-sensitive dye (39).

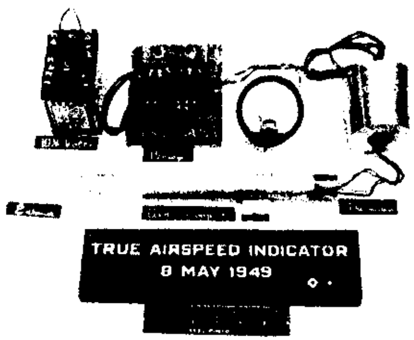
Cloud Type Indicator. By measuring the daylight from a small portion of the northern sky, it was found that the variations in reflection caused by blue sky or various cloud types which passed this area produced a curve which could be interpreted in terms of particular types of cloud (40).



Vertical Wind Tunnel for the Suspension of Water Drops in an Air Stream



Condensation Nuclei Meter Flown in B-17 Airplane



Differential Vortex Thermometer
Used to Measure True Air Speed

IV. LABORATORY STUDIES

The interest and activity in cloud seeding and the fundamental physics of clouds, following the initial experiments, were so varied that it is difficult to give an orderly account of the progress in this field. Research both in the laboratory and in the atmosphere continued to reveal new and interesting facts. The following pages contain summaries of the more important laboratory studies which were conducted in this field by the Research Group of Project Cirrus.

PERSONNEL

It would be difficult, if not impossible, to list the names of all the people contributing to these laboratory studies, but the following twelve persons played important parts either continuously throughout the life of the project, or at one time or another during its existence.

Dr. Irving Langmuir, under whose direction the project evolved, planned the methods and techniques for the various programs, analyzed flight results, and set up procedures for the routine analysis of such results. He also provided convincing mathematics for many of the theories evolved.

Dr. Vincent J. Schaefer, who worked with Langmuir in the planning of the project, carried out both field and laboratory experiments on the fundamental processes involved in changes of cloud forms.

Dr. Bernard Vonnegut also carried out extensive field and laboratory experiments on subjects associated with the project. Particularly he concentrated on theories and techniques associated with the use of silver iodide for seeding.

Raymond E. Falconer worked on various phases of instrumentation of the flight plans, on laboratory studies, and on other related problems. He worked closely with Langmuir in his rainfall periodicity studies. After the termination of the Operations Group, the establishment and maintenance of a weather station in the Knolls penthouse was his primary responsibility.

Victor Fraenckel served as General Electric representative on the Steering Committee and as contract liaison man.

Kiah Maynard was the Research Laboratory representative on all flight tests and on the Operations Group when it was active. He gathered data and maintained records of all flight tests. He was associated with Falconer in the operation of the weather station at the Knolls penthouse.

Raymond L. Neubauer was associated with the later stages of the project in the development of instruments and studies of silver-iodide smokes.

Robert Smith-Johannsen, associated with the project during its earlier history, was principally concerned with the study of the supercooling of water.

Duncan Blanchard was temporarily associated with the project in connection with the study of water droplets.

Myer Geller, temporarily associated with the project, contributed important calculating work.

Charles Woodman, temporarily associated with the project, contributed important mathematical work.

Arthur Parr, a Research Laboratory machinist, built almost all the special equipment and developmental instruments involved.

ICE NUCLEI

One of the most important phenomena associated with the study of the physics of clouds is the formation, distribution, and relative abundance of nuclei for the formation of ice crystals. This subject, therefore, occupied the attention of the principal members of the Research Group to a large extent during the course of the project.

Considerable work was done in developing instruments and methods for detecting the presence of, and counting, such nuclei in the atmosphere. Relatively early in the history of the project, a station was established by Schaefer at the observatory atop Mount Washington for regular observations of the concentration of such ice-forming nuclei, and these observations continued over five years. Subsequently, Schaefer found in the laboratory that certain kinds of soils, when dispersed as a dust, were moderately good nuclei under certain atmospheric conditions (41).

Other investigators have since confirmed that soil particles are among the most effective ice nuclei occurring in the atmosphere, and Kumai (42) identified soil clay nuclei (kaolin and montmorillonite) in snow crystals using electron microscopy. However, a clear understanding of the nature and origin of natural ice nuclei is still lacking; the range of possibilities varies from the bottom of the atmosphere to the top--from soils, plant leaves (43), steel mill effluent, and automobile exhaust (44) to meteor dust (45).

At the time of writing this report [1952] the number of ice nuclei needed to initiate a chain reaction in a supercooled cloud is not yet known, but evidence found early in the history of the project, suggesting that a critical concentration is found in the range of 10,000 to 50,000 nuclei per cubic meter, has consistently been strengthened since (46).

Observations of ice nuclei were also conducted at the Research and Development Division of the New Mexico School of Mines at Socorro, with whom the Project Cirrus scientists maintained a close liaison.

New Mexico Institute of Mining and Technology had, through the leadership of its President, Dr. E. J. Workman, developed a very able and productive group of scientists in atmospheric physics, studying such phenomena as cloud circulation, thunderstorm electricity, and aerosols. Workman and his associates, S. E. Reynolds, Benjamin Seeley, and William Crozier, contributed much to Project Cirrus through discussions and cooperative research programs, as well as by generously extending the use of all of their apparatus and facilities. The friendships and exchanges of ideas between scientists of New Mexico Tech and Project Cirrus continued after the project ended. In 1963, six years following the death of Dr. Langmuir, New Mexico Tech completed the construction of a cloud physics observatory on Mount Baldy, near Socorro, which Workman named Langmuir Laboratory (48).

A significant fact resulting from the Mount Washington studies was that relatively high concentrations of active ice-forming nuclei rarely occur in the atmosphere (47). If the observed results are a true representation of the average mean condition of the atmosphere, it is obvious that, by the artificial introduction of sublimation nuclei into the atmosphere, man possesses a powerful method of modifying many cloud systems.

One prolific source of ice-forming nuclei might be the Great Plains and the more arid regions immediately adjacent to the Continental Divide. Wind storms, dust devils, and strong convective activity could easily account for the formation of ice-forming nuclei aerosols (47). It seems probable that the smoke produced by forest fires is a poor source of such nuclei (47). An attempt was made to determine the role that bacteria and the spores of fungi might play in this respect (47) and to evaluate the role of industrial smokes of various kinds (49).

Adiabatic Expansion of Gas. An important contribution to the early knowledge of meteorological phenomena was made through Vonnegut's observations that, when gas is cooled to below -39°C by adiabatic expansion, very large numbers of ice crystals are formed (50). For example, the low temperature produced at airplane propeller tips and wings can seed supersaturated air or supercooled clouds, resulting in persistent vapor trails or [illegible] modification. Cwilong had reported (51) that ice crystals could be produced by this method, but he apparently had not appreciated the enormous numbers which are so produced.

Such vapor trails (produced by adiabatic cooling of air in wing tip and propeller vortices) are generally transient, small-dimension phenomena of lesser importance than implied. Condensation trails, involving the release of water vapor in engine exhaust, can and do produce persistent streaks or cloud sheets in ice-supersaturated air.

It was found that the adiabatic expansion resulting from the bursting of a rubber balloon a millimeter in diameter produced over 10,000,000 ice crystals. Schaefer made a popgun which did the same thing, lending itself to careful control of temperature, pressure, and humidity.

These air expansion experiments provided corroboration of conclusions already reached with dry ice and furnished additional quantitative data on nucleation which were found very useful.

Chemical Effects. An interesting effect noticed by Vonnegut while carrying out some studies of ice crystals in a cold chamber was that the presence of normal butyl alcohol caused the crystals to form as hexagonal columns instead of hexagonal plates (52). This phenomenon was studied by Schaefer in some detail, but no practical application of the findings was developed.

Spontaneous Ice Formation. Project work done as early as 1946 indicated that ice crystals formed spontaneously in water-saturated air when the temperature reached the neighborhood of -35 or -40°C. Schaefer conducted considerable research into this subject and determined that the critical temperature was -38.9 ± 0.1 degrees (53). This phenomenon is probably of considerable significance in relation to the formation of cirrus clouds and ice crystal fogs in the free atmosphere.

Crystal Structure, Growth and Multiplication.

(a) Schaefer's study of the various types of snow crystals, which started before the establishment of Project Cirrus, continued throughout the project. In 1948 he published a simple yet inclusive list of ten types of solid precipitation for classification purposes (54).

This classification of snow (p. 22) was agreed upon by the International Commission on Snow and Ice in 1951. It is still widely used throughout the world although some researchers now employ the more detailed classification of Magono and Lee (56).

(b) Experiments by Schaefer in 1949 indicated that snow particles tend to shed minute fragments of ice when they are placed in air slightly warmer than their own temperature. An ice-forming nucleus appearing in a supercooled cloud grows rapidly, especially in the temperature range of -12 to -16°C, where the difference between the partial vapor pressure of ice and of water passes through a maximum. When the crystal becomes large enough, it sheds a considerable number of ice particles as it falls through the cloud. These particles then serve as new nuclei and repeat the cycle. In this manner, a few ice-forming nuclei in a cubic meter of cloud may start a chain reaction which, within a few minutes, could shift a supercooled cloud to a mass of snow crystals (55).

A fundamental problem confronting cloud physicists today is how to account for the high concentrations of ice crystals found in some clouds. These enhanced concentrations of crystals are sometimes 1 to 4 orders of magnitude greater than the ice nucleus concentrations just below the cloud base. An ice-multiplication mechanism is suggested. One possibility is that mentioned above [and updated (57)], while Mossop (58) has listed and evaluated some 12 other possibilities. Recently Hallett and Mossop (59) have presented rather convincing laboratory evidence that a riming-splinter mechanism at temperatures near -5°C may explain many of the field observations.

SILVER IODIDE

After the discovery that silver-iodide smokes serve as excellent nuclei for the formation of ice crystals, the project was faced with the problem of finding some way of generating the smoke efficiently and in quantity. It was found that smokes consisting of exceedingly fine particles could be easily produced by vaporizing silver iodide at a high temperature and then rapidly quenching the vapor. This was readily accomplished by burning silver-iodide-impregnated charcoal or injecting a spray of silver-iodide solution into a hot flame. Simple generators based on this principle were made which could produce 10^{14} nuclei per second--enough to seed from 4000 to 40,000 cubic kilometers of air per hour (14).†

A very interesting discovery resulting from one of Vonnegut's studies is that silver-iodide particles do not react immediately as ice-forming nuclei when introduced into a supercooled cloud of water droplets. Even 50 minutes after introducing a smoke sample into the cold chamber, ice crystals could be seen to form at a measurable rate. The general conclusion reached as a result of this study was that the rate of reaction at -13°C is 30 to 40 times faster than at -10°C (25).

According to this interpretation, nucleation by silver iodide is a stochastic affair. The probability that a silver iodide particle in a supercooled cloud will nucleate an ice crystal within a given time is determined only by the temperature and is quite independent of the length of time that the particle has been in the cloud. To date, this concept has received little attention in the scientific literature of cloud seeding, and apparently has neither been accepted nor rejected.

The first unambiguous results in cloud seeding using silver-iodide generators were obtained in 1948, when silver-iodide nuclei produced by one of Vonnegut's generators installed in an airplane resulted in cloud modification similar to that produced by dry ice (60).

Most investigators all over the world had little trouble in duplicating the effects produced by seeding supercooled clouds with dry ice. This was sometimes not the case, however, when clouds were seeded with aerosol particles intended to serve as freezing nuclei, such as silver iodide. In some cases the failure probably resulted from using substances that had little or no activity in nucleating ice. For example, nuclei consisting of lead oxide or potassium iodide were used in the 1948 Weather Bureau experiments instead of silver iodide (61). In other cases negative results were obtained probably because the silver iodide was improperly dispersed as an aerosol. An account of this is to be found in reports of Australian experiments carried out in 1952, in which it is said of silver iodide, "This agent proved to be much less effective than dry ice, and in most cases no visible results appeared."(62)

Experiments were conducted to determine whether the burning of charcoal particles used in silver-iodide seeding from an airplane would be seriously affected by the moisture in clouds. It was concluded that such burning is not seriously affected if the charcoal is thoroughly ignited (22).

Some experiments were conducted to discover the value of a turbojet burner

†Equivalent to approximately 100 nuclei per liter to 10 per liter, respectively.

as a silver-iodide smoke generator. It was decided that such a method might be of value if larger generators were needed than those already in use (23).

Experiments were also made in tracing silver-iodide smokes after their release by seeding generators (60).

The nature of silver iodide is such as to suggest the possibility that its effectiveness as a seeding aoent might be reduced by the action of ultraviolet and near-ultraviolet radiation from the sun. Accordingly, an investigation was made to determine its rate of decay under expected conditions of radiation in the free atmosphere. The results of work in this field, not only by Project Cirrus but also the New Mexico School of Mining and Technology, suggested that far greater quantities of silver-iodide particles might be required for seeding operations under conditions of bright sunlight than would be needed at night or under conditions of cloud cover. But later work and observations indicated that the effect of sunlight might not be as bad as was forecast (63, 64).

This summation appears valid despite conflicting results of several subsequent investigators that indicated photo-deactivation rates of silver iodide anywhere from a factor of 2 to 10⁶ per hour. Apparently the decay rate is inversely proportional to particle size, humidity and purity of the aerosol. Because of the high humidity within clouds and the "impurities" inherent with solution burners, typical silver iodide seeding operations probably involve photolytic decay rates of less than a factor of 10 per hour.

Experimental work showed that it is possible to convert supercooled ground fogs to ice crystals by releasing silver-iodide smokes (13).

RAINDROP STUDIES

Although many of the details are still lacking, studies conducted by Project Cirrus began to provide answers to the question of how rain is formed. In 1947, reports were received of successful results obtained by dry-ice seeding of cumulus clouds over Hawaii having a temperature above the freezing point. Langmuir examined theoretical calculations he had prepared in 1944 in studies relating to work at Mount Washington Observatory. As a result he developed a theory which agreed very well with the reactions reported (64).

According to Langmuir's theory, actively growing cumulus clouds having an average drop size of 20 microns, a liquid water content exceeding 2.5 g/m^3, and a vertical thickness of more than a mile are in a favorable state for starting a chain reaction. This could be achieved by introducing water drops greater than 50 microns in diameter into the actively growing part of the cloud.

Large drops in such a cloud would fall at a greater velocity than would small drops. In falling, they would overtake and collide with the small drops and thereby increase in size. In time the large drops would become so large that surface tension could no longer hold them together, and they would break up into two or more smaller drops. These in turn would grow and break up, and the number of large drops would increase in this manner by a chain reaction.

The process would not be sufficient to produce large numbers of raindrops in a cloud without a vertical updraft. However, in the case of clouds with suitable updraft conditions, many stages of the chain reaction are carried out, resulting in the production of rain.

To determine the validity of several of the important phenomena involved in this theory, various studies were initiated in the laboratory and experiments were conducted in the field. Blanchard devised a splendid method for studying the properties of free-falling water droplets in air, using a vertical wind tunnel.

A large variety of these vertical wind tunnels are in use today. One of the largest (1.8 m throat diameter) is at the State University of New York at Albany (67). A very sophisticated version can be found at the University of California at Los Angeles (68).

A series of striking stroboscopic photographs was made, showing the oscillations, gyrations, pulsations, and fractures that go on as water drops fall at their terminal velocity (65). Another activity concerned itself with devising means of sampling raindrops and measuring diameter (65). His chain-reaction theory led Langmuir to postulate that cumulus clouds having sufficient updrafts could be seeded with a few large water drops. Seeding with water drops was carried out with apparent success in tropical clouds (69), as will be discussed (p. 25).

CONDENSATION NUCLEI

Condensation nuclei play an important role in the behavior of the atmosphere. In 1948 Vonnegut devised a method of obtaining a continuous record of the concentration of condensation nuclei in the atmosphere (28). Various experiments were conducted with this equipment, both aground and aloft. The results suggest that the continuous measurement of the concentration of condensation nuclei may be very useful in meteorological investigations.

It is now well recognized that the concentrations of "large" (greater than ~ 0.1μ) condensation nuclei strongly influence the microstructure and stability of clouds (71). Smaller "Aitken" nuclei (less than 0.1μ) measured with expansion counters, play a significant role in atmospheric conductivity, visibility, haze, gas-particle reactions, and several yet-to-be defined pollution processes.

ELECTRICAL PHENOMENA

It was observed in 1943 by Schaefer that interesting atmospheric electrical measurements could be obtained by connecting one end of a shielded cable to an insulated needle presented to the sky and the other end to a sensitive recording microammeter, one side of which was well grounded (70). Among the interesting observations made during successive years was that this instrument indicated the passage of charged clouds over the observation point.

Continuous records were kept by Falconer from 1948 on, using the data provided by this equipment, and an attempt was made to correlate the measured corona-discharge currents with other meteorological phenomena, such as frontal passages, wind direction, precipitation, and reflected light from the northern sky, particularly with apparently clear skies (72).

When Workman and Reynolds announced in 1948 their discovery of the formation of a large electrical potential when water containing small quantities of certain salts is in the process of freezing, Schaefer decided to check the experiments by an independent investigation. Accordingly, test equipment was set up and observations were made. The Workman-Reynolds electrical effects were immediately observed. The results of this experiment have very important implications with respect to the development of lightning in thunderstorms (73).

Some qualitative experiments were made by Vonnegut and Neubauer to determine the effects of high voltage on the formation of water drops (74). It was found that streams of highly electrified, uniform droplets about 0.1 millimeter in diameter could be produced by applying potentials of from 5 to 10 kilovolts, ac or dc, to liquids in small capillaries. Aerosols of uniform size and having a particle radius of a micron or less could be formed if the capillary was positively charged and if liquids having low electrical conductivity were used. Aerosols formed in this way showed the colors of higher-order Tyndall spectra.

STUDY OF CLOUD TYPES

In connection with an investigation of snowstorm intensities, Schaefer started measuring variations in sky brightness using a light-sensitive instrument. Falconer subsequently carried on the measurements in more detail. It was discovered that the variations in the curve made by this instrument were 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. Test installations were made by Falconer at various points aground and aloft, and considerable data were gathered (40).

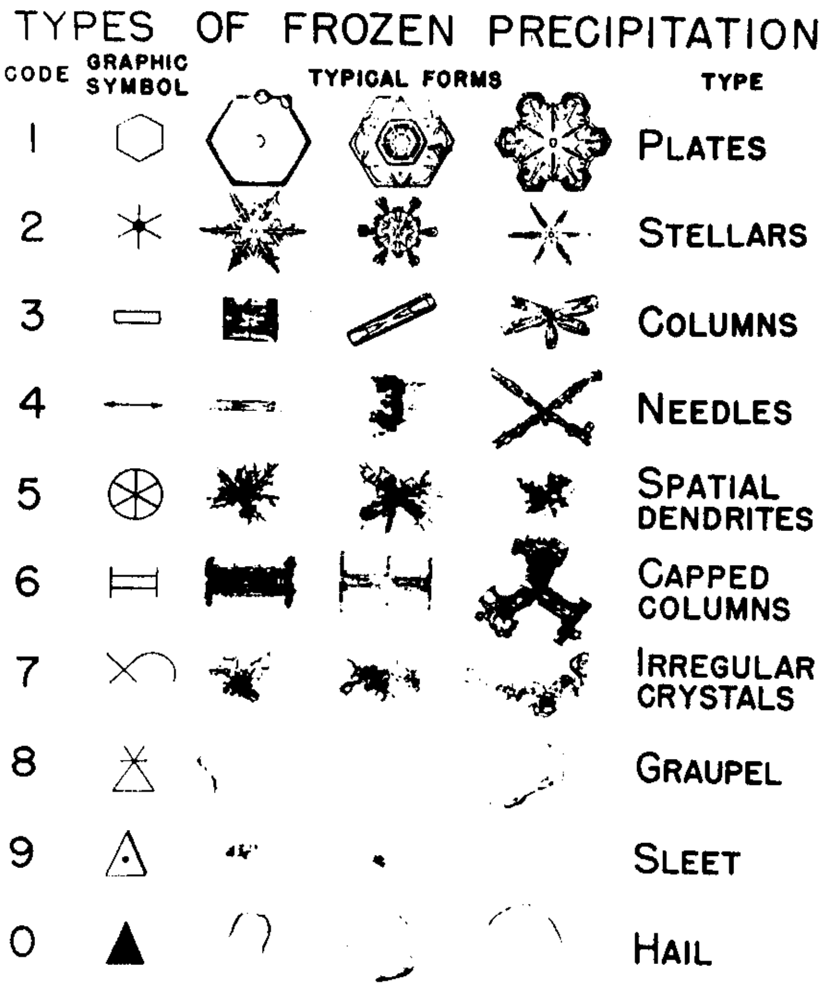
Such an instrument might be useful in automatic weather stations, to give some indication of sky conditions in remote locations.

ANALYTICAL WORK

Of great significance, both in connection with activities of the Research Group and with those of the Operations Group, was the analytical work performed by Langmuir. It constituted one of the most important contributions to the project.

From the outset he studied and analyzed the various test flights, and extensive reports were prepared analyzing cumulus and stratus cloud seedings. His analysis of the cumulus seedings over Hawaii and the chain-reaction theory of rainfall which resulted have already been mentioned. Langmuir paid particular attention to the seeding operations carried on in New Mexico, and to the possible effects of silver-iodide seeding, and these activities are described more fully in a later section of this report (pp. 29, 37, et seq.).

Such a large quantity of data was accumulated by flight, field and laboratory activities during the more active period of the project that the Research Group finally suggested early in 1950 to the Technical Steering Committee that flight operations be terminated at Schenectady in order that the accumulated data might be evaluated and reports prepared on the findings.



Snow Crystal Classification developed by V. J. Schaefer and adopted by the International Commission on Snow and Ice in 1951.

V. CIRRUS AND STRATUS STUDIES

CIRRUS CLOUDS

The significance of cirrus clouds and the role they play in various weather phenomena were, of course, subjects of intense interest to the Project. Various studies of and experiments with such cloud forms were conducted, although more attention was paid to stratus and cumulus clouds.

A regular daily observation program was begun in 1947 to explore the possibility of inducing the development of cirrus-type clouds under clear sky conditions. It was believed that supersaturation with respect to ice probably occurs fairly frequently at temperatures warmer than -39°C in air devoid of foreign-particle nuclei. Lacking such nuclei, a considerable degree of supersaturation could develop, as is often shown by the generation of so-called vapor trails behind high-flying aircraft.

To explore these possibilities, Falconer initiated a project in which balloons carrying dry ice in open-mesh bags were released on a daily schedule and followed by theodolite. Many of these produced visible trails of ice crystals, and in several instances the trails were quite noticeable (20, 21, 27, 39).

Several seedings were also carried out from an airplane in clear air, using both dry ice and silver iodide. In clear air supersaturated with respect to ice, the seeding operation produced a cloud of ice crystals. The results of these operations indicated that, if the humidity is low, even at temperatures below -39°C, appreciable supersaturations with respect to ice can exist without the formation of ice crystals. Ice crystals can then be created, however, by seeding with either dry ice or silver iodide (24).

In six of the Project Cirrus test flights a considerable effort was directed toward obtaining photographic evidence of the appearance of the tops of natural cirrus clouds. It was found that, despite the various irregularities seen from below, the tops of such clouds are extremely flat.

Most meteorologists and weather students agree that a cirrus cloud formation is often associated with the overrunning of cold air by a warmer tongue of moist air. Whenever the moisture conditions in the warm overriding air reach saturation with respect to water and the colder air below has a temperature of -39°C or colder, ice crystals will form spontaneously at the inversion interface. The number of primary crystals that form will depend on the concentration of condensation nuclei and ice nuclei in the moist air mass. The number and size of secondary crystals that form will probably be some multiple of the effective number of condensation nuclei. Since these conditions for the ice-crystal formation are of a marginal nature, the variability and often unique appearance of true and false cirrus clouds may be closely related to these spontaneous crystal formation phenomena. Based on this reasoning, Schaefer concluded that it is likely that the concentration of supercooled water droplets at the transition temperature of -39°C is of primary importance in the formation of cirrus crystals (53).

Langmuir, analyzing the behavior of cumulus clouds, described an action which he called cirrus-pumping. This occurs when, with few or no nuclei present, the cloud rises to great heights. If it rises to a height when the temperature gets down to -39°C or thereabouts, minute ice crystals are formed in great numbers, almost instantaneously. These have a lower vapor pressure than any supercooled water droplets present and rapidly grow at their expense. This, in turn, liberates a large amount of heat simultaneously over the whole top of the cloud, and this upper part rises still further, forming a cirrus crown shaped something like a pancake.

The pancake grows in dimension and gets thinner, and it sometimes drifts gradually off to one side, so that it assumes the general appearance of an anvil--a type of cloud characteristic of the tropics. One large cloud of this type, said Langmuir, might sometimes produce cirrus clouds which would spread over 25,000 square kilometers. Outside of the tropics, they may often occur during the summer in semi-arid regions such as New Mexico, Arizona, or Idaho (75).

STRATUS CLOUDS

Much more attention was paid to stratus clouds. The flight test of December 20, 1946, for example, was conducted when the sky was completely overcast, and it produced snow (1). In the flight test of March 6, 1947, under the auspices of Project Cirrus, seeding was conducted on stratus clouds. Looking down on the cloud, it was observed, first, that a deep groove had been produced along the top of the seeded area, and snow fell. Soon the sky cleared up in a spectacular fashion, so that there was a cloudless area 32 kilometers long and 8 kilometers wide where the seeding had taken place. There were no other breaks in the overcast in any direction (76). Further tests on stratus clouds produced similar results.

The conclusion was therefore reached in the earliest days of the project that cloud seeding could produce holes in stratus clouds. Thus a plane should be able to clear a hole for itself. The result would be not only to increase visibility but also to eliminate icing conditions. Langmuir made an exhaustive analysis of the photographic data obtained on these early test flights, reaching some very interesting conclusions regarding the nature and behavior of stratus clouds (77).

It was soon found that a very useful technique in seeding stratus clouds was to seed in patterns--L shapes, race-track shapes, Greek gammas, etc. Thus it would be possible to watch for modification of the clouds following the same pattern. And invariably modification did occur, agreeing with the pattern of the seeding. In many cases clear areas were produced in the cloud deck.

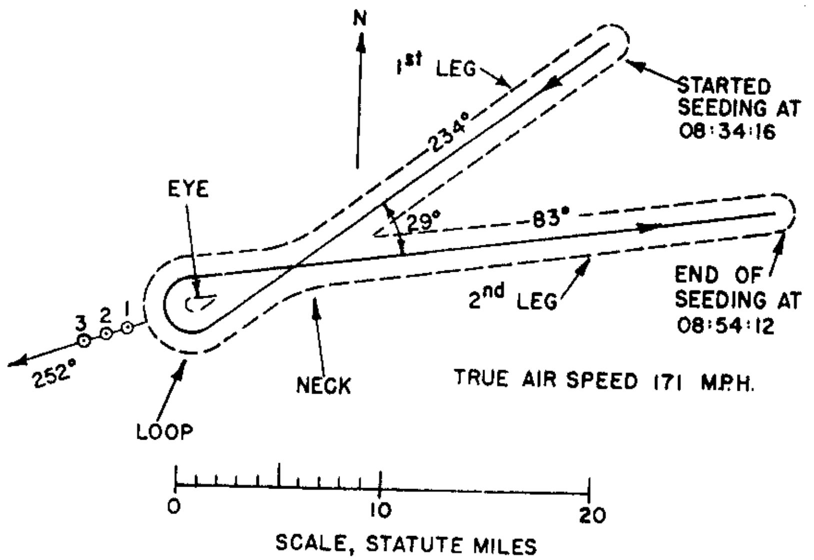
Among the stratus cloud studies made by the project were:

(1) The effect of seeding supercooled stratus clouds with various amounts of dry ice and silver iodide;

(2) The optimum quantity of seeding agent required to produce large cleared areas in an otherwise solid deck of supercooled clouds.

These results were duplicated by several investigators in various locales (78, 79, 80, 81). Vickers and Church (82) conducted an extensive series of experiments to determine the optimum clearing of stratus clouds with dry ice. Among their findings was evidence that seeding effectiveness increased linearly with decreasing cloud temperature and that about 2 kilograms of dry ice per kilometer constituted an optimum seeding rate; 1 kilogram per kilometer was nearly as good, but rates less than .5 kilograms per kilometer were generally ineffective.

The clearing of supercooled fog on an operational basis has been accomplished at many airports around the world (83). Dry ice, liquid CO_2, or liquid propane are customarily employed. In this country the preponderance of fog (~95%) is of the warm fog type (warmer than 0°C) where such nucleants are ineffective.



The dimensions and shape of the seeded Gamma Pattern from photopanel data. The position of the three point drops, 20 grams, 2 grams, and 200 grams, are indicated by the small circles marked 1, 2, and 3 at the left of the loop. The two dashed lines parallel to the seeding track show the approximate maximum development of the modified clouds one hour after seeding.

VI. CUMULUS STUDIES

The most spectacular, fruitful, and controversial results produced by the activities of the project were those resulting from the work on cumulus clouds. This work, which started in the earliest days of the project, continued throughout its duration and led to some other very interesting activities.

Flight tests on November 23 and 29, 1946, were made on isolated cumulus-type clouds. The whole of each cloud was changed into ice within five minutes after seeding, and snow began falling from the base of the cloud (20). But it was realized that experiments with small cumulus clouds were of little interest, for the effects lasted but a few minutes. Other experiments were conducted with cumulus clouds in the early days of the project and, although many of them were made to snow, the results were of comparatively little interest.

By the summer of 1947, however, some spectacular results were obtained with cumulus clouds, especially with thunderstorms. These were so impressive that it was decided to make some studies of cumulus clouds and thunderstorms in New York State's Sacandaga Reservoir territory, not far from Schenectady.

This reservoir is situated just south of the southeast corner of the Adirondack Mountains. Evidence pointed to the probability that this large body of shallow water provides the moisture which feeds thunderstorms in eastern New York State. It was believed that the unusual conditions there could be used to observe the effect of seeding the intense thunderstorms which developed. Actually, no seeding was performed there, although many photographs were taken and considerable time was spent in a study of conditions in that area. It was found that storms elsewhere were better developed and less transient in nature, hence more suitable for field investigations.

HONDURAS

In 1948 and 1949, Langmuir visited Honduras, Guatemala, and Costa Rica to study tropical cloud formations, and particularly to learn what was being done by Joe Silverthorne, a commercial cloud seeder, in seeding clouds for the United Fruit Company. The work was being conducted for the purpose of testing out the possibility of controlling rainfall, and particularly in the hope of stopping blow-downs that result from winds associated with thunderstorms, which occasionally destroy large stands of fruit trees.

At Langmuir's suggestion, Silverthorne tried out a number of experiments early in 1949 and made many worthwhile observations. It was sometimes desired to produce rain, and sometimes it was desired to prevent rain. On the one hand, by overseeding the top of a high cumulus cloud, rain would be prevented. The top of the cloud would float off to a higher altitude, where it would be blown away by the counter trade wind. If, on the other hand, the cloud was seeded just above the freezing level, heavy rain might be produced. Similarly, water seeding by means of water-filled balloons released from airplanes might dissipate a cloud and produce rain at low altitudes, but it seemed that in such instances dry-ice seeding would be much more effective.

April 18, 1949. The results of the flight on this day, with Langmuir accompanying Silverthorne aloft, were so outstanding as to merit detailed comment (69). The following is extracted from an account of the flight by Langmuir in the Project Cirrus report to the government of July 30, 1951:

"We flew up to Point Sal and found a mass of dry air above the moist air coming from the sea at an altitude of about 6000 or 7000 feet (2.0-2.1 kilometers) .....From a height of about 8000 feet (2.4 kilometers), looking south, a whole panorama of high cumulus clouds could be seen rising above the smoke, which extended up to about 11,000 or 12,000 feet (3.3-3.6 kilometers) further inland, although it was much lower than this near the sea.

"A large cloud was found which rose, I believe, to a height of about 25,000 feet (8.3 kilometers), and we seeded it by making a series of short passes into the cloud at an altitude of approximately 21,000 feet (6.3 kilometers)--two pellets [dry ice] about one inch (2.5 centimeters) cubed being dropped into the cloud at 50-second intervals during these passes. The whole circuit of the cloud was made, and then the plane moved off a short distance, enabling us to see the effect produced.

"A band around the cloud, perhaps 500 (150 meters) or 1000 feet (300 meters) high, was observed which obviously consisted of ice crystals and which ultimately detached itself from the lower part of the cloud and floated off as a huge mass of ice crystals that could be seen for a long time.

"After the top of this cloud had turned to ice crystals and had detached itself, there was left under this cloud nothing but a group of lower clouds that reached only about 14,000 feet (4.2 kilometers), which was below the freezing level. Later we flew down among these clouds and found that cloud bases had gone down from 12,000 feet (3.6 kilometers) to about 7000 feet (2.1 kilometers). It was difficult to see whether any rain was falling because of the smoke, but from the lowering of the cloud base we concluded that rain had fallen from the lower part, while the top of the cloud had detached itself and floated off towards the northeast.

"Shortly after seeding this cloud with 10 to 12 pellets, we picked out a smaller cloud nearby whose top reached about 20,000 feet (6 kilometers) and dropped one single pellet of dry ice one inch (2.5 cm) cubed on this cloud. About 8 or 10 minutes later we found that this whole cloud had changed to ice crystals. We flew through the ice crystal cloud and verified the fact that they were entirely ice crystals. You could see them blowing into the cabin, and we also found that the cloud gradually dissipated. It probably rained out from the lower part of the cloud but this was done in the smoke level where we could not see it, and the top of the cloud then gradually mixed with the surrounding dry air which had been deprived of its source of supply of moisture from below.

"In other words, on this day we had beautiful examples of two effects that can be produced by seeding with pellets of dry ice. First the seeding of the top of the cloud can cause the top to float off from the lower part. However, in this case some of the ice crystals reach the lower part of the cloud and cause rain to dissipate it. In the other seeded cloud, which was much lower and reached only a few thousand feet above the freezing level, the whole cloud rapidly dissipated as the upper part changed to ice and the lower part rained out."

The results of the flight of April 18 constituted for Langmuir a wonderful demonstration of the effectiveness of single large pellets of dry ice for modifying large cumulus clouds. It quickly became obvious to him that the set-up for carrying out cloud-seeding experiments in Honduras was unique. Silverthorne made flights virtually every day, and, somewhere within a 150-mile (240 kilometer) range, clouds were nearly always found suitable for seeding. Such clouds were almost always orographic and associated with certain mountains.

Many interesting experiments were conducted, and almost always the clouds could be profoundly modified with single pellets of dry ice. The latter part of Silverthorne's seeding operations used 10-20 pellets, presumably to make sure the crystals were more uniformly distributed.

PRIEST RIVER STUDY

Meanwhile the study of cumulus clouds had been approached from another angle. Early in 1948 a visit was paid to the Research Laboratory and Project Cirrus by H. T. Gisborne of the Northern Rocky Mountain Forest and Range Experiment Station, United States Forest Service. Gisborne was in charge of fire research for Region No. 1. He wanted to learn more about cloud modification studies.

This fitted in nicely with Schaefer's interest in the same subject. He was anxious to study thunderstorms in a good breeding ground, and Gisborne wanted to see if anything could be done to reduce forest fires by thunderstorm modification. As a result, Schaefer visited the Laboratory at Priest River, Idaho, in July of that year (1948). He conducted quite a study of conditions there and made rather complete recommendations for a plan of future activity--a plan which should produce beneficial results from both standpoints: Gisborne's practical aspects and Schaefer's theoretical ones (74, 84).

Actually, the recommendations were never put into effect. A considerable force for the completion of the project disappeared with the death of Gisborne. Although the project is still incomplete, interest still exists, however, both at Schenectady and at Priest River.

In the mid-fifties, the U. S. Forest Service resumed its interest in attempting to modify lightning damage by cloud seeding. Project Skyfire was formed which involved several cooperating groups including Schaefer (then with the Munitalp Foundation). In 1956 a silver-iodide ground seeding program was initiated in Montana in hopes of limiting the size of crystals and the charge separation taking place in deep cumulus clouds. Preliminary results suggested a 33% reduction in the number of lightning strikes but at a statistically insignificant level. Project Skyfire was expanded to include experiments in interior Alaska where, in 1957, more than 5 million acres of forest land were burned by lightning fires (85).

RESULTS IN HAWAII

Further data, supplied from still another source, had some unexpected and very interesting implications and results. Early in 1947 a request for information on techniques of dry-ice seeding was received from the Pineapple Research Institute of Honolulu, Hawaii. This information was supplied by the Research Group of Project Cirrus, which had been supplying similar information to meet numerous requests stimulated by the published reports of the historic snowmaking flight over Pittsfield in 1946. But in this case there was an unexpected aftermath.

In October, Honolulu newspaper accounts were received in Schenectady, describing experiments carried out over the island of Molokai by Dr. L. B. Leopold and Maurice Halstead of the Pineapple Research Institute. A few weeks later, copies of a preliminary report were received from these two men, describing interesting results obtained by dumping dry ice into cumulus clouds having temperatures above the freezing point.

This was an important development. Although Langmuir had given some thought to the effects of seeding nonsupercooled clouds, he hadn't done much about it, and this new work caused him to restudy theoretical calculations he had prepared in 1944 in connection with the work at Mount Washington (86) (p. 4). He now had a new approach to the subject of weather modification: the growth of rain.

RAIN CHAIN REACTION

Prior to and during the period of the Project Cirrus experiments, the prevailing view among meteorologists was that practically all rain of any importance occurred through the action of the Bergeron (ice crystal) process. For a time at least this view was accepted almost without reservation by the scientific staff of Project Cirrus. This assumption, that the Bergeron process was the primary rain-forming mechanism, necessarily engendered the belief that the newly developed techniques of cloud seeding were more effective and foolproof than we now know them to be. As we now recognize, much of the rain that is formed, not only in warm, but also in supercooled clouds, is produced by a rapid droplet collisional process that may or may not involve ice. It is now generally recognized that under certain conditions cloud seeding might possibly decrease rather than increase the formation of precipitation, by turning the cloud to ice crystals and thereby preventing an efficient drop coalescence or accretion process from taking place. The Hawaiian observations of the acceleration of rain production in a nonsupercooled cloud and the subsequent observation of warm cloud precipitation in Puerto Rico kindled the interests of Project Cirrus in rain formation in warm clouds and led to Langmuir's formulation of the chain reaction theory of rain formation which follows.

A typical large drop of water grows in size as it falls through the cloud, growing faster and faster until it gets so big that it breaks up, producing smaller droplets. If there are rising air currents, the little droplets will be borne aloft into the cloud again, growing in size as they go, until they get so big that they start falling again. This process continues in a chain reaction, causing the whole cloud to produce heavy rain. Under the right circumstances, according to this theory, seeding with water would be just as good as with dry ice (87).

It was recognized that the ambient cooling effect of dry ice was not instrumental in any possible modifications of warm clouds. Rather the frost that forms on dry ice was believed to melt after the dry ice had sublimed, leaving large droplets to seed the cumuli.

The outgrowth of this, in turn, was considerable work by Project Cirrus to test Langmuir's theory and apply some of its principles in practice. For example, to determine the validity of several of the important phenomena which his theory postulated, extensive laboratory studies were conducted on the growth of water droplets and of the behavior of droplets floating in the air (65, 88). Later, the Research Group did considerable work in the study of the drop size and size distribution of various types of precipitation (89, 66).

As another approach to the subject, an extensive series of experiments was conducted to explore the possibility of inducing precipitation or other modification in growing cumulus clouds by water seeding (69).

The complete exposition of the theory by Langmuir was a beautiful example of theoretical analysis and mathematical calculation (87). Among other things, it reviewed the knowledge of cloud physics which had already been gained in the light of the new theory, summing up the probable behavior of both stratus and cumulus clouds. It went so far as to suggest that the chain reaction could, under the right conditions, be started by introducing even a single drop of water into a cloud, although the action would be most rapid when many large drops were introduced near the top of the cloud. It outlined the probable behavior of self-propagating storms. It postulated that the phenomena that occur in artificial seeding with dry ice or with water are essentially no different from those that occur spontaneously in nature. "However," it went on, "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." It concluded with the following summary:

"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."

Langmuir's chain reaction hypothesis relating to the continuous breakup of large raindrops was largely ignored for the next decade or two. Ironically, at the First International Conference on Weather Modification in 1968, sponsored by the American Meteorological Society, several independent investigators and papers dealt with this subject. Thus, there is revived interest in and more acceptance of the mechanism (91), although clear-cut experimental evidence is still lacking (92).

STUDIES IN PUERTO RICO

All these studies and tests which had been made, and theories which had been evolved as a result, with regard to the nature, behavior, and modification of cumulus clouds were an important background to another significant milestone in the history of Project Cirrus. That was the expedition to Puerto Rico in February, 1949 (90).

The objective of this trip was mainly to determine the type and physical characteristics of the clouds that occur in Puerto Rico during the winter months, particularly the month of February, and, if suitable clouds were encountered, to develop and possibly to evaluate water-seeding techniques. Considerable personnel took part in the project, a supply of planes was available, and a large quantity of photographs was made.

At least two new precipitation sequences were observed, and considerable data were accumulated to permit a better understanding of the processes involved. Also studied was the trade wind inversion, a dominant feature which controls cloud and precipitation development in the West Indies region during February. A better understanding of this phenomenon should lead to a better understanding of tropical meteorology.

The cumulus clouds were observed to have a different character than those common in the eastern United States. Contacts made with interested local people in Puerto Rico were expected to lead to the accumulation of some excellent supplementary data on raindrop size, convergence of winds, and the observation of double orographic cloud streams from the Liquillo Mountains.

The carrying out of successful ground-air operations on three different occasions, using time-lapse photographs as part of the ground coverage, demonstrated conclusively to the members of the project the value of carrying out such studies of clouds which develop in definite cloud-breeding regions. Similar regions in the United States known to possess such developments were Albuquerque, New Mexico, and Priest River, Idaho. Schaefer had already visited Priest River, and arrangements had been made for investigations and experiments there. Also, a test mission had been conducted at Albuquerque the previous year, details of which will be found in the next section of this report.

Despite the fact that no suitable clouds were found for testing out water-seeding techniques during the period, many valuable results were obtained which it was expected would lead to a much better understanding of the formation of rain in tropical clouds. One of the very significant results of the expedition was the observation of the important effect of salt nuclei on the formation of precipitation in thin tropical clouds. Said one of the reports: "This seems, on first sight, to be of great importance in explaining the rain showers which are of daily occurrence and random distribution in the vicinity of Puerto Rico. Rarely is rain observed from such clouds in the eastern United States." Said Langmuir:

"Observations in Puerto Rico in 1949 and in the Hawaiian Islands in 1951 have shown that the rainfall depends on relatively large particles of sea salt in the air, in accord with the publications of A. H. Woodcock and Mary Gifford. Calculations of the rate of growth of salt particles indicate that it should frequently be possible to induce heavy rainfall by introducing salt into the trade wind at the rate of about one ton per hour in the form of fine dust particles of about 25 microns in diameter. The heat generated by the condensation may liberate so much heat as to produce profound changes in the air flow and the synoptic conditions in neighboring areas" (93).

Several groups subsequently have experimented with the seeding of warm clouds with water to stimulate precipitation, the most notable effort being that of the University of Chicago (94). Clouds were seeded from above with water drops (median diameter of 250μ) at reported rates of 300 liters and 1000 liters per kilometer in both Puerto Rico and the central United States. While neither seeding rate produced observable radar echoes in the United States, the higher rate did show a statistically significant increase in precipitation in Puerto Rico. Thus some positive results were obtained in maritime clouds, but the amount of water required to "prime the pump" was considered impractical.

More feasible is the concept of releasing large (10-20μ) salt particles into the cloud updraft to produce large drops capable of stimulating droplet growth by coalescence. Initial experiments were conducted by Mordy et al. (95) in Hawaii. Encouraging calculations by Bowen (62) were followed by further trial experiments in East Africa (96), later in India (97, 98) and recently in the United States (91). The Indian experimenters suggested that a 20% increase in rainfall might be expected in summer monsoon conditions.

EARLY WORK IN NEW MEXICO

Although interest in cumulus clouds and thunderstorms was high among the members of the Research Group in 1948, the cumulus season passed in the vicinity of Schenectady without any significant flights having been carried out. It was realized that the best results could be obtained from the seeding of cumulus clouds in a region where storms originate rather than in a region which, like the Schenectady area, is traversed by storms. Chairman Stine of the Operations Committee had experience as a forecaster in New Mexico, and he strongly recommended that region as a base for experiments with cumulus clouds. This recommendation was seconded by Schaefer, who knew of the work being done in this field by Dr. E. J. Workman's group at the New Mexico School of Mines and who had obtained a promise of cooperation from Workman.

Accordingly, it was decided to attempt a flight to Albuquerque, New Mexico, to determine whether the radar and other facilities of Dr. Workman's group would be of assistance in this respect. In view of the waning cumulus season even at the location, preparations were made to carry out full-scale tests if proper clouds were formed. As a result, members of the project spent three days at Albuquerque during mid-October of 1948. A working arrangement was quickly made with Workman and his staff for radar tracking and photography of the tests to be made. Two seeding flights were made, one on October 12 and the other on October 14. The second of these two flights was performed under such satisfactory conditions that the results obtained were considered particularly significant (99).

For example, an exceptionally complete aerial photographic record was made of the conditions of the cloud that was seeded from one of the planes, including 176 photographs 10.1 X 12.8 centimeters, plus pictures taken every 45 seconds of a group of instruments giving time, altitude, air speed, heading of the plane, and other pertinent information. Every time a photograph was taken of the cloud, another picture would be taken of a clock and the other instruments. In this way an invaluable flight record was made of the test.

Further data were collected on the ground. Time-lapse movies were made of the clouds as seen from the station, as well as a series of still pictures, and radar was used to detect any rain that might fall. Although some excellent supporting data were thus obtained, unfortunately it was not as complete as it might be, because of a failure of the radio communications between the airplane and the radar station. But significant radar observations were made, and photographs were taken of the radar scope, giving a complete set of records of radar observations for a considerable period of time.

Four seeding operations were conducted on the October 14 flight. The details of these seedings and the results obtained were discussed at considerable length by Langmuir in an occasional report (99). His findings indicated that rainfall was produced over an area of more than 100,000 square kilometers as a result of the seeding--about a quarter of the area of the State of New Mexico. And substantially all of the rain for the whole of New Mexico that fell on October 14 and 15 was concluded to be the result of the seeding operations near Albuquerque on October 14. "The odds in favor of this conclusion as compared to the assumption that the rain was due to natural causes are many millions to one."

An early estimate by Langmuir was that about 100 million tons of rainfall was produced. Later, using the rain reports from 330 stations given in a U. S. Weather Bureau publication, he concluded that the original estimate was unduly conservative (99). Said he: "The evidence indicated that the rain started from near the point of seeding shortly after the time of seeding and then spread gradually at a rate which at no place exceeded 10 meters per second, over an area of at least 31,000 square kilometers north to northeast of Albuquerque with an average of about 0.89 centimeters. This corresponded to about 300 million tons."

SILVER IODIDE AT NEW MEXICO

So satisfactory were the tests conducted at Albuquerque in 1948 that it was decided to make a further study of cumulus clouds at that location in the middle of July the following year. Much more elaborate plans were made for this second expedition; for example, not one but a number of airplanes took part, and virtually all the members of the Research and Operations Groups went along.

Prior to the arrival of the main body of the project, Langmuir and Schaefer investigated the general cloud situation in the various mountain regions nearby and decided the cloud systems along the Rio Grande Valley near Albuquerque were superior for their purpose to anything they could find in other parts of Arizona and New Mexico. In addition, the excellent radar, photographic, and shop facilities of the Experimental Range of the New Mexico School of Mines appeared to be ideal for carrying out the operations planned.

Between July 13 and July 22 a total of ten flights was conducted, on eight of which two or three planes participated. Excellent cooperation was enjoyed in every phase of the operation, and an extensive mass of data was obtained both in the air and at the ground stations which were set up. Seeding operations with varying amounts of dry ice and the ground operation of a silver-iodide generator were the subjects for the flight studies (75).

Again the dry-ice seedin was successful, and the results of th various airborne seeding operations we. e quite satisfactory. But a new factor was introduced into this second expedition which put an entirely different aspect upon the results and had a tremendous influence on the course of future investigations and analysis. This was the effect of ground seeding with silver iodide.

As usual, close attention was paid to changes in weather conditions, in order to observe any correlation between such changes and the dry-ice seeding. Although Vonnegut was conducting some silver-iodide seeding on the ground, this was disregarded by Langmuir, who was concentrating on the airborne dry-ice seedings. Consequently, when he noticed some weather conditions which could not be explained by the airborne seeding, he was puzzled. Then he suddenly became conscious of the fact that Vonnegut had been trying to call the ground seeding of silver iodide to his attention, and he immediately realized that this might explain the discrepancies he had observed. Further study convinced him that this was, indeed, the case.

Not only that, but the results of the seeding activities in New Mexico the preceding year were reconsidered in the light of this development. And it appeared reasonable to conclude that the similar widespread effects produced in October, 1948, were the result of the silver-iodide seeding which was done at that time, rather than of the dry-ice seeding, which had been the previous interpretation.

Langmuir made, as was his habit, an exhaustive analysis of the available data and presented a striking summary of his findings (75) from which the following is quoted:

"I wish particularly in this paper to describe the more widespread effects that were produced by the operation of the silver-iodide generator on the ground during July, 1949, near Albuquerque. The first seeding with silver iodide during this stay in New Mexico was on July 15, 1949, but the generator was not run for more than a couple of hours on each day thereafter until the 19th, when it was operated for a short time only, late in the afternoon. On July 20 it was not operated at all, but on the 21st it was operated for 13 hours, starting about 5:30 a.m. and using 300 grams, or a total of 2/3 pounds of silver iodide.

"Tests made by Dr. Vonnegut have shown that each gram of silver iodide dispersed under these conditions produced 10^{16} sublimation nuclei that are slowly effective at -5°C but very rapidly effective at -10°C.

The statement concerning the number of nuclei per gram that would be effective at -5°C was not based on actual measurements of the number of nuclei effective at this temperature. Instead, it was an extrapolation founded on the suggestion by Vonnegut that, if given enough time, all the nuclei becoming effective at -20°C would also eventually initiate ice crystals at -5°C (see annotation, page 19).

This estimate of the number of particles active at -5°C is probably much too high. Even granting the assumption that the nucleation process is stochastic, it is likely that most of the particles will either be precipitated or deactivated long before they serve as ice nuclei. A more realistic estimate can be based on cold box measurements [see Fletcher (100)]. These show that a well designed aerosol generator that produces 10^{16} particles per gram effective at -20°C and approximately 10^{15} per gram at -15°C will yield only about 10^{11} effective nuclei per gram at -5°C.

"The new probability theory.....has served [as] a valuable guide in devising an objective method of evaluating the distribution in space and time of the rain which follows the operation of the silver-iodide generator on the ground or in the airplane flights near Albuquerque. To illustrate the results, we will analyze the data obtained on two days, October 14, 1948 (Flight 45) and July 21, 1949 (Flight 110).

"These days were chosen because large amounts of silver iodide were used, but no seeding was done on the immediately preceding days. Furthermore, the wind direction on both days was rather similar. On both days the Weather Bureau predicted no substantial amount of rain. Both mornings were nearly cloudless, and on both days SW winds prevailed from the cloud bases at 12,000 feet (3.6 kilometers) up to 20,000 feet (6 kilometers). At lower and higher altitudes and later in the day there were also winds from the E, W, and NW. On both days, visual effects indicated thunderstorms and heavy rain over wide areas were observed a few hours after the start of the seeding operations.

"In the July operation our techniques had been improved compared to those of the preceding October. In October radar observations covered only a period of about an hour in the afternoon, for at that time it was not suspected that the rain that lasted well on to the morning of the 15th had anything to do with the seeding.

"On July 21, 1949, however, we had complete radar coverage from early in the morning until late at night. Photographs of the clouds were taken not only from planes but from the ground, including time-lapse motion pictures with photographs every few seconds.

"Shortly before 8:30 a.m. on July 21, 1949, a single large cumulus cloud began to form about 25 miles (40 kilometers) S of the field station near Albuquerque in a sky that was otherwise cloudless. This cloud was located near the Manzano Mountains, and the silver-iodide smoke had been blowing from the N about 10 miles per hour (4.5 meters per second) so that it should have reached the position of the cloud.

"Between 8:30 and 9:57 the cloud grew in height slowly at the uniform rate of 160 feet per minute (.81 meters per second). At 9:57, when the top of the cloud was at 26,000 feet (7.8 kilometers) (temperature -23°C), the upward velocity of the top of the cloud increased quite suddenly, so that the cloud rose 1200 feet per minute (6 meters per second) until at 10:12 it had reached 44,000 feet (13.2 kilometers) (temperature -65°C).

"At 10:06, when the top of the cloud was 36,000 feet (10.8 kilometers) (temperature -49°C), the first radar echo return was obtained from the cloud at an altitude of 20,500 feet (6.2 kilometers) (temperature -9°C). The distance given by radar was 25 miles (40 kilometers) at an azimuth of 165°, which was exactly where the cloud was found to be from visual observations. The area of precipitation in the cloud was about one square mile at that time and was deep within the mass of the cloud. Within four minutes, the precipitation area had increased to seven square miles (18 square kilometers), and within six minutes after the first echo appeared, the precipitation had extended upward to 34,000 feet (10.2 kilometers), where the temperature was -43°C.

"The chain reaction in this cloud started at low altitude at a time and place which agreed well with the trajectory of the silver-iodide smoke.

"The first flash of lightning was seen at 10:10, four minutes after the first radar echo was detected. In all, perhaps a dozen flashes of lightning formed from this cloud, and very heavy rain was seen to fall to the ground. The top of the cloud moved towards the W, but the lower part of the cloud, from which the rain was falling, moved gradually to the NE.

"At 10:45, a second cloud about eight miles (13 kilometers) still further to the NE developed a radar echo, and from that time on during the day there was an increasing number of rainstorms giving very heavy showers in the neighborhood. During the late afternoon 1.2 inches (3 centimeters) of rain fell at the station where the generator was located. The phenomena observed near and at Albuquerque from the ground and the radio reports of exceptionally heavy rain at Santa Fe gave immediate evidence of the success of this operation in producing heavy rain."

Langmuir's report then analyzes river flow data and rain gauge data for the region. In discussing the rain gauge data, he says:

"The Weather Bureau observer with Project Cirrus in New Mexico stated that he considered it possible or even probable that seeding operations carried on there could have increased the naturally occurring rain by five per cent, but certainly not more than 10 per cent. If this were true, it would be possible to conclude that seeding operations have economic value only if experiments are carried on many hundreds of days, and a statistical analysis is made of the rainfall data for all of these operations.†

"The rainfall data actually show, however, that the rainfall on both October 14, 1948, and July 21, 1949, was exceptionally high and could not have possibly been accounted for as the result of naturally occurring rain. This proof is made by the analysis described in this paper.

"The map of the State of New Mexico, which represents about 120,000 square miles (307,000 square kilometers), was divided into eight octants or 45° sectors radiating out from Albuquerque. Then concentric circles having radii of 30 (4.8 kilometers), 75 (120 kilometers), and 125 (200 kilometers) and 175 miles (280 kilometers) were drawn on the map. This divided the whole state into 27 regions whose average distances and directions from Albuquerque were known.

"By entering on the map for each of these regions the average rainfall for Flights 45 and 110, a comparison could be made of the distribution of the rain on those two days. An objective way of evaluating the similarity between such two distributions is to employ the statistical device known as the correlation coefficient. This was found in this case to be +0.78 ± 0.076. The chance that such a high value would occur among these figures if one set of them were shuffled giving a random distribution on two days could thus hardly be the result of chance. There must be an underlying cause.

"We believe that the close similarity in distribution is dependent not only on the rather uniform synoptic situations over the states that prevailed on these days, but also depended on the fact that on both days the probability of rainfall depended on the nuclei that spread radially out from Albuquerque, the

---

†A prophetic negative statement that now appears to be the rule rather than the exception.

concentration decreasing as the distance from Albuquerque increased.

"The next step was to investigate just what characteristics of this distribution were so similar on these two days. On each of the two days, nearly all of the rain that fell occurred within four of the eight octants. If each sector were divided into four to six parts arranged radially so that each would contain equal numbers of observing stations (about eight per region), the analysis showed that the average rainfall rose rapidly to a maximum in intensity about 30 miles (48 kilometers) from the point of seeding and that in each of the four sectors it decreased regularly as the distance from the source of the silver-iodide smoke increased. In fact, this decrease followed quite accurately equations (2) and (3), which indicated that the rainfall depended on the concentration of nuclei, and this, in turn, varied inversely in proportion to the distance from the source.

"This analysis makes it possible to separate the effects of the artificial silver-iodide nuclei from that of the background of sublimation nuclei that were already present in the atmosphere.

".....We must conclude that nearly all of the rainfall that occurred on October 14, 1948, and July 21, 1949, was the result of seeding.

"The agreements between the intensity of the average rainfall in separate regions and the theoretical equations were so good in each of the four sectors on October 14 and July 21 that the probability factors for each sector ranged from 10^2 to 10^3. Taking all the octants together, the probability factor rose to about 10^8 to 1.

"For each of the eight octants that gave appreciable rain, the rain started progressively later as the distance from the source of the silver iodide increased. The advancing edge of the rain area thus moved from Albuquerque on July 21 at a velocity of about 14 miles per hour (6.3 meters per second) and on October 25 at a speed of about 25 miles per hour (11 meters per second). These velocities agree well with the wind velocities observed at various altitudes.

"The method of correlation coefficient can be applied to the relation of the time of the start of the rain to the distance from Albuquerque. This indicates that there is another probability factor which is the order of 10^8 to 1.

"Taking these results altogether, it seems to me we may say that the results have proved conclusively that silver-iodide seeding produced practically all of the rain in the State of New Mexico on both of these days.

"I have not mentioned what happened on the other days. The results, although somewhat more complicated due to the overlapping of the effect of seeding on successive days, are almost as striking as those of Flights 45 and 110, in which we used silver-iodide seeding. Very high probability factors are found, which help confirm the results indicated by the analysis of Flights 45 and 110.

"The total amounts of rain that fell in the state on the two days as a result of seeding were found to be 800 million tons on October 14, 1948, and 1600 million tons on July 21, 1949. If these units are not so familiar to you, I may say that on October 14, 1948, the total amount of rain resulting from seeding was 160 billion gallons and on July 21, 1949, 320 billion gallons.

"Dr. Vonnegut has measured the number of effective sublimation nuclei produced by the type of silver-iodide smoke generator used in our New Mexico experiments for each gram of silver iodide used.....One thus finds that, to get a 30-percent chance of rain per day within a given area in New Mexico, the cost of the silver iodide is only $1 for 4000 square miles (10,000 square kilometers).

"If similar conditions prevailed over the whole United States, the cost per day to double the rainfall would be only of the order of a couple of hundred dollars. This verified an estimate that I made in November, 1947, in an address before the National Academy of Sciences that 'a few pounds of silver iodide would be enough to nucleate all the air of the United States at one time, so that it would contain one particle per cubic inch (60 per liter), which is far more than the number of ice nuclei which occur normally under natural conditions.' Such a distribution of silver-iodide nuclei 'in the atmosphere might perhaps have a profound effect upon the climate'."

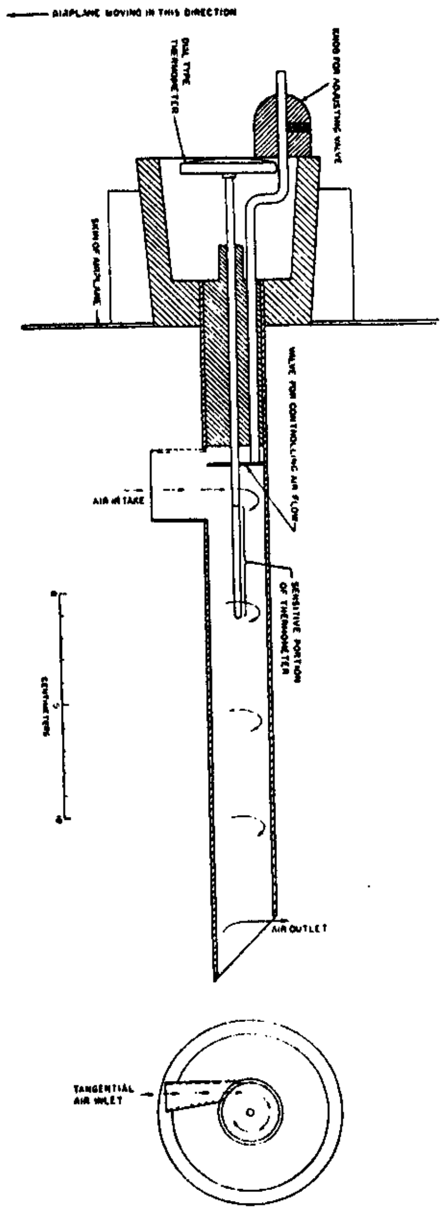
The report then discusses a new theory which Langmuir had developed of the rate of growth of snow crystals in supercooled clouds containing known numbers of sublimation nuclei. After a brief exposition on the basis of this theory, he says:

"From the probability theory of the growth of showers from artificial nucleation, one obtains the result that the total amount of rain produced by operating a ground generator increases in proportion to the square of the amount of silver iodide used. Thus, with three times as much silver iodide one would get nine times the rainfall. The intensities of the showers would be no greater, but they would extend over a greater area.

Virtually all recent precipitation augmentation experiments refute the dramatic rainfall increases suggested above. The effects induced by cloud seeding have proven to be extremely complex, and they vary with locale, season, stage of development of a cloud, and the dominant precipitation mechanism(s) governing specific clouds. It is now known that seeding can <u>reduce</u> rainfall (101) as well as <u>increase</u> it, with maximum increases generally being of the order of 10-20 percent--<u>National Academy of Sciences Report 1350, 1966</u>.

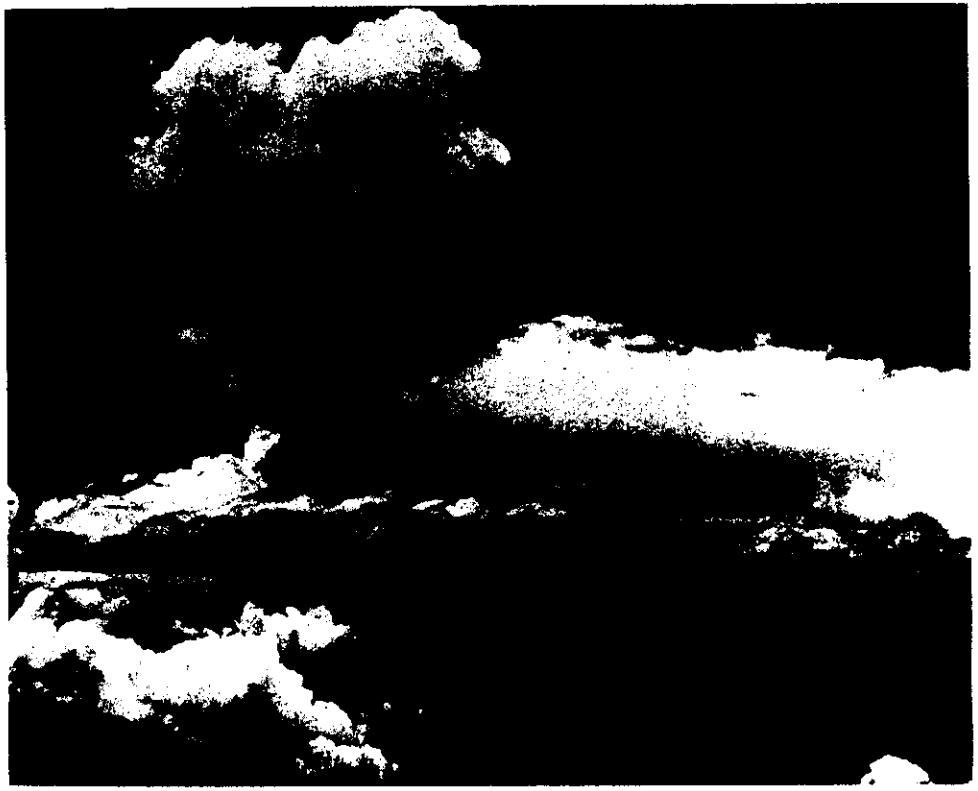
"It is very important that regular tests on certain selected days of each week be carried out throughout the year, using amounts of seeding agents just sufficient to obtain conclusive statistical data as to their effectiveness in producing widespread rain. It is to be expected that the results will vary greatly in different parts of the country, because of the changes in synoptic situations."

The significance of the two test projects at New Mexico is thus apparent. They indicated not only the possibilities of silver-iodide seeding from the ground, but they suggested a widespread effect on the weather of the nation. And, as a result, the project conducted some experiments in periodic seeding which were destined to have a profound--and controversial--significance.

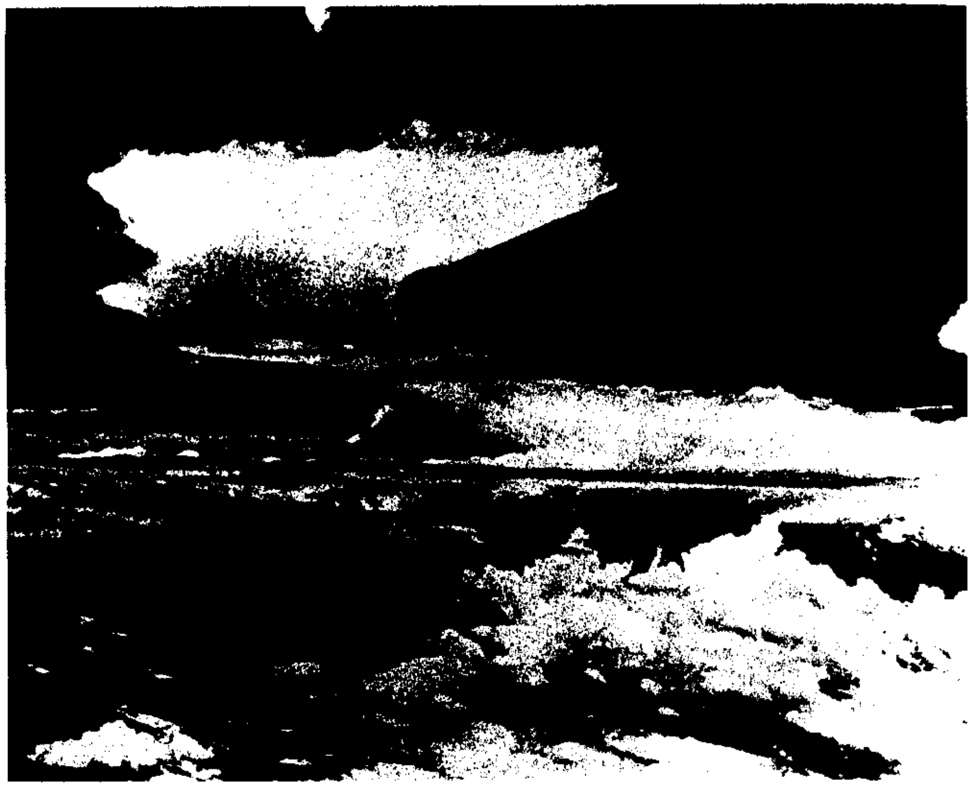


Vortex Thermometer

New Mexico Cumulus Before Seeding. On a July morning in 1950 near Socorro, New Mexico, these small cumulus clouds at 15,000 feet were the only ones to be seen. At 9:58 a.m. one of these clouds, about 15 miles from Socorro, was seeded by making one pass through it at 2,500 feet above the base with a spray nozzle silver iodide burner in operation.



Cumulus Cloud After Seeding. The cloud tops soon changed from a hard white appearance to a grey cirrus-like structure. In 20 minutes it had grown greatly in size.



Fully Developed Seeded Cloud. The cloud continued to grow, and in a little over an hour it had become a small thunderstorm, producing rain. On the same day some distance away seeding with dry ice produced similar results.

VII. PERIODIC SEEDING

NEW MEXICO WORK

By this time, a rather close liaison had been established with Workman and his co-workers at the New Mexico School of Mines. So, in view of the significance of Langmuir's analysis of the effects and possibilities of silver-iodide ground seeding, and in order to test as soon as possible his ideas on periodic seeding, a schedule of operations on this basis was established without further ado at New Mexico.

Starting in December, 1949, a silver-iodide ground-based generator was operated there on a schedule so planned as to introduce, if possible, a seven-day periodicity into the weather cycles of the nation. Seeding was performed eight hours a day on Tuesday, Wednesday and Thursday of each week. This schedule of regular weekly periodic seedings used about 1000 grams of silver iodide per week, and it continued with a few modifications until the middle of 1951.

Data were gathered by Falconer, and almost immediately Langmuir found evidences of a definite weekly periodicity in rainfall in the Ohio River Basin. Again, he conducted an exhaustive analysis of the facts and performed mathematical calculations to determine the probabilities that these variations in weather could have taken place by pure chance.

He reported his findings and his conclusions to the National Academy of Sciences, October 12, 1950 (102); to the American Meteorological Society of New York City on January 30, 1951 (102); and also to the New York Academy of Sciences on October 23, 1951 (93). He pointed out that, during 1950, there was a marked and statistically highly significant seven-day periodicity in many weather elements. The significance was so high, said he, that it could not be explained on the basis of chance and could not have occurred from natural causes. The analysis involved not only rainfall but also pressure, humidity, cloudiness, and temperature over much of the United States.

In his paper to the New York Academy of Sciences (93), Langmuir said:

"Almost immediately, that is, during December 1949 and January 1950, it was noted that the rainfall in the Ohio River Basin began to show a definite weekly periodicity. A convenient way of measuring the degree of periodicity was to calculate the correlation coefficient CC between the rainfall on the successive days during a 28-day period, with the sine or the cosine of the time expressed as fractions of a week, the phase being taken to be 0 on Sundays.

"Just before the start of the periodic seedings, the correlation coefficient CC(7) based on the seven average values for the successive days of the week of the 28-day period amounted to only 0.23, but in the next 28-day period the value of CC(7) rose to 0.91.

"Table 1 gives the average rainfall in inches per station day during 140 days at 20 stations designed as Group A in the Ohio Valley Basin, representative of an area of about 600,000 square miles (1,500,000 square kilometers). The successive rows correspond to five successive 28-day periods. It will be noted that the average rainfall on Monday was 0.272", whereas on Saturday it was only 0.064", a ratio of 4.3:1. The next to the last column gives CC(28), the periodic correlation coefficients for each 28-day period, and the last column gives the phases in the successive periods. Taking the 35 separate values for the 4-week averages given in the table, one gets CC(35) = 0.689 with a phase of 1.60 days. This result is statistically highly significant.

"These periodicities in rainfall were evident at almost any set of stations in the northeastern part of the United States. Table 2 gives the rainfall on successive Tuesdays and Saturdays during a 12-week period during the winter of 1949-1950 at Buffalo, Wilkes-Barre, and Philadelphia. This periodicity is almost the same as that found in the Ohio River Basin but with a one-day phase lag. The striking contrast between the total rains on Tuesdays and Saturdays runs parallel to the total number of days on which rains of 0.1" (2.5 millimeters) or more occurred on Tuesdays and on Saturdays.

"Maps have been prepared giving for 24 successive 28-day periods the distribution of correlation coefficients, CC(28), among 17 subdivisions of the United States, these data being based on daily weather reports of 24-hour rainfall at 160 stations. During the first five 28-day periods there were always several adjacent subdivisions that showed high weekly periodicities in rainfall. After May 1950, however, the periodicities became somewhat sporadic, although highly significant periodicities over large areas still occurred during more than half of the periods after July 1950. Presumably the large amount of commercial silver-iodide seeding in the western states (not done with a weekly periodicity) masks the effects of the periodic seedings in New Mexico. By a map, the areas were shown in which known seeding operations have been carried on in 1951. In 15 states west of the 95° W meridian (excluding Texas) about 550,000 square miles (1,410,000 square kilometers) or 37 percent of the total area of these states were under seeding contracts during 1951.

"Maps for the months from December 1949 through 1950, taken from the

Monthly Weather Review, illustrated the distribution of abnormally large rainfalls over the United States. The heavy rains nearly always occurred in a band extending from the southwestern to the northeastern states.

"An analysis of the periodicity in the rainfall induced by periodic seeding was presented in a paper read October 12, 1950, before the National Academy of Sciences. The areas havi a high weekly periodicity were generally the same as those showing the highest abnormalities in rainfall. Such heavy rains can only occur if the winds and the barometric pressures cause an adequate supply of moisture to flow from the Gulf of Mexico. The periodicities in the pressure differences between Corpus Christi and Jacksonville were studied. During the first 140 days after seeding began, there was a highly significant weekly periodicity indicating a periodic air flow from the Gulf.

"The upper air temperatures, even up to the stratosphere, showed a high weekly periodicity over more than half of the United States. Nine stations representative of an area of 1,300,000 square miles (3,300,000 square kilometers) gave 950 mb temperatures having CC(28) greater than 0.5. These data were published, in detail for Chicago and in summary for eight other stations, in the Dec. issue of 'The Bulletin of the American Meteorological Society', and a statistical analysis was given which proved that these periodicities were highly significant. Mr. William Lewis and Mr. E. Wahl, Bull. Amer. Met. Soc. 32:192-3 (1951), and Mr. Harry Wexler, Chem. Eng. News 29:3933 (1951), maintained, however, that these data on the periodicities in temperature were not truly significant and similar weekly periodicities have frequently occurred in the past.

"The degree of periodicity in upper-air temperatures observed in 1950 during April, July, and November shows a statistical significance of a much higher order of magnitude than those referred to by Lewis, Wahl, and Wexler. To illustrate this, an analysis has been made of the temperatures at the 700 mb level at nine stations in the United States at the intersections of the 80, 90, and 100° W meridians with the 35, 40, and 45° N parallels.

"The value of CC(28) at these nine points of intersection ranged from 0.50 to 0.85. The area represented is 1.5 million square miles (3,800,000 square kilometers).

"Recently we have extended this grid of regularly spaced stations to include the intersections of the 45°N parallel with the 70°W and 110°W meridians, these points giving CC values of 0.66 and 0.65 respectively. The 30°N, 80°W intersection just off Jacksonville, Florida, also gave a correlation of 0.65. We thus have an area of two million square miles or 2/3 of the area of the United States in which CC(28) exceeds 0.50 with a mean value of CC(28) = 0.67.

"We have also examined these periodicities at corresponding points for preceding and for following periods. The 28-day period in May showed low correlations. On the other hand, the two preceding periods gave highly significant values. Apparently the high periodicity in the upper air temperatures started about January 25, 1950, and continued on until about May 1, 1950, covering an average area of about half of the United States.

"For the nine points of intersection during a 28-day period in April, 1950, the total variance of the temperature was determined by taking the total sums of the squares of the deviations of these temperatures from their mean and dividing by 27, the number of degrees of freedom. The data obtained in this way are called the 'total variance'. By multiplying these values for each of the nine stations by the corresponding square of the correlation coefficient CC(28), one obtained the 'periodic component of the variance'.

"Exactly similar calculations were made for a 28-day period in April, 1949, when there was no periodic seeding..... The average values for all these nine points show that the 'periodic variance' in 1950 was 18 times as great as in 1949.

"Table 4 gives the corresponding values of the 'residual component of variance' obtained by subtracting the 'period variance' from the 'total variance'. These data then indicate how all the other kinds of periodicities, beside the seven-day periodicity, compared with one another in the two years. It will be seen that there is only about 10 percent difference between the average variance of this type for 1950 and 1949.

"It seems, therefore, that the temperature fluctuations in 1950 essentially differed from those in 1949 only in the superimposition of an extremely high seven-day periodicity."

As indicated in this extract, Langmuir's conclusions were contested by representatives of the United States Weather Bureau.

EASTERN U. S. WORK

In addition to the periodic seeding conducted in New Mexico, similar seeding was initiated in the Schoharie Valley, New York, and at the base of Mount Washington. An interesting result of the seeding at Mount Washington was observed by Joseph B. Dodge, who has charge of the Appalachian Mountain Club lodges in the White Mountains for skiers and mountain climbers. Dodge, who knew nothing of the seeding, pointed out that, judging by the maps of snow coverage in Maine and New Hampshire there were two bands of snow running at a

diverging angle in the direction of those two states and coming to a point back at Mount Washington. This was a season in which there was not much snow, but along the line of these two bands there had been exceptionally heavy snow. The results of further study indicated that the lack of snow may have been caused by overseeding, but that along the two lines of heavy snow there had been just a light amount of seeding.

LATER PERIODICITY

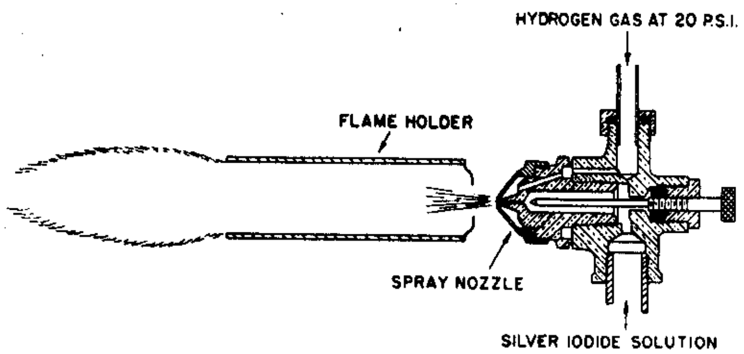
Early in 1952, during the course of their normal analyses of weather conditions throughout the United States, Falconer and Maynard again found evidence of periodicity. Further study showed that the periodicity was on a seven-day basis and that it progressed regularly from west to east. The correlation coefficients were calculated by Maynard and found generally to be of a very high order. For one 28-day period the correlation coefficient was the highest so far obtained for the country as a whole.

It was thought possible that this phenomenon might be caused by a corresponding periodicity in the commercial seeding going on in various parts of the west. Inasmuch as the periodicity in the weather progressed uniformly across the United States, it was possible to trace it on a map back to a likely point of origin. The commercial seeding organization active in that area was then asked by Schaefer for a schedule of its seeding operations, which it willingly furnished. It was found that the commercial seeding had a periodicity corresponding to that observed in the weather.

Langmuir, in analyzing the data thus obtained, observed that it would be difficult to determine cause and effect. In other words, it would be difficult to know whether the periodicity in weather was caused by periodic seeding or vice versa, for commercial seeding organizations generally do not seed at any random time but rather choose for seeding those days when weather conditions are propitious. If the conditions are "good" for the production of rain, the operator seeds. As a result, although it might rain naturally, the seeding may increase the quantity of rain--and it may produce rain when none would have fallen naturally. On the other hand, if conditions are not right for rain, the operator does not seed, for seeding will not produce rain except when meteorological conditions are suitable.

Meanwhile, F. H. Hawkins, Jr., of the U. S. Weather Bureau, in the May 1952 issue of the Monthly Weather Review, called attention to the same periodicity and stated that, as far as could be determined, no seeding which was under way that spring could compare in periodicity with the marked spacing of rainfall at that time.

Langmuir, however, examined the data on western seeding operations and was able to show that the observed periodicity in weather conditions coincided with the schedule of commercial operations. He reported his findings to this effect at the annual meeting of the Institute of Mathematical Statistics in East Lansing, Michigan, on September 4, 1952.



SILVER IODIDE SMOKE GENERATOR

Irving Langmuir at his desk at the time of Project Cirrus.

VIII. HURRICANES AND FOREST FIRES

In addition to the normal studies and tests with which Project Cirrus concerned itself, there were two additional activities in which it engaged early in its history. One was a study of tropical hurricanes and the other, an attempt to cause rain in a forest-fire area. Both took place in 1947.

HURRICANE STUDY

The hurricane study was planned by the various participating government agencies for the purpose of determining whether seeding operations could be carried out in such storms. These agencies hoped that the experience thus gained would permit the planning of further operations in the future, with the hope of possibly steering or in other ways modifying tropical hurricanes.

It was planned to study a "young" storm as soon as possible after it had assumed the form of a hurricane. A group of General Electric personnel was requested to act as consultants on these operations.

After a week of intensive organization and briefing, both groups were maintained in "stand-by" position, but the season progressed for some time without any suitable storms occurring. Finally on October 10, 1947, word was flashed from Miami, Florida, that a storm was forming below Swan Island in the Caribbean Sea. Plans were immediately activated, and the next evening the project's two B-17's were at Mobile, Alabama. The storm had traveled with such high speed, however, that by that time it was crossing Florida. The unit flew to MacDill Field, Florida, the next day, joining forces with the 53rd Weather Reconnaissance group. Plans were laid for take-off early in the morning of October 13. The storm was expected to be from 480 to 640 kilometers east of Florida by that time.

The following account of the observed features of the storm, the seeding operation, and observed effects was prepared by Lt. Com. Daniel F. Rex, at that time chairman of the Operations Group (27):

"The storm consisted of an eye approximately 30 miles (48 kilometers) in diameter, surrounded by a thick wall of clouds extending from about 800 feet (240 meters) up into the cirrus overcast at 20,000 feet (6 kilometers) and being some 30-50 miles (48-80 kilometers) thick radially. Several decks (4 or 5) of stratified shelf clouds extended out from the outer wall, the upper-most deck having tops at 10,000 feet (3 kilometers). These shelf clouds appeared as large areas (100-200 square miles) (250-500 square kilometers) of solid, thin (1000-2000 feet thick) (300-600 meters) undercast, separated by large breaks through which the surface was often visible. An exceedingly active squall line, appearing as an almost continuous line of cumulonimbus with cirrus tops to an estimated 60,000 feet (18 kilometers), was observed as a spiral extending out from the center-base at 20,000 feet (6 kilometers) near the outer wall, lifting to 35,000 feet (10.5 kilometers) at the edge.

"Approach to the storm center was effected from the southwest, this course bringing the group into the storm's right rear quadrant. After a brief reconnaissance flight around the outer wall, the decision was made to seed a track over the uppermost cloud shelf and at a distance from the center sufficient to permit the control aircraft to fly contact 5000 feet (1.5 kilometers) above the seeding aircraft.

"A formation intrail was used, with the seeding aircraft (B-17 No. 5560) leading at cloud top level. The photoreconnaissance aircraft (B-17 No. 7746) followed the seed ship, 3000 feet (.9 kilometers) above and 1/2 mile (.8 kilometers) astern, with the control aircraft (B-29 No. 816) trailing 500 feet (150 meters) above and 15-20 miles (24-32 kilometers) astern.

"Seeding commenced at 29.8 degrees North, 74.9 degrees West at 11:38 EST at an altitude of 19,200 feet (5.8 kilometers), the outside air temperature being approximately -5°C. Continuous seeding was effected along a straight course to 30.2 degrees N, 73.9 degrees W, thence to 30.8 degrees N, 73.1 degrees W, at which point (12:08 EST) seeding was stopped. During this 30-minute period 80 pounds (36 kilograms) of solid carbon dioxide was dispensed along the 110-mile (180 kilometer) track. In addition, two mass drops of 50 pounds (22 kilograms) each were made into a large cumulus top at 30.7 degrees N, 73.4 degrees W.

"Upon completion of this phase, all planes flew a reverse course back along the seeded track, taking visual and photographic observations. No attempt was made to penetrate through the wall of the storm into the eye or to seed in or near the above-mentioned squall line, owing to the failure of the group's homing aids (radio, compass, and visual flares). It was thought that such an attempt, although desirable, would likely result in a separation of the aircraft, with subsequent abortion of the primary mission.

"Visual observation of the seeded area showed a pronounced modification of the cloud deck seeded. No organized trough was observed; rather, the overcast previously observed appeared as an area of widely scattered snow clouds. The disturbed area covered perhaps 300 square miles (770 square kilometers). No convective activity was seen to follow the seeding process at any time during the mission."

In addition to this account by Rex, the following brief conclusions were prepared, after the test, by Schaefer, who carried on observations from the B-29 (103):

"1. Many suitable clouds for seeding operations occur in this type of hurricane.

"2. The seeding operation produced an area showing snow showers and stable snow clouds with light rain in the above-freezing region. The stable snow clouds covered considerable area and might have persisted long enough to affect other supercooled clouds. I concur with the estimate of Commander Rex that about 300 square miles (770 square kilometers) showed modification due to seeding operation.

"3. The region where profound effects might have been produced was in the extremely active squall line mentioned by Commander Rex. This was not attempted for the reasons indicated.

"4. No build-ups were seen following the seeding operation. This was to be expected, owing to the thin character of the supercooled clouds along the seeding path.

"5. Owing to the complex structure of this 'old' storm, it is believed that a 'young' hurricane would provide much more satisfactory data for estimating the effect of seeding operations.

"6. The operation pointed out the importance of making future studies a part of the hurricane reconnaissance program. Experimental seeding should be made by a group quite familiar with the structure of the particular storm, stationed in fairly close proximity, so that a number of forays would be made in rapid succession.

"While the hurricane study project secured important information and provided excellent training for the Project Cirrus personnel, the time required for planning such an operation and in analyzing the data raises the question of whether the results justify further activities of this kind by this particular group until the urgent and much simpler operations are completed at Schenectady."

Langmuir made some interesting observations with regard to the nature of the hurricane (1). Speaking of the results of the seeding test, he said: "The main thing that we learn from this flight is that we need to know enormously more than we do at present about hurricanes." He concluded:

"It seems to me that next year's program should be to study hurricanes away from land, maybe out considerably beyond Bermuda, out in the middle of the Atlantic.....I think the chances are excellent that, with increased knowledge, we should be able to abolish the evil effects of these hurricanes."

An interesting feature of the seeding experiment was that the hurricane changed its motion from a northeasterly to a westerly course that took it across the coast into Georgia. Conceivably this unusual behavior may have been the result of the seeding; however, an analysis by Hook, et al. (104), suggests that the track was ".....the normal outcome of accompanying anomalies in the general circulation....."

Fifteen years were to elapse before a concerted field program to assess hurricane abatement was launched. In 1962 Project Stormfury--a joint Department of Commerce (NOAA) and Department of Defense (Navy) program--was formed with its principal objective experimentation to reduce the intensity of hurricanes. From 1962 to 1971, only three hurricanes were seeded because of rigid safety precautions imposed on when and where a tropical storm could be seeded. Hurricane Debbie, seeded on 18 and 20 August 1969, gave some evidence of responding to the treatment by a measured decrease in maximum wind velocity on both days (105). An elaborate system of seeding and monitoring such storms has been developed as well as numerical models (106) to aid in interpreting the results.

OPERATION RED

On October 29, 1947, a flight operation was carried out in Vermont and New Hampshire. At that time severe forest fires were raging uncontrolled in various parts of New England. Although it was not the policy of Project Cirrus to carry out such a widespread operation, it was felt that it would be worth the additional effort required to make such a flight for the experience to be gained, particularly since it would be possible to use Schenectady as the base of operations.

The flight was well planned from an operational point of view, but the results were not spectacular, because of the absence over much of the area of suitable clouds--contrary to a forecast the previous day. Instead of encountering a cloud deck at 5.4 kilometers as indicated by the forecast, the top of the stratus was about 3 kilometers, with isolated cumulus reaching a maximum of about 4.2 kilometers.

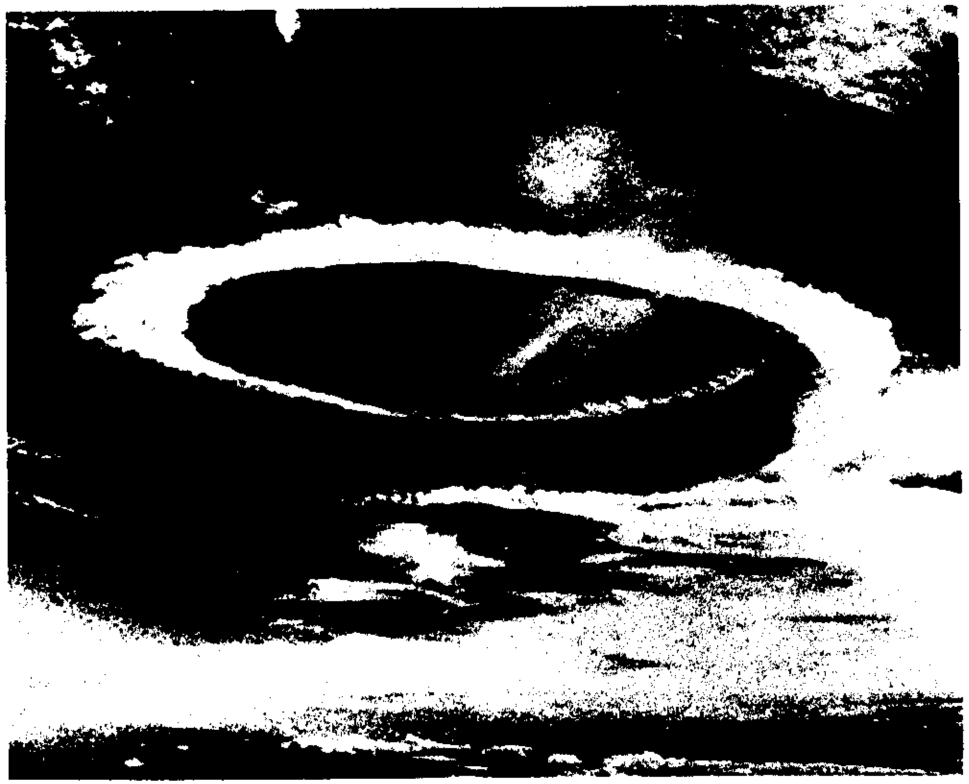
Seeding operations were carried out by two B-17's, the one normally in use by Project Cirrus and another furnished by Major Keating of Olmsted Field of the Signal Corps Weather Squadron. The site of operation was over some of the stratus near Montpelier, Vermont, and in the cumulus developments. Practically all of the latter showed the effect of seeding after five to eight minutes. Subsequent reports indicated the development of some fairly intense local showers along the flight path.

The next day word was received from Alan Bemis of the Massachusetts Institute of Technology Radar Research Group that there had been a sudden increase in radar echoes in the vicinity of Concord, New Hampshire shortly after the seeding runs. Fortunately Bemis had learned of the proposed operations and had made it a point to obtain complete radar coverage of the area in which the two planes operated. He subsequently supplied the Operations Group with a reel of 35-mm film of the radar scopes as recorded by his group on October 29.

The results obtained by the radar group under Bemis emphasized to the members of Project Cirrus the effectiveness of this type of instrumentation as an adjunct to their cloud-modification studies. It raised the hope that a close relationship between the two research groups might be effected.

In the opinion of Langmuir the result was inconclusive, because scattered showers began to form that day, starting about one or two hours before Project Cirrus seeded.

Clear Air Seeding. When the moisture in the atmosphere is supersaturated with respect to ice but unsaturated with respect to liquid water, seeding can produce ice crystal cloud formation. These clouds were produced by dispensing crushed dry ice under such conditions.



Clear Air Seeding. This cloud of ice crystals, about five miles in diameter, was produced by releasing silver iodide from a B-17 airplane at an altitude of 25,000 feet.

IX. COOPERATION WITH OTHER PROJECTS

It was only natural that the activities of Project Cirrus should stimulate others to undertake experiments in cloud seeding. Considerable publicity resulted from Schaefer's historic snow-making flight over Pittsfield in November, 1946, and the fact that the Research Laboratory of the General Electric Company was involved took the affair out of the class of cheap sensationalism and provided a background of authenticity that provoked the interest of scientists and weather students the world over, as well as others with varying motives. Continuing publicity of further General Electric and Project Cirrus weather research and experiment caused further interest. Many inquiries were received asking for information in general, and assistance in particular, in connection with specific projects. No attempt will be made to list all of these, but some are of particular interest.

PINEAPPLE RESEARCH INSTITUTE, HONOLULU, HAWAII

On March 24, 1947, a request for dry-ice seeding techniques was received from the Pineapple Institute of Honolulu, Hawaii. Although the records do not show it, presumably the information was needed because of the importance of rain on pineapple growing in Hawaii, and the Institute wanted to keep abreast of any developments.

At any rate, available information was supplied by Project Cirrus. Later newspaper accounts were received at Schenectady describing experiments carried out over the island of Molokai in 1947 by Dr. Luna B. Leopold and Mr. Maurice Halstead. Still later, copies of a preliminary report (107) were received from these men, describing interesting results obtained by dumping dry ice into cumulus clouds having a temperature above the freezing point. As described previously (p. 27), this led to Langmuir's famous theory of the chain reaction of a rainstorm.

MILLIKEN AND FARWELL MOBILE, ALABAMA

For two or three seasons, some time about 1947 or 1948, experiments were conducted in the cloud seeding of thunderstorms with dry ice by the firm of Milliken & Farwell, a sugar company of Mobile, Alabama. Activities concentrated on big cumulus clouds in the neighborhood of the Mississippi delta. Information was requested from Project Cirrus, and Langmuir cooperated actively. He later reported very interesting results and said the photographs taken were the best he had ever seen.

UNITED FRUIT COMPANY, HONDURAS

On preceding pages an account was given of the work done by Joe Silverthorne in seeding clouds for the United Fruit Company in Honduras. This work was carried on for the purpose of testing the possibility of controlling rainfall, and particularly in the hope of stopping blow-downs that result from winds associated with thunderstorms, which occasionally destroy large stands of fruit trees.

Langmuir visited Honduras in 1948 and 1949 and cooperated actively with Silverthorne. His observations convinced him of the effectiveness of single pellets of dry ice in modifying large cumulus clouds; almost always the clouds could be profoundly modified with single pellets (69).

NEW YORK CITY WATER SHORTAGE

This famous case received a great deal of publicity. In order to keep the record straight as to what happened and the part played by Project Cirrus, a brief account of the case, as told by Langmuir, is incorporated.

Although the work was done by and for New York City, it was another case of General Electric having some connection with the activity. When Langmuir presented a paper on weather modification to the American Meteorological Society in New York in 1950, New York was in the midst of a water shortage. At a news conference associated with the AMS meeting, newsmen asked Langmuir if seeding could be of any use in alleviating New York's water shortage. He replied that he knew nothing about New York; his only experience had been in the west.

The newsmen then asked what Langmuir would advise for New York. He replied that the best thing for New York to do would be to get a good meteorologist and have him look into it. That advice was reported by the New York Herald Tribune. Later, when the supply of water was becoming less and less, this paper ran an editorial saying that things were getting desperate and that it was up to the city to do something about it. Seeding was mentioned in the editorial, and also Langmuir's advice to get a good meteorologist.

As a result, Stephen Carney, then New York's water commissioner, got in touch with Langmuir and arranged for a meeting. Carney and two others visited Schenectady. Schaefer recommended Dr. Wallace E. Howell, director of the Mount Washington Observatory, who had been actively associated with Project Cirrus and the General Electric scientists even before the project started. Howell's services were retained as a result.

Howell's experiments have never been published, and opinions vary about the results obtained. An interesting result was a group of lawsuits totaling in the neighborhood of $2,000,000. The possibility of such suits had been mentioned in the general discussions which preceded the actual seeding, and at that time Langmuir had commented that it would be entirely possible that such suits would be cheap compared with the results which might be obtained. The city, he said, had already been committed to spend $600,000,000 to add from 2 to 30% more water to its available supply, and if they could get as little as 20% more water by seeding, it would be worth the $2,000,000 and any interest on it.

COMMERCIAL SEEDING IN THE WEST

A tremendous amount of interest in the possibilities of controlling precipitation was aroused in the west, especially in the great agricultural regions where an adequate supply of water is highly important and a drought can have catastrophic consequences. Many cooperative groups of water users were formed, and organizations sprang up for the purpose of engaging in cloud seeding on a commercial basis. At the time of writing (May, 1952), some 1.4 million square kilometers of the United States west of the Mississippi were subject to cloud seeding by commercial operators, according to current estimates (News release, James Stokley, for release May 12, 1952).

Although many private individuals have undertaken to do their own seeding, most of this work has been done by a small number of commercial organizations. Topping the list is the Water Resources Development Corporation, with offices in Denver, Colorado, and Pasadena, California, whose rainmaking contracts were reported to cover an area of over 1.2 million square kilometers, or about 12 times the area under irrigation in the United States. "Farmers and ranchers paid millions of dollars for the services of this organization, which contemplates extending its operations to Central America, South America, South Africa and Europe."† Others include the Precipitation Control Company, Phoenix, Arizona; North American Weather Consultants, Pasadena, California; Olson & Taylor Corporation, Shelby, Montana; and Wallace E. Howell Associates, Cambridge, Massachusetts.

So many and so active are the organizations for this purpose, that there has been some concern over the effects of introducing such quantities of silver iodide into the atmosphere. Studies by the Research Group of the project indicated that silver iodide can continue in the atmosphere for an almost indefinite period, and although its usefulness can be inhibited by sunlight, the practical effects of such photochemical decay are not significant when the silver iodide is within or below the clouds. Finally, the described analyses and calculations of Langmuir indicate that periodic silver-iodide seeding in New Mexico produced a tendency toward periodic rainfall and temperature fluctuations that extended significantly all over the United States. Currently, some members of the Research Group feel that there is a definite possibility that some abnormal flood conditions of recent years have been caused, at least to a contributing degree, by commercial seeding operations in the west.

Few cloud physicists would subscribe to this view today; precipitation increases by seeding are far more modest than then supposed. The Rapid City, South Dakota, flood of 1972, when nearby seeding was under way, brought this question into sharp focus (108).

In addition to the commercial operators, who seed for the benefit of others, at least one electric power company has done extensive work in this field for its own benefit. This is the California Electric Power Company of Riverside, California. This company's use of seeding stems from its concern over an adequate supply of water to operate its hydroelectric generating stations. Not only does it credit the seeding with increasing its hydroelectric output by many millions of kilowatt-hours, but it also declares it has produced millions of extra tons of water for the city of Los Angeles.

Interesting cloud-seeding experiments were also conducted by John A. Battle, consulting meteorologist of Beaumont, California, in California, for the San Diego County Weather Corporation and the Santa Ana River Weather Corporation. The experiments were conducted over the entire area of San Diego County plus the Santa Ana River drainage area in Orange, Riverside and San Bernardino Counties. The two corporations responsible represented various water agencies in those regions, where the relative scarcity of water makes any possibility of increasing the annual rainfall attractive.

Silver iodide was used in the seeding. Unseeded areas were used for control zones, in comparison with seeded areas. About 20 percent more rain fell in the target area than in the control area; in other words, 1.7 billion cubic meters of additional water. Statistical analyses indicated that the chances that the cloud seeding did not have a positive effect on the measured precipitation varied anywhere from 1 in 12 to 1 in 10,000, depending on the area involved (109).

---

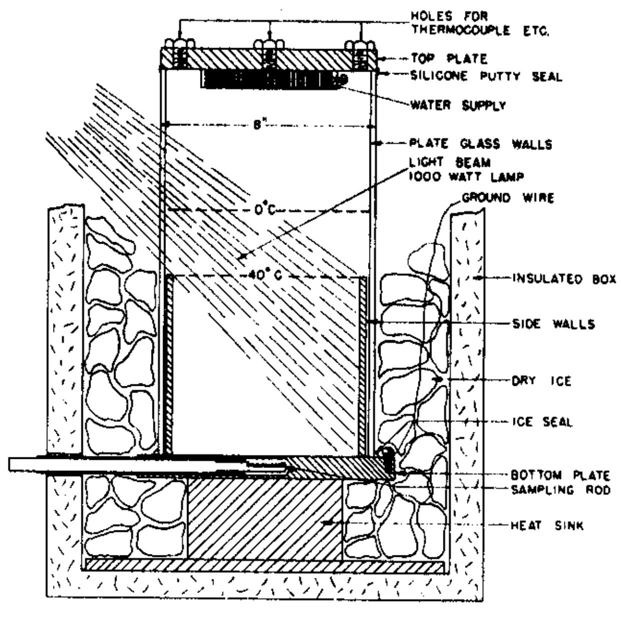
†Page 2, Senate report #1514 (5/12/52) on "Creating an Advisory Committee to Study and Evaluate Experiments in Weather Modification."

Much of the cloud seeding currently taking place in this country is still concentrated in the west, where the need for water is more acute. For example, the Bureau of Reclamation initiated a 5-year pilot program in southwestern Colorado in 1970 to determine whether the winter snowpack could be increased to add to the flow of the Colorado River (110). This river provides water for seven states and, by treaty, the country of Mexico. Prior experiments in Colorado (111) suggested that a 16% increase (or 2.3 million acre-feet) (3×10^9 cubic meters) of water could be added to the Colorado River Basin.

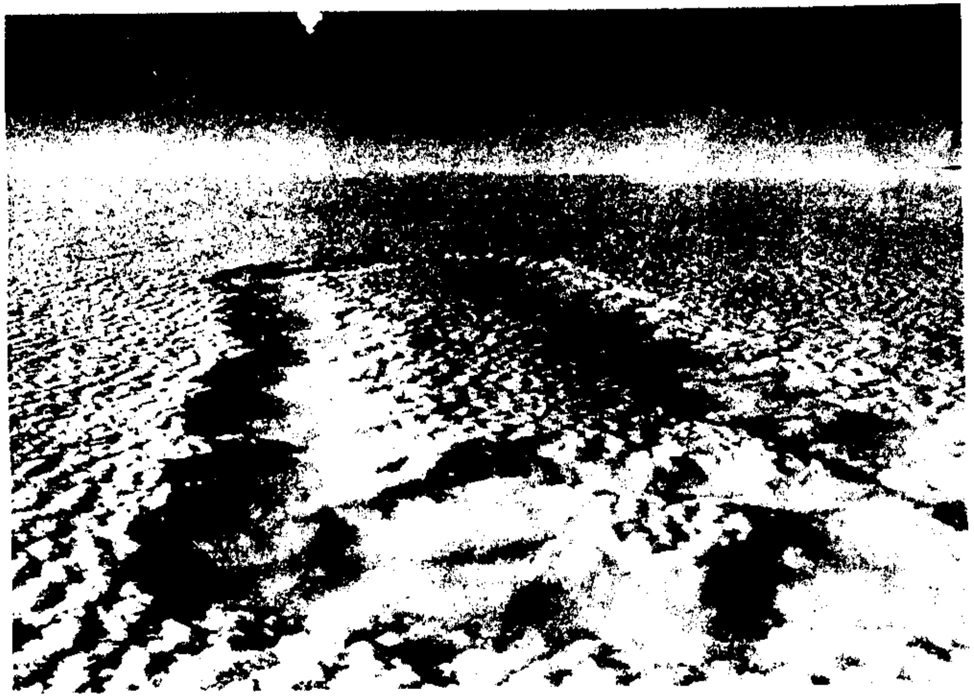
WORK OF OTHER GOVERNMENTS

Active research in cloud seeding has been carried on in many foreign countries. Again, the work was stimulated by the reports of successful tests made by Project Cirrus, and in virtually all cases the foreign work was based on information either obtained by direct contact with Project Cirrus or through the study of published data. Among the foreign countries engaged in such work are Canada, Cuba, Peru, England, France, Switzerland, Israel, Algeria, Tanganyika, Union of South Africa, Formosa, Japan, and Australia.

These and many more countries are now engaged in various theoretical and experimental studies of weather modification. In 1971 the first International Conference on Weather Modification was held in Canberra, Australia, attesting to the world-wide interest in the subject. Two subsequent international weather modification conferences, sponsored by the World Meteorological Organization, were held in Tashkent, USSR, in October 1973 (400 participants were present representing some 28 nations), and in Boulder, Colorado, in July 1976 with high participation. The WMO is now planning an international field experiment to assess the rain-making potential in a country with marginal rainfall--the so-called Precipitation Enhancement Program (112).



Continuous Cloud Chamber



Racetrack pattern approximately 20 miles long produced by dropping crushed dry ice from an airplane. The safety pin like loop at the near end of the pattern resulted when the dry ice dispenser was inadvertently left running as the airplane began climbing to attain altitude from which to photograph the results.

X. CONCLUSIONS

Contract DA36-039-sc-15345 (the last in the series) terminated September 30, 1952, after a little over five years of the active life of Project Cirrus as a government-sponsored activity. By that time all the early exploratory phases of cloud seeding and allied research concerned with the physics of clouds were virtually complete. So many other research projects had been stimulated that continued progress in the search for new basic knowledge of weather phenomena seems assured.

OVER-ALL RESULTS

It is not, of course, easy to predict the ultimate results of the work done by Project Cirrus. But it seems certain that the pioneering and spectacular work of the General Electric scientists in cloud physics, cloud seeding and weather modification will eventually have a profound influence on domestic and world economics.

Says the report accompanying Senate Bill 2225:

"If practical, weather control promises tremendous benefits for a small investment. Research work in the field involves no test plants or production facilities and very little expensive equipment. The seeding agents, carbon dioxide or silver iodide, are inexpensive, yet when used in small quantities they apparently produce weather phenomena of the highest magnitude. If these phenomena cause only a small increase in precipitation, this small increase can be economically important.

"An inch of rain, converted into runoff and concentrated into a reservoir, can produce electric power worth hundreds of thousands of dollars. A small fraction of an inch of extra rain, falling on crops during the period of germination, can greatly increase crop yields. But artificial nucleation may have useful potentialities in addition to that of stimulating rainfall. It may have possibilities for increasing snowpack in mountainous areas, for holding back and 'softening' rainstorms, thereby reducing soil erosion, for inhibiting hail, for breaking up hurricanes, and for precipitating out and thereby cutting holes in clouds so that aircraft can operate."

Some of the possibilities inherent in cloud seeding as evaluated by Project Cirrus scientists follow:

Widespread Weather Modification. The results of the various New Mexico tests, coupled with observations of the effects of other ground seeding with silver iodide, point to significant possibilities in the widespread modifying of weather conditions. Such work could easily have profound economic, political, and military effect.

Modifying Orographic Clouds. Orographic clouds, which form as moist air is forced to rise when it encounters a barrier such as a mountain range, are very common in mountainous regions, and they often form continuously for many days. Relatively little precipitation from them reaches the earth, except as rime deposits on trees and rocks or as scattered snow crystals. If techniques could be devised to cause a widespread and effective precipitation of such clouds, the depth of the snow pack in the vicinity of mountains might be markedly increased. Such a result would be of much importance, since the snow pack on mountain slopes is very valuable in stabilizing the streams which flow from such regions. These streams are important for electric power and water supply. (See contribution to this knowledge by California Electric Power Co., p. 70.)

Producing Regions of Ice Nuclei. The production of high concentrations of ice nuclei or potential ice nuclei in specific regions of the free atmosphere is an interesting possibility. Cold middle clouds, even though having no appreciable moisture, may be used as "holding reservoirs" to store ice crystals until they come into contact with lower clouds of greater thickness or are entrained into cool or cold cumulus.

An example of this type of seeding occurred during the hurricane project in October, 1947 (p. 41). A relatively thin layer of stratus clouds covering an area of nearly 770 square kilometers was transformed to snow crystals. The subsequent fate of the crystals is still a moot question, but if a considerable number of them had been entrained into the lower levels of a line of towering cumulus observed during the flight and situated in the southeast quadrant of the storm, the entrainment might have exercised a profound effect on the subsequent development of those cumulus clouds.

Similarly, the ice crystal residue from seeded, but small, cumulus clouds may be entrained at a low level into much larger cumulus forming in their vicinity. In this way, an effect of considerable magnitude is produced as the supercooled regions are injected at a lower level than would otherwise be possible.

It will take much careful study to establish methods for utilizing this type of seeding. Eventually, it may become of great importance.

Modifying Stratiform Clouds. The widespread modification of stratus clouds by artificial means is possible at the present time whenever such clouds are supercooled. Under such conditions, the clouds may be either further stabilized by overseeding, or precipitation may be triggered by using the optimum number of ice nuclei. Observed results of the seeding of stratus clouds indicate that holes can be made by this method, which is bound to be of value in aircraft operations.

<u>Modifying Supercooled Ground Fogs.</u> Supercooled ground fogs formed by advection or radiation may be modified and even dispersed if care is exercised to prevent overseeding. Too high a concentration of ice nuclei introduced into such fogs might actually make the fogs worse.

> *As previously mentioned, the clearing of supercooled fogs has been accomplished at several airports around the world with modest amounts of nucleating agents. In theory one should be able to overseed a supercooled fog and make so many tiny crystals that they remain suspended and worsen fog visibility. In practice, however, it has proven difficult or impossible to overseed fogs, or clouds, even with extremely large quantities of dry ice or silver iodide. It appears that sufficient crystal growth still occurs and that crystal-crystal aggregation to form larger falling snowflakes can take place (113).*

The prevention of the formation of ice fog is another possibility from the proper manipulation of seeding techniques. By introducing an optimum number of sublimation nuclei into the air in regions where such fogs are troublesome, it may be possible to continuously remove from the air the moisture responsible for the formation of this interesting but often troublesome type of ground fog.

The ice crystals generated in the vortices of airplane propellers plus the moisture added to the air by the combustion exhaust of the plane are the causes which generally lead to the formation of ice fogs at airports. Whether the removal of supersaturation with respect to ice by seeding methods will be of sufficient magnitude to prevent the ice-fogging effects produced by plane operations can be determined most conclusively by actual experiment.

<u>Protection of Aircraft.</u> There is no question about being able to modify icing clouds in the vicinities of airports and along heavily traveled air lanes. The problem rather, is whether it may have a practical application. Low clouds which restrict visibility for landing approaches around airports, thick clouds in which planes must cruise as they wait for permission to land, and thick clouds which might deposit a serious icing load on the plane as it tries to climb up through them--these comprise hazards to safe plane operations. And when such clouds are supercooled, they may sometimes be profoundly modified.

The simplest means for carrying out such cloud modification would be to employ a plane, well equipped for flying under serious icing conditions, for patrolling the air lanes. The plane would report weather and cloud conditions and, whenever serious supercooled clouds occurred, would carry out seeding operations.

In flying through a supercooled cloud, the airplane itself may produce a fairly effective modification. The vortices which form at the trailing edges of the wings and particularly from the propeller tips form large numbers of ice crystals.

<u>Modifying Thunderstorms.</u> It may be possible that silver-iodide seeding from ground generators would be particularly useful in modifying orographic "towering" cumulus to prevent their growth into thunderstorms. By determining the air trajectory from the ground into the cold part of the cloud, potential ice nuclei may be sent aloft by a very simple procedure. If subsequent experiments indicate that it is important to seed such clouds at a temperature only a few degrees colder than the freezing point, it may become necessary to use dry ice dispensed from planes or carried into the clouds by free balloons or projectiles.

Towering cumulus also forms over flat country at times when the atmosphere is conditionally unstable. Dangerous and often deadly lightning strokes, torrential rains, destructive winds, and sometimes hail and tornadoes are the end products of such developments. Since the high, vertical thickness of a supercooled cloud seems to be the basic requisite in the formation of a thunderstorm, it may be quite feasible by proper seeding methods to prevent this phase from developing.

The manner in which the seeding is done may produce a wide variation in the end results obtained. By seeding each cumulus tower with large numbers of crystals shortly after it rises above the freezing level, the cloud would be continuously dissipated and no extensive regions of supercooled cloud could develop. On the other hand, it might be desirable to seed such clouds to realize the maximum possible energy release. This presumably would involve seeding each cumulus tower just previous to the point of its maximum development. If this could be done effectively, it might be possible to build the storm into a much larger one than would develop under natural conditions.

<u>Preventing Hail.</u> The possibility that hailstorms might be prevented by seeding techniques is of considerable economic importance. A great amount of basic information is needed on the various properties of storms that produce hail. In some parts of the country where severe hail damage is frequent, storms are formed over certain mountain ridges and peaks that serve as cloud barriers. Such clouds should be particularly suited for modification by ground generators, since the air trajectory is definitely related to the flow of air up the mountain and into the clouds.

> *Over the past decade, one of the most actively pursued weather modification efforts has been hail suppression. The concept of heavy seeding with silver iodide or lead iodide to reduce the sizes of hail pellets (via competition) has been employed. In Russia, claims of crop damage reduction of up to 70 to 90 percent have been reported (114). Conversely, the National Hail Research Experiment in the United States led to inconclusive statistical results, with the suggestion that the seeding method involved may actually have increased hailfall (115).*

APPARENT LIMITATIONS

As in any of the physical phenomena, there are definite limitations to the degree in which experimental meteorology may be employed in modifying clouds in the free atmosphere. Some of these apparent limitations may disappear as our knowledge increases, although most of the restrictions now recognized are imposed by known physical laws.

Foremost of these restrictions is the factor of cloud type and size. Certain clouds, such as the fair-weather cumulus, have such a small volume and restricted area that, even though they are easily modified when supercooled, their total liquid-water content is inconsequential. Another complicating factor is that the air below larger clouds is sometimes so dry that a considerable amount of precipitation evaporates before it reaches the ground.

Another type of cloud which is difficult to modify is the warm ground fog formed by radiation or advection. Such fogs are often extensive and of considerable economic importance, especially from the standpoint of airplane traffic control. But the natural structure of a fog precludes any simple method of modifying it. Generally, the vertical thickness is not more than 100 meters or so, with a cloudless sky above. This rules out the possibility of modifying from above by forming precipitation in higher clouds to "rain out" the fog.

> *A highly practical means of modifying warm fog has continued to elude weather modifiers, although some effective results have been obtained by rather costly heating of the air (British Project Fido; U.S.A.F. Arcata and Vandenberg A.F.B. experiments; Paris Orly-Airport System). More marginal techniques have produced limited clearing by helicopter downwash of dryer air from above (116) and by seeding the fog with giant hygroscopic nuclei (117, 118). The latter technique represented a variation of the air-drying approach used by Houghton and Radford (119), one of the few scientific weather modification programs preceding Project Cirrus.*

Another weather situation where no method of relief is now apparent is in the case of drought. This condition generally results from the stability of a complex weather pattern in a manner which, at present, is not very well understood. Drought is generally accompanied by either cloudless skies or clouds of small vertical and horizontal development, because of strong inversions or thick layers of dry air.

The development of convergence is an important feature in the formation of appreciable amount of rainfall in many parts of the world. As a rule, such developments are generally accompanied by the occurrence of natural precipitation, which continues so long as the convergent movement is present. About the only thing that artificial modification of clouds might do under such atmospheric conditions is to initiate the precipitation cycle a few hours before it would start naturally, or under some conditions, to delay the onset of precipitation by overseeding.

> *Another possibility is that appropriate seeding might increase the amount of precipitation beyond what would naturally occur. This premise underlies several recent projects, recognizing that rigorous statistical design of experiments becomes increasingly important in order to distinguish between natural and modified rainfall (119).*

CONTROVERSIAL ASPECTS

As is so often the case with the proposal of striking or revolutionary new concepts in science, the validity of the observations and conclusions of the members of the Research Group, both before and after the establishment of Project Cirrus, was challenged by many. As a result, quite a school of opposing thought has been built up. This is a normal, healthy condition of affairs, and the results would be of no particular consequence were it not for the fact that the possibilities inherent in artificial weather modification have such great economic significance.

Although criticism and challenge have by no means been confined to any one person or group, the spearhead of the opposition, so to speak, has been the United States Weather Bureau. This unit has kept a watchful eye on all the developments associated with Project Cirrus. In many cases it designated observers to work with the project on specific operations. It has conducted experiments of its own to test the validity of Project Cirrus findings, notably the Cloud Physics Project, jointly conducted by the Weather Bureau and the United States Air Force.

The running controversy between representatives of the Weather Bureau and Langmuir is summarized in an article (120) available in his office files. In it Langmuir discusses and answers the various criticisms and challenges. He summarizes the importance of the situation in the following paragraphs:

"The possibility of such wide-scale control of weather conditions, of course, offers important military applications, but since nearly all meteorologists are much influenced by the opinions and the attitudes of the Weather Bureau men, the opposition on the part of the Weather Bureau and other groups has, up to the present, prevented the starting of any military applications. It was, therefore, of the utmost importance to clear this matter up without getting too much publicity."

Langmuir has since explained orally that, in view of this situation, he has resorted to the use of publicity only when other methods of bringing matters to a head had failed. At the time of the preparation of this report, however, both he and the other scientists associated with Project Cirrus had begun to feel that it would only be a matter of time before the Weather Bureau would change its attitude. It is believed that the described results obtained by the California Electric Power Company (p. 46) have had a great deal to do with that change of attitude.

Some picture of the Weather Bureau side of the controversy may be found in testimony (121) presented during hearings before Senate subcommittees on three bills, as follows:

S.5, a bill to provide for research into and demonstration of practical means for the economical production, from sea or other saline waters, or from the atmosphere (including cloud formations), of water suitable for agricultural, industrial, municipal, and other beneficial consumptive uses, and for other purposes.

S.222, a bill to provide for the development and regulation of methods of weather modification and control.

S.798, a bill to authorize the Secretary of Agriculture to conduct research and experiments with respect to methods of controlling and producing precipitation in moisture-deficient areas.

The attitude of the Weather Bureau is summarized in a statement presented to the above groups on March 14, 1951, by W. F. McDonald, assistant chief of the United States Weather Bureau, and a further clarification of Weather Bureau views is found in the subsequent questioning of Mr. McDonald by members of the committees.

The fact that the challenges to the validity of Project Cirrus claims are not confined to the Weather Bureau is also indicated during the same Senate hearings. Statements were made at those hearings by other individuals not associated with the Weather Bureau, and some of those individuals did not agree with the findings of Project Cirrus. Among them were Hans H. Neuberger, professor of meteorology and chief of the Division of Meteorology, Pennsylvania State College, Charles L. Hosler, a staff member of that college, and Henry G. Houghton, professor of meteorology and head of the Department of Meteorology, Massachusetts Institute of Technology.

The Weather Bureau (now the National Oceanic and Atmospheric Administration) has assumed a major role in the investigation of weather modification potential. Their recent projects include Project Stormfury (hurricane modification as mentioned), Great Lakes snowstorm redistribution (122), Florida cumulus rainfall enhancement (123, 124), participation in the National Hail Research Experiment, lightning abatement (125), fog modification and numerous basic research studies in weather modification.

LEGISLATION

For various reasons, national legislation has been suggested, and actually introduced, to regulate and control artificial weather modification. Of the three bills referred to in the preceding paragraphs, two (S.222 and S.798) specifically covered this proposed regulation and control (S.222) and authorized the Secretary of Agriculture to conduct research and experiments (S.798).

Since that time a new bill was drafted and introduced in the Senate, 82d Congress, second session: S.2225. This bill would create a temporary advisory committee of nine persons to study and evaluate experiments in weather modification, continuing no longer than July 30, 1955. The committee would report to Congress at the earliest possible moment on the advisability of the Government regulating, by means of licenses or otherwise, the activities of persons attempting to modify the weather. The advisory committee would consist of five members appointed from public life by the President plus the Secretaries of Defense, Interior, Agriculture, and Commerce, or their designees. The bill was referred to the Committee on Interstate and Foreign Commerce on October 8, 1951, and reported out with amendments on May 12, 1952.

The General Electric attitude toward legislation was summed up at the above hearings by Vice President and Director of Research, C. G. Suits, and by Schaefer and Vonnegut, who accompanied him to the hearings. Said Suits, in part:

"These facts which underlie experimental meteorology are not in the controversial area; they have been demonstrated and proven. What controversy has arisen has been concerned with such matters as (1) the economical importance of induced rainfall--by 'induced rainfall' I mean artificially induced rainfall (2) where long-range effects of cloud seeding exist, and (3) whether induced rainfall may not have occurred naturally in the absence of seeding. There is a great mass of information bearing on these questions, and it would not be possible to discuss it all here.

"It is my considered opinion, however, that the results of the most recent work are of the very greatest importance to the Nation. We have at hand a means of exerting a very considerable degree of control of weather phenomena. Precisely how much control can be accomplished will come from further study. Much work remains to be done, and it would be a national tragedy if legislation did not provide a proper framework for developing the full potentialities of weather modification methods. It would be hard to imagine anything more important to the country than weather modification and control."

Another extract from the Suits statement:

"I wish to be very clear on one point. The work my company has done in this field, initially at our own expense and more recently under a Signal Corps contract with the participation of the Office of Naval Research and the United States Air Force, has had no single practical application within the Company. The work originated as an unexpected result of one of the many fundamental investigations which we undertake in the search for new knowledge. It was continued because the leaders of my company and responsible representatives of the Government believed that the possibilities of weather modification might be of great importance to the Nation as a whole. On December 27, 1950, my company announced that for the present and until further notice it does not intend to enforce any of its patents relating to weather modification by the artificial production of snow and rain.

"A contractor of the Government for research in this field, where the general public is the intended beneficiary, should not be subjected to the uncertainties of legal liability hazards which are inherent in experimental weather modification. The provisions of S.222 would greatly minimize the legal hazards which now exist. Some such solution of this problem must be found if private agencies are to engage in research in this field, and by that I mean under contract with the Government."

Other aspects of the need for legislation were voiced at that time by Schaefer. The following quotes from his statement illustrate these other aspects:

"It is very important, in my opinion, that weather studies involving

experimental meteorology be conducted in such a manner that all of the modifications attempted by man-conducted seeding operations be known and controlled. If this is not done, the effort of attempting to understand the reactions which occur is a hopeless one.....

"It is obvious that some type of national legislation is of the utmost importance at this time to protect the public in the future from unscrupulous individuals who would play on the gullibility, hope, or desperation of individuals or groups in need of water or other relief from an undesirable climatic situation."

Vonnegut, also, in his statement read at those hearings, urged the adoption of suitable legislation. In addition to the reasons voiced by Suits and Schaefer, he added others, which are found in the following extract:

"The problems of weather control are so large and of such nationwide importance that only Federal legislation can insure that this powerful new tool will result in the greatest good for the largest number of people. In the absence of this legislation, I believe that the development of the benefits to be derived from cloud seeding may be greatly retarded or prevented and that possibly much harm can result from storms, droughts, or floods produced by uncontrolled seeding.

"Theory has predicted and experiments are confirming the fact that a few pounds of silver iodide released into the atmosphere in the form of fine particles can exercise a profound influence over the weather hundreds of miles away from the point of release. Clearly no private individual or group can be permitted to carry on operations likely to affect weather conditions over thousands or hundreds of thousands of square miles.

"The potentialities, both for good and bad, which attend silver-iodide seeding are so large that the development and use of this technique must be placed in the hands of the Federal Government.

"Secondly, it is highly desirable that the Government pass laws regulating cloud seeding, in order to promote the rapid development of this science. Many facts are yet to be learned concerning the best methods of seeding to obtain desirable results. These facts can be determined only by experiments in the atmosphere. The analysis of the results of cloud-seeding experiments is a complicated and difficult problem. If, as in the case at present, many seeding experiments are being independently and simultaneously carried out in many places, the problem of analysis becomes even more difficult and frequently impossible. Federal regulation is necessary to insure the rapid development of the benefits of cloud seeding.

"Thirdly, the science of weather control can be of such great benefit to the entire country that the responsibility for its advancement must rest with the

Government. Legislation should provide funds for research by Government and by private groups into fundamental scientific problems connected with the weather."

At the time of the preparation of this history, no national legislation had yet been enacted to cover any of the needs outlined in the foregoing.

The Federal Government now makes adequate provisions for reporting field activities and requiring Environmental Impact Statements (Public Law 205, 92nd Congress), but has refrained from entering into matters of licensing and control. The latter is generally deemed the responsibility of individual states. While more than half the states have some form of weather modification statutes, few are considered to be ideal (126).

This photograph of Langmuir (Raymond Falconer on his right) was taken in 1956 when he appeared on the NBC television show, "Today", with Dave Garroway. He utilized this opportunity to urge again that some governmental agency carry out hurricane seeding experiments. In 1963 such a program was initiated by the U. S. Navy and the U. S. Weather Bureau.

Epilogue (1978)

In retrospect, it appears accurate to state that Project Cirrus activities stirred the imagination of scientists the world over. It also incurred the skepticism of some and stimulated the profit motive of a few anxious to capitalize on a new technology. An important by-product, if not the most important effect, was the stimulus the weather modification discoveries provided to the field of cloud physics. McDonald (127) recounts the very slow progress being made in cloud physics during the 1900's, when such research was apparently only of academic interest. He states:

"When, after 1946, there seemed to exist some prospect of control over a natural phenomenon whose economic value is so high, support of cloud physics research jumped by what I would estimate must surely have been a factor of two to three orders of magnitude, and total numbers of workers in the field must have increased by a factor of something like two orders of magnitude."

Led by a vital Nobel Laureate and comprised of several investigators unique in their own right, the small Project Cirrus group in slightly more than five years accomplished what must be considered remarkable. During that short span, theories were expounded on precipitation mechanisms in cold and warm clouds; effective cloud seeding agents including dry ice and silver iodide were discovered; ground and aircraft generators were developed not too dissimilar from those in use today; and a variety of new instruments and techniques was devised to monitor cloud behavior. Amidst all this, over 180 aircraft experiments and 84 ground experiments were conducted--from Puerto Rico to Honduras to Hawaii and in some dozen states in between.

As Havens' account suggests, few of the weather modification concepts being pursued today were overlooked by the Project Cirrus group, although in-depth study obviously was not always possible. The work on supercooled stratus-type clouds, which the project title denotes, has solidly withstood the test of time.

Ironically, as a portion of the research turned to deep, complex cumulus clouds, some of the arrows went wide of the mark. Langmuir's convictions on rainfall periodicities and the degree to which rainfall could be increased were far too optimistic according to present views. Considering the variability of weather and the extent to which statistics can lead to conflicting interpretations even today, perhaps one should not be surprised. Not to be overlooked were Langmuir's pioneering theoretical efforts on droplet growth by diffusion, hydrometeor collision efficiencies, the chain-reaction mechanism involving droplet breakup, and the importance of latent heat release in cloud development and modification.

The extensive studies of silver iodide and many other ice nucleating substances continues. Other inorganic materials, such as copper oxide, copper sulfide, and cuprous iodide, have been found to nucleate ice formation at temperatures only several degrees below the freezing point. Some of these substances have a crystal structure apparently unrelated to that of ice. By suitable modifications of their surface, the ice nucleating capability of silicate particles possibly may be improved (128). Organic substances bearing little similarity to ice have been found to serve as effective nuclei, for example, phloroglucinol (129) and metaldehyde (130).

Studies have been carried out to investigate the effect of crystal lattice parameters. The structure of silver iodide, which is approximately 1.5% larger than ice, has been reduced in size by the substitution of either bromine for the iodine or by copper for the silver (131, 132), with an improvement of the ability of these modified crystal substances to nucleate ice formation. These and other studies have shown that the efficacy of ice nuclei is a very complicated matter depending on a variety of factors acting together, such as lattice parameter, surface electrical potential, solubility, photochemistry, particle size, the surface distribution of hydrophilic sites, the nature of the soluble iodides used in producing the solutions of the silver iodide, etc. It appears, however, that the discovery of a material greatly superior to silver iodide is not very likely.

Project Cirrus's investigations of ways that man can intentionally affect the weather cast a new light on how man's activities might unintentionally have a large influence on weather processes. Along with the scientific study of deliberate weather modification, a new vigorous research activity is developing to explore how man may be affecting his environment by the gases, aerosols and heat he emits into the atmosphere in the course of his many activities. Studies indicate that there may be far more unintentional cloud seeding as a result of pollution than was appreciated during the early days of Project Cirrus. In recent years several international workshops on inadvertent weather modification have been held. These are undoubtedly only the first of many similar ones that will be held in the future on this subject.

Environmentalists have been justly concerned that cloud seeding might disrupt ecological balances and pose hazards when seeding materials enter the water supply. Recent studies (133, 134) suggest that there is little cause for concern on this score.

One might anticipate because Project Cirrus involved the cooperative activity of personnel derived from four separate and frequently competitive organizations--the U. S. Army Signal Corps, the U. S. Air Force, the U. S. Navy, and the General Electric Company--that this would have posed serious organizational problems. Such was not the case. What rivalry existed was friendly, morale was high, and a strong spirit of cooperation existed throughout the cour e of the project.

It seems apparent that th coming years should witness a definitive evaluation of several weather modification concepts. Progress in the field may come grudgingly because of budgetary priorities, environmental and legal concerns, and the realization that substantial data are needed for statistically significant findings.

Since the termination of Project Cirrus, two powerful new tools have become available to investigate cloud seeding. The modern computer makes it possible by modeling to study the effects on systems ranging in size from small clouds to giant storms. Weather satellites now provide a new detailed view from above of the dynamics of weather processes that will doubtless give new insights into how seeding affects the behavior of weather processes.

Inadvertent weather and climate modification likely will overshadow planned modification--if not already the case--as the global population increases and becomes more industrialized. The problems will be both challenging and exciting, but in terms of rapidly mobilizing, coordinating, and executing a cooperative program similar in pioneering scope to Project Cirrus, history is not likely to repeat itself.

BIBLIOGRAPHY

1. Langmuir, I., 1948: The growth of particles in smokes and clouds and the production of snow from supercooled clouds. Proc. Amer. Phil. Soc. 92, 167.
2. Vonnegut, B, 1947: The nucleation of ice formation by silver iodide. J. Appl. Phys. 18, 593-595.
3. Schaefer, V. J., August 8, 1946: "Final Report on Icing Research". Available in Research Laboratory files.
4. Langmuir, I., and K. B. Blodgett, 1945: "A mathematical investigation of water droplet trajectories". Work done under Army Contract W-33-038-ac-9151, December 1944-July 1945.
5. Hocking, L. M., 1959: The collision efficiency of small drops. Quart. J. Roy. Meteor. Soc. 85, 44.
6. Shafrir, U., and M. Neiburger, 1963: Collision efficiencies of two spheres falling in a viscous medium. J. Geophys. Res. 68, 4141-4148.
7. Davis, M. S., and J. D. Sartor: Theoretical collision efficiencies for small cloud droplets in Stokes flow. Nature 215, 1371-1372.
8. Beard, K. V., and H. R. Pruppacher, 1971: A wind tunnel investigation of collection kernels for small water drops in air. Quart. J. Roy. Meteor. Soc. 97, 242-248.
9. Brazier-Smith, P. R., S. G. Jennings, and J. Latham, 1972: The interaction of falling water drops: Coalescence. Proc. Roy. Soc. A, 326, 393-408.
10. Langmuir, I., August 16, 1946: "Memorandum on Introduction of Ice Nuclei into Clouds". Never published, but available in Research Laboratory Library.
11. Schaefer, V. J., 1948: The production of clouds containing supercooled water droplets or ice crystals under laboratory conditions. Bull. Amer. Meteor. Soc. 29, 175.
12. Vonnegut, B., 1948: Variation with temperature of the nucleation rate of supercooled liquid tin and water drops. J. Coll. Sci. 3, 563.
13. Vonnegut, B., 1947: The nucleation of ice formation by silver iodide. J. Appl. Phys. 18, 593.
14. Vonnegut, B., 1949: "Silver-iodide Smoke". Project Cirrus Occasional Report No. 13, July 1, 1949.
15. Vonnegut, B, 1969: Historical note on the nucleation of ice formation by silver iodide. Bull. Amer. Meteor. Soc. 50, 248.
16. Blanchard, D. C., 1978: Tor Bergeron and his "Autobiographical Notes"; Some autobiographic notes in connection with the ice nucleus theory of precipitation release. Bull. Amer. Meteor. Soc. 59, 389-390.
17. Final Report, Project Cirrus, Contract W-36-039-SC-32427, December 31, 1948.
18. Malkus, J. S., and R. H. Simpson, 1964: Modification experiments on tropical cumulus clouds. Science 145, 541-548.
19. Schaefer, V. J., 1948: The natural and artificial formation of snow in the atmosphere. Trans. Amer. Geophys. Union 29, 492.
20. First Quarterly Progress Report, Project Cirrus, July 15, 1947.
21. Second Quarterly Progress Report, Project Cirrus, November 15, 1947.
22. Vonnegut, B., 1947: "Nucleation of Ice Formation by Silver Iodide Particles". Supplement to First Quarterly Progress Report, Project Cirrus, November 15, 1947.
23. Vonnegut, B., 1950: Techniques for generating silver-iodide smoke. J. Coll. Sci. 5, 37.
24. Vonnegut, B., and K. Maynard, 1952: Spray-nozzle type silver-iodide smoke generator for airplane use. Bull. Amer. Meteor. Soc. 33, 420-428.
25. Vonnegut, B., 1949: Nucleation of supercooled water clouds by silver iodide smokes. Chem. Rev. 44, 277-289.
26. Schaefer, V. J., and R. E. Falconer, 1948: "A New Plane Model Cloud Meter". Project Cirrus Occasional Report No. 2, May 15, 1948.
27. Third Quarterly Progress Report, Project Cirrus, February 15, 1948.
28. Vonnegut, B., 1950: Continuous-recording condensation nuclei meter. Proc. 1st Nat. Air Poll. Symp. 1, 36 (Project Cirrus Occasional Report No. 19, January 1, 1950.
29. Vonnegut, B., 1949: Vortex thermometer for measuring true air temperatures and true air speeds in flight. Rev. Sci. Instrum. 21, 136.
30. Vonnegut, B., 1954: A vortex whistle. J. Acoust. Soc. Amer. 26, 18.
31. Seventh Quarterly Progress Report, Project Cirrus, March 15, 1949.
32. Eighth Quarterly Progress Report, Project Cirrus, June 15, 1949.
33. Ninth Quarterly Progress Report, Project Cirrus, September 15, 1949.
34. Eleventh Quarterly Progress Report, Project Cirrus, March 30, 1950.
35. Vonnegut, B., and R. L. Neubauer, 1952: Detection and measurement of aerosol particles by the use of an electrically heated filament. Analyt. Chem. 24, 1000.
36. Vonnegut, B., and R. L. Neubauer, 1953: "Counting Sodium-containing particles in the atmosphere by their spectral emission in a hydrogen flame. Bull. Amer. Meteor. Soc. 34, 163-169.

37. Schaefer, V. J., 1952: Continuous cloud chamber for studying small particles in the atmosphere. Ind. Eng. Chem. 44, 1381.
38. Fourteenth Quarterly Progress Report, Project Cirrus, January 30, 1951.
39. Fourth Quarterly Progress Report, Project Cirrus, July 1, 1948.
40. Falconer, R. E., 1965: A simple method for obtainin a continuous record of the prese :e and type of clouds in the sky o ring the day. Pure & Appl. Geophys. (PAGEOPH) 60 (1965/I), 234-244.
41. Schaefer, V. J., 1949: The formation of ice crystals in the laboratory and the atmosphere. Chem. Rev. 44, 291.
42. Kumai, M., 1951: Electron-microscope study of snow crystal nuclei. J. Meteor. 8, 151.
43. Schnell, R. C., and G. Vali, 1973: World-wide source of leaf-derived freezing nuclei. Nature 246, 212-215.
44. Schaefer, V. J., 1966: Ice nuclei from automobile exhaust and iodine vapor. Science 154, 1555-1557.
45. Bowen, E. G., 1953: The influence of meteoritic dust on rainfall. Aust. J. Phys. 6, 490.
46. Schaefer, V. J., 1954: The concentration of ice nuclei in air passing the summit of Mt. Washington. Bull. Amer. Meteor. Soc. 35, 310-314.
47. Schaefer, V. J., 1950: The occurrence of ice-crystal nuclei in the free atmosphere. Proc. 1st Nat. Air Poll. Symp., 26-35.
48. The Irving Langmuir Laboratory for Atmospheric Research, The New Mexico Institute of Mining and Technology, Socorro, New Mexico, 1977.
49. Vonnegut, B., and R. E. Falconer, 1948: "Smoke from Smelting Operations as a Possible Source of Silver-iodide Nuclei". Project Cirrus Occasional Report No. 4, June 15, 1948.
50. Vonnegut, B., 1948: Production of ice crystals by the adiabatic expansion of gas. J. Appl. Phys. 19, 959.
51. Cwilong, B. M., 1945: Sublimation in a Wilson chamber. Nature 155, 361.
52. Vonnegut, B., 1948: Influence of butyl alcohol on shape of snow crystals formed in the laboratory. Science 107, 621.
53. Schaefer, V. J., 1952: Formation of ice crystals in ordinary and nuclei-free air. Ind. Eng. Chem. 44, 1300.
54. Schaefer, V. J., 1948: Types of solid precipitation in snowstorms. Weatherwise 1, 6.
55. Schaefer, V. J., 1950: Experimental meteorology. J. Appl. Math. Phys. 1, 153.
56. Magono, C., and C. W. Lee, 1966: Meteorological classification of natural snow crystals. J. Faculty Sci., Hokkaido Univ., Ser. VII, 2, 321-335.
57. Schaefer, V. J., and R. J. Cheng, 1971: The production of ice crystal fragments by sublimation and electrification. J. Rech. Atmos. 5, 5-10.
58. Mossop, S., 1970: Concentrations of ice crystals in clouds. Bull. Amer. Meteor. Soc. 51, 474.
59. Hallett, J., and S. C. Mossop, 1974: Production of secondary ice particles during the riming process. Nature 249, 26-28.
60. Vonnegut, B., 1950: Experiments with silver-iodide smokes in the natural atmosphere. Bull. Amer. Meteor. Soc. 31, 151.
61. Coons, R. D., E. L. Jones, and R. Gunn, 1948: Second partial report on the artificial production of precipitation--cumuliform clouds--Ohio. Bull. Amer. Meteor. Soc. 29, 544-546.
62. Bowen, E. G., 1952: Australian experiments in artificial rainmaking. Bull. Amer. Meteor. Soc. 33, 244-246.
63. Schaefer, V. J., B. Vonnegut, S. E. Reynolds, and W. Hume II, 1951: Effect of sunlight on the action of silver-iodide particles as sublimation nuclei. Bull. Amer. Meteor. Soc. 32, 47.
64. Vonnegut, B., and R. L. Neubauer, 1951: Recent Experiments on the Effect of Ultraviolet Light on Silver-iodide nuclei. Bull. Amer. Meteor. Soc. 32, 356.
65. Blanchard, D. C., 1950: The behavior of water drops at terminal velocity in air. Trans. Amer. Geophys. Union 31, 836-842.
66. Blanchard, D. C., 1949: "The Use of Sooted Screens for Determining Raindrop Size and Distribution." Project Cirrus Occasional Report No. 16, November 15, 1949.
67. Spengler, J. D., 1970: "Large Vertical Wind Tunnel for Hydrometeor Studies." Proc. 2nd Nat. Conf. Wea. Mod., Amer. Meteor. Soc., Boston, 289-293.
68. Pruppacher, H. R., and M. Neiburger, 1968: "Design and Performance of the UCLA Cloud Tunnel". Proc. Int. Conf. Cloud Phys., Toronto, 389-392.
69. Langmuir, Irving, 1950: "Studies of Tropical Clouds". Project Cirrus Occasional Report No. 25, July 1, 1950.
70. Schaefer, V. J., 1947: Properties of particles of snow and the electrical effects they produce in storms. Trans. Amer. Geophys. Union 28,587.
71. Twomey, S., and P. Squires, 1959: The influence of cloud nucleus population on the microstructure and stability of convective clouds. Tellus 11, 408.

72. Falconer, R. E., 1949: "Some Correlations between Variations in the Atmospheric Potential Gradient at Schenectady and Certain Meteorological Phenomena". Project Cirrus Occasional Report No. 18, December 1, 1949.
73. Schaefer, V. J., 1950: A confirmation of the Workman-Reynolds effect. Phys. Rev. 77, 721.
74. Vonnegut, B., and R. L. Neubauer, 1952: Production of monodisperse liquid particles by electrical atomization. J. Colloid Sci. 7, 616-622.
75. Langmuir, I., 1950: "Progress in Cloud Modification by Project Cirrus". Project Cirrus Occasional Report No. 21, April 15, 1950.
76. Langmuir, I., 1948: "Studies of the Effects Produced by Dry-Ice Seeding of Stratus Clouds". Project Cirrus Occasional Report No. 10, December 31, 1948.
77. Langmuir, I., and C. A. Woodman, 1950: "A Gamma Pattern Seeding of Stratus Clouds, Flight 52, and a Racetrack Pattern Seeding of Stratus Clouds, Flight 53". Project Cirrus Occasional Report No. 23, June 1, 1950.
78. aufm Kampe, H. J., J. J. Kelley, and H. K. Weickmann, 1957: Seeding experiments in sub-cooled stratus clouds. Meteor. Monogr. 2, Amer. Meteor. Soc., Boston, 86.
79. Jiusto, J. E., and R. R. Rogers, 1961: "Experiments on Greenland Whiteout Modification-1960". Tech. Rep. 84, U. S. Cold Regions Res. and Eng. Lab., Hanover, N. H., 23 pp.
80. Borovikov, A. M., et al., 1961: "Cloud Physics". (English translation by Israel Program for Scientific Translations, Jerusalem, 1963].
81. Appleman, H. S., and T. A. Studer, 1968: Projects: Warm Fog, Cold Fog III, Cold Wand, Cold Horn, and Cold Fan. Air Wea. Svc., USAF, Tech. Rep. 209, 1, 38 pp.
82. Vickers, W. W., and J. F. Church, 1966: Investigation of optimal design for supercooled cloud dispersal equipment and techniques. J. Appl. Meteor. 5, 105-118.
83. Neiburger, M., 1969: "Artificial Modification of Clouds and Precipitation". World Meteor. Org. Tech. Note 105, WMO-No. 249, TP 137, Geneva, Switzerland, 33 pp.
84. Schaefer, V. J., 1977: An early account of a flight to modify lightning storms. J. Wea. Mod. 9, 1-7.
85. Dawson, G., D. W. Fuquay, and H. W. Kasemir, 1974: "Lightning Modification". In Weather and Climate Modification (ed. W. Hess), Wiley and Sons, 596-629.
86. Langmuir, I., 1949: "Supercooled Water Droplets in Rising Currents of Cold Saturated Air". Research Laboratory Report No. RL-223, August, 1949.
87. Langmuir, I., 1948: The production of rain by a chain reaction in cumulus clouds at temperatures above freezing. J. Meteor. 5, 175.
88. Blanchard, D. C., 1949: "Experiments with Water Drops and the Interaction between Them at Terminal Velocity in Air". Project Cirrus Occasional Report No. 17, December 15, 1949.
89. Blanchard, D. C., 1949: "The Distribution of Raindrops in Natural Rain". Project Cirrus Occasional Report No. 15, November 15, 1949.
90. Schaefer, V. J., 1950: "Report on Cloud Studies in Puerto Rico". Project Cirrus Occasional Report No. 20, January 15, 1950.
91. Biswas, K. R., and A. S. Dennis, 1971: Formation of a rain shower by salt seeding. J. Appl. Meteor. 10, 780-784.
92. Blanchard, D. C., 1972: Comments on "Formation of a Rain Shower by Salt Seeding". J. Appl. Meteor. 11, 556-557.
93. Langmuir, I., 1951: Cloud seeding by means of dry ice, silver iodide, and sodium chloride. Trans. N. Y. Acad. Sci. 14, 40.
94. Braham, R. R., L. J. Battan, and H. R. Byers, 1957: Artificial nucleation of cumulus clouds. Meteor. Monogr. 2, Amer. Meteor. Soc. Boston, 47.
95. Woodcock, A. H., and W. A. Mordy, 1955: Salt nuclei wind and daily rainfall in Hawaii. Tellus, 7, 291-300.
96. Davies, D. A., 1954: Experiments on artificial stimulation of rain in East Africa. Nature 174, 256.
97. Fournier d'Albe, E. M., A. M. Lateef, S. I. Rasool, and I. H. Zaidi, 1955: The cloud seeding trials in the central Punjab, Jul-Sep 1954. Quart. J. Roy. Meteor. Soc. 81, 574.
98. Biswas, K. R., R. K. Kapoor, K. K. Kanuga, and Bh. V. Ramana Murty, 1967: Cloud seeding experiment using common salt. J. Appl. Meteor. 6, 914-923.
99. Langmuir, I., 1950: "Results of the seeding of cumulus clouds in New Mexico". Project Cirrus Occasional Report No. 24, June 1, 1950.
100. Fletcher, N. H., 1966: The Physics of Rainclouds. Cambridge Univ. Press, 390 pp.
101. Braham, R. R., 1966: "Project Whitetop: A Convective Cloud Randomization Seeding Project". Dept. Geophys. Sciences, Univ. of Chicago.
102. Langmuir, I., 1950: A Seven-day periodicity in weather in the United States during April 1950. Bull. Amer. Meteor. Soc. 31, 386.
103. Fifth Quarterly Progress Report, Project Cirrus, September 15, 1948.

104. Mook, C. P., E. W. Hoover, and R. A. Hoover, 1957: An analysis of the movement of a hurricane off the east coast of the United States, October 12-14, 1947. Mon. Wea. Rev. 85, 243-250.
105. Gentry, R. C., 1970: Hurricane Debbie modification experiments, August, 1969. Science 168, 473-475.
106. Rosenthal, S. ., 1971: A circularly symme..ic primitive-equation model of tropical cyclones and its response to artificial enhancement of the convective heating functions. Mon. Wea. Rev. 99, 414-426.
107. Leopold, L. B., and M. H. Halstead, 1948: First trials of the Schaefer-Langmuir dry-ice cloud-seeding technique in Hawaii. Bull. Amer. Meteor. Soc. 29, 525.
108. Farhar, B. C., 1974: The impact of the Rapid City flood on public opinion about weather modification. Bull. Amer. Meteor. Soc. 55, 759-764.
109. "Report of Cloud-seeding Experiments in the San Diego County and the Santa Ana River Watershed", revised edition June 10, 1952, published by John A. Battle, consulting meteorologist, Beaumont, CA.
110. Grant, L. O., and A. M. Kahan, 1974: "Weather Modification for Augmenting Orographic Precipitation". In Weather and Climate Modification, W. Hess, ed., Wiley and Sons.
111. Grant, L. O., and P. W. Mielke, 1967: "A Randomized Cloud Seeding Experiment at Climax, Colorado, 1960-65". Vol. V., Weather Modification Exps., Proc. 5th Berkeley Symp. on Math. Stat. and Prob., Univ. Calif. Press, 115-131.
112. List, R, 1976: "Objectives and Status of the WMO Precipitation Enhancement Project". 2nd WMO Scientific Conf. on Wea. Mod., Boulder, CO, WMO No. 443, 445-457.
113. Holroyd, E. W., and J. E. Jiusto, 1971: Snowfall from a heavily-seeded cloud. J. Appl. Meteor. 10, 266-269.
114. Burtsev, I. I., I. I. Gavoronsky and A. I. Kartsivadze, 1973: "Hail Process Investigation and Hail Suppression Activities in the USSR", Proc. WMO/IAMAP Scientific Conf. on Wea. Mod., Tashkent, WMO No. 399, 189-197.
115. Long, A. B., E. L. Crow, and A. W. Huggins, 1976: "Analysis of the Hailfall During 1972-74 in the National Hail Research Experiment". 2nd Scientific Conf. on Wea. Mod., Boulder, WMO No. 443, 265-272.
116. Plank, V. G., A. A. Spatola, and J. R. Hicks, 1971: Summary results of the Lewisburg fog clearing program. J. Appl. Meteor. 10, 763-779.
117. Jiusto, J. E., R. J. Pilie, and W. C. Kocmond, 1968: Fog modification with giant hygroscopic nuclei. J. Appl. Meteor. 7, 860-869.
118. Weinstein, A. I., and B. A. Silverman, 1973: A numerical analysis of some practical aspects of airborne urea seeding for warm fog dispersal at airports. J. Appl. Meteor. 12, 771-780.
119. Houghton, H. G., and W. H. Radford, 1938: "On the Local Dissipation of Natural Fog". MIT Papers in Phys. Oceanog. Meteor. 6, 3.
120. Langmuir, I., "Widespread Modifications of Synoptic Weather Conditions Induced by Localized Silver-iodide Seeding". Prepared in January 1951 and never published.
121. "Weather Control and Augmented Potable Water Supply". Extracts from hearings before subcommittees of the Committees on Interior and Insular Affairs, Interstate & Foreign Commerce, and Agriculture & Forestry, United States Senate, 82nd Congress, First Sessions, on S.5, S.222, and S.798, Washington, D. C., March 14, 15, 16, 19, and April 5, 1951, U. S. Government Printing Office.
122. Weickmann, H. K., 1974: "The Mitigation of Great Lakes Storms". In Weather and Climate Modification, W. Hess, ed., Wiley and Sons, 318-355.
123. Simpson, J., and W. L. Woodley, 1971: Seeding cumulus in Florida: New 1970 results. Science 172, 117-126.
124. Woodley, W. L., and R. I. Sax, 1976: "The Florida Area Cumulus Experiment". NOAA Tech. Rep. ERL 354-WMPO 6, 204 pp.
125. Kasemir, H. W., F. J. Holitza, W. E. Cobb, and W. D. Rust, 1976: Lightning suppression by chaff seeding at the base of thunderstorms. J. Geophys. Res. 81, 1965-1970.
126. Taubenfeld, H. J., ed., 1968: Weather Modification and the Law. Oceana Publications, Inc., Dobbs Ferry, New York.
127. McDonald, J. E., 1958: "The Physics of Cloud Modification". Advances in Geophysics 5, Academic Press, 223-303.
128. Zettlemoyer, A. C., N. Tcheurekdjian, and C. L. Hosler, 1963: Ice nucleation by hydrophobic substrates. Z. Agnew Math. Phys. 14, 496-502.
129. Bashkirov, G. M., and P. N. Krasikov, 1957: Experiments with certain substances as crystallization agents for supercooled fog. Trudy Glav. Geofiz. Obs. A. I, Voeikova, 72, 118.
130. Fukuta, N., 1963: Ice nucleation by metaldehyde. Nature, 199, 475.

131. Vonnegut, B., and H. Chessin, 1971: Ice nucleation by coprecipitated silver iodide and silver bromide. Science 174, 945-946.
132. Passarelli, R. E., Jr., H. Chessin, and B. Vonnegut, 1974: Ice nucleation in a supercooled cloud by CuI-3AgI and AgI aerosols. J. Appl. Meteor. 13, 946-948.
133. Klein, D. A., ed., 1978: Environmental Impacts of Artificial Ice Nucleating Agents, Dowden, Hutchinson and Ross (Stroudsberg, PA), 256 pp.
134. "Technology Assessment of Winter Orographic Snowpack Augmentation in the Upper Colorado River Basin, Summary Report", Stanford Research Institute, Menlo Park, California, 1972.

APPENDIX 1

CONTRACTUAL HISTORY

The two research projects, involving first the work on gas masks and smoke filters and then the work on smoke generators, extended over a period from October 1940 through February 1944. This work was done under two contracts (NDCrc-104 and OEMsr-131) with the Office of Scientific Research and Development.

From October 1943 through June 1946, precipitation static research was carried on under Signal Corps contract W-33-106-sc-65 and, subsequently, under Air Force contracts W-33-038-AC-9151 and W-33-038-AC-15801.

The meteorological research which became Project Cirrus, was supported for a time by the General Electric Company. In February 1947, the first of three Signal Corps contracts (W-36-039-sc-32427, W-36-039-sc-38141, and DA-36-039-sc-15345) was signed. The last of these remained in force until the end of September 1952.

APPENDIX 2

ALPHABETICAL LIST OF PERSONNEL

Mrs. Margaret Bakuzonis, GE
Raymond Bellucci, civilian mathematician
S/Sgt. C. S. Belote, USAF, radio operator
S/Sgt. Roy E. Berry, USAF, crew chief
George Blair, GE
Duncan Blanchard, GE
Major D. Blue, USMA
Dr. C. J. Brasefield, Signal Corps, Steering Committee Alternate
1st Lt. Mitchell B. Bressette, USAF, navigator
Vincent Bruck, Signal Corps, photographer
Robert C. Bulock, Signal Corps
Major E. Cartwright, USAF
Theodore Catellie, Signal Corps photographer
Cmdr. R. A. Chandler, Navy, Steering Committee Alternate
Capt. Clarence N. Chamberlain, Jr., USAF, pilot
T/Sgt. Vernon H. Davis, Signal Corps, Supply Sgt.
M/Sgt. Eugene R. Dickson, USAF, crew chief
E. G. Droessler, ONR, Steering Committee
Mrs. Analee Durant, secretary
Lt. Max A. Eaton, Navy, Steering Committee
Robert F. Egger, AL2, USN, radio and radar operator
Raymond Falconer, GE
Lt. Cdr. Elwood B. Faust, USN, pilot
Dr. Michael J. Ferrence, Signal Corps, Steering Committee
Charles S. Ferris, civilian electrician
Victor Fraenckel, GE
S/Sgt. Russell C. Friedl, USAF, crew chief
1st Lt. Carl J. Fuhrmann, USAF, pilot
Myer Geller, GE
Miss Constance Godell, secretary
Cmdr. G. D. Good, Navy, Steering Committee Alternate
T/5 C. E. Hall, Signal Corps, driver
Cpt. Francis N. Ham, Signal Corps, driver
Roger Hammond, GE News Bureau, communications media liaison
Lt. Cdr. B. K. Harrison, USN, pilot
1st Lt. Ted E. Hoffman, USAF, pilot
T/Sgt. C. E. Hughey, USAF, crew chief
Thomas J. Hurley, Signal Corps, photographer
Lt. J. W. Iler, USN, pilot
Cpl. Billy G. Jackson, Signal Corps, photographer
Cpl. Ernst S. Johnson, Signal Corps, photographer
T/Sgt. Martin M. Kalich, USAF, radio operator
Major P. J. Keating, USAF, Steering Committee
John Kelly, Signal Corps, civilian technician
Major Rudolph C. Koerner, Jr., Signal Corps
Cpl. James W. Land, Signal Corps, Supply Sgt.
Dr. Irving Langmuir, GE
William Lewis, U. S. Weather Bureau cons.
Kiah Maynard, GE
AERM1 E. R. Millan, USN, aerologist
S/Sgt. H. E. Millett, USAF, crew chief
Landon Morris, Signal Corps, photographer
Raymond L. Neubauer, GE
S/Sgt. J. H. Niven, USAF, radio operator
William N. Perry, ADC, USN, pilot
Capt. John A. Plummer, USAF, pilot
Harold Pontecorvo, Signal Corps, photographer
Alexander Preede, Signal Corps, photographer
T/Sgt. William M. Ratcliffe, USAF, crew chief
Carl R. Remscheid, AG1, USN, aerologist
Lt. Cdr. Daniel F. Rex, USN
Edward Rudzik, AD3, USN, engineer
AERM1 R. F. Rayan, USN, aerologist
Capt. Michael A. Sbarra, USAF, pilot
Dr. Vincent Schaefer, GE
Lt. Cdr. Paul J. Siegel, USN, pilot
Robert Smith-Johannsen, GE
Donald Southard, Signal Corps, photographer
Col. N. C. Spender, USAF, Steering Committee
Samuel Stine, Signal Corps
George Swistak, Signal Corps, photographer
ACMM Adam Szepkowsky, USN, chief
Lt. Cdr. C. E. Tilden, USN
Lt. David D. Tracy, USAF, navigator
Lt. Col. J. Tucker, USAF, Steering Committee Alternate
1st Lt. Henry W. Tutt, USAF, pilot
Dr. Bernard Vonnegut, GE
Howard J. Wells, AGC, USN, aerologist
CAERM G. B. West, USN, aerologist
Roger Wight, Signal Corps (civilian)
Capt. Carl F. Wood, USAF, pilot
Charles Woodman, GE

APPENDIX 3

PROJECT CIRRUS UNNUMBERED FLIGHT TESTS

DATE	LOCATION	OPERATION
11/13/46	Pittsfield	DI seeding
11/23	Schenectady	DI seeding, isolated cumulus
11/29	Schenectady	DI seeding, isolated cumulus
12/20	Schenectady	DI seeding
03/06/47	Schenectady	DE seeding
03/07	Schenectady	DE seeding
03/12	Schenectady	DE seeding
04/07	Schenectady	DE seeding
05/08	Schenectady	DI and SI seeding
08/05	Schenectady	Instrument check
08/06	Schenectady	Instrument check
08/07	Schdy-Westover, MA	Weighing
08/11	Schenectady	Instrument calibration
08/13	West Point	DI and SI seeding
08/15	Schenectady	SI seeding
08/18	Schenectady	Instrument check
08/20	Schenectady	Instrument check
08/21	Schdy-Indian Lake	DI and SI seeding
08/25	Schenectady	DI and SI seeding
08/27	Schenectady	Instrument check
08/28	Schenectady	Instrument check
08/29	Schenectady	Instrument check
09/19	Schenectady	Dry run for hurricane
09/25	Schenectady	Instrument check
09/30	Schenectady	Instrument check
10/07	Schenectady	Tracing SI
10/10	Schdy-Mitchell Field	Hurricane study
10/11	Olmstead, PA-Brookley, AL	Hurricane study
10/12	Brookley-McDill, FL	Hurricane study
10/13	Florida	Hurricane study
10/14	McDill-Olmstead, PA	Hurricane study
10/15	Olmstead-Schdy	Hurricane study
05/31/48	Schenectady	Water drop tests, pumping
06/02	Schenectady	Water drop tests, balloons
10/18	Schenectady	DI seeding
11/30	Schenectady	Stereoscopic camera test
12/14	Schenectady	Info. Flight #3 - balloon soundings
02/07/50	Boston-Schenectady	Observation - tie-in with Ground Operation #75

PROJECT CIRRUS NUMBERED TEST FLIGHTS

FLIGHT NUMBER	DATE	LOCATION	OPERATION
1	09/11/47	Schenectady	DI seeding
2	10/20	New Hampshire	Forest-fire seeding; Oper. Red
3	11/12-13	Olmstead, PA; Brookley, AL	Water seeding
4	11/17	Schenectady	Racing SI
5	12/11/47	Schenectady	SI seeding
6	12/12	Schenectady	DI seeding
7	01/13/48	Schenectady	DI pattern seeding
8	01/14	Schenectady	DI seeding
9	01/22	Schenectady	None
10	01/28	Middletown, PA	Servicing
11	02/02	Schenectady	DI pattern seeding
12	03/09	Schenectady	DI pattern seeding
13	03/31	Sacanadaga Reservoir	Training

FLIGHT NUMBER	DATE	LOCATION	OPERATION
14	04/07	Schenectady	DI seeding
15	04/07	Schenectady	DI pattern seeding
16	04/08	Schenectady	DI seeding
17	04/13	Schenectady	DI pattern seeding
18	04/15	Schenectady	DI seeding
19	04/19	Schenectady	DI seeding
20	04/21	Schenectady	DI seeding
21	04/28	Schenectady	DI pattern seeding
22	04/28	Schenectady	Observation
23	04/29	Cape Cod	DI seeding--MIT project
24	04/30	Schenectady	Seeding
25	05/07	Schenectady	Water seeding
26	05/07	Schenectady	Nothing
27	05/18	Schenectady	DI pattern seeding
28	05/21	Schenectady	DI seeding
29	06/03	Off New Jersey Coast	DI cumulus seeding
30	07/09	Schenectady	Water seeding
31	07/16	Schenectady	DI seeding
32	07/20	Schenectady	DI and water seeding
33	07/26	Lake George	DI seeding
34	07/30	Glens Falls	DI and water seeding
35	08/03	Catskill, NY	DI seeding
36	08/04	Schenectady	Water Seeding
37	08/06	Schenectady	Water seeding
38	08/09	Schenectady	DI and water seeding
39	08/10	Schenectady	DI seeding
40	08/31	Schenectady	DI and water seeding
41	09/01	Schenectady	Water seeding
42	09/16	Schenectady	Calibration
43	09/22	Lake George	Photography
44	10/12	Albuquerque, NM	Water ice and DI seeding
45	10/14	Albuquerque, NM	SI and DI seeding
46	10/13	Schenectady	Water ice and DI seeding
47	10/14	Schenectady	Water ice seeding
48	11/15	Schenectady	DI seeding--pattern
49	11/16	Schenectady	DI seeding--pattern
50	11/17	East of Albany	DI seeding--pattern
51	11/23	Schenectady	DI pattern seeding
52	11/24	Schdy and Amsterdam, NY	DI pattern seeding
53	11/24	Schdy and Rome, NY	DI pattern seeding
54	12/01/48	Schdy-NW of Albany	DI pattern seeding
55	12/08	S of Utica	DI seeding
56	12/09	N of Schenectady	DI seeding
57	12/21	E of Albany	SI & DI seeding; pattern
58	12/22	Albany & East	DI seeding; pattern
59	01/14/49	W of Coxsackie	DI seeding; pattern
60	02/04	Puerto Rico	Survey
61	02/05	Puerto Rico	Survey & water seeding
62	02/05	Puerto Rico	Water seeding
63	02/06	Puerto Rico	Survey
64	02/08	Puerto Rico	Water seeding
65	02/08	Puerto Rico	Survey
66	02/10	Puerto Rico	Survey
67	02/11	Puerto Rico	Survey
68	02/11	Puerto Rico	Survey
69	02/12	Puerto Rico	Survey
70	02/12	Puerto Rico	Survey
71	03/03	S of Lake Ontario	DI & SI seeding; pattern
72	03/04	Sprakers, NY	Temperature soundings
73	03/10	Albany	SI seeding; pattern
74	03/15	W of Syracuse	DI seeding
75	03/16	Ft. Dix, NJ & return	Testing vortex thermometer
76	03/17	Schenectady	Temperature soundings
77	03/24	Schdy-Rome-Middletown-Amsterdam	Testing cloud meter; photo
78	03/25	E of Albany	Testing vortex thermometer
79	03/30	Schenectady	DI pattern seeding
80	03/31	Albany vicinity	DI pattern seeding
81	04/07	Schenectady	Testing vortex thermometer
82	04/08	Schenectady	DI seeding

FLIGHT NUMBER	DATE	LOCATION	OPERATION
83	04/18	Schenectady	SI pattern seeding
84	04/22	West Point & return	Testing vortex thermometer
85	04/25	Schenectady	Instrument testing
86	04/28	Rome, NY, & return	Observation
87	05/03	Schenectady	Testing condensation nuclei meter
88	05/05	Schenectady	Instrument testing
89	05/05	Ashokan Reservoir	DI seeding
90	05/09	Schenectady	Instrument testing
91	05/10	Schenectady	Instrument testing
92	05/11	Little Falls & Rome	Instrument testing
93	05/16	Schenectady	Instrument testing
94	05/18	Schenectady	Instrument testing
95	05/24	Schdy-Rome & return	Testing condensation nuclei counter
96	05/24	Schenectady	Instrument check
97	05/27	Schenectady	Testing vortex thermometer
98	06/09	Schenectady	Testing vortex thermometer, high altitude
99	06/17	Ballston Spa	Salt water seeding
100	06/22	Winchester, VT	DI seeding
101	06/29/49	Schenectady	Instrument test
102	07/06	Schenectady	Instrument test
103	07/13	Albuquerque, NM	DI seeding
104	07/14	Albuquerque, NM	DI, liquid CO_2 & water seeding
105	07/15	Albuquerque, NM	DI & liquid CO_2 seeding
106	07/16	Albuquerque, NM	DI seeding
107	07/18	Albuquerque, NM	DI & SI seeding
108	07/19	Albuquerque, NM	DI seeding
109	07/20	Albuquerque, NM	SI ground & DI air seeding
110	07/21	Albuquerque, NM	SI ground & DI air seeding
111	07/22	Albuquerque, NM	SI ground & DI air seeding
112	07/23	Albuquerque, NM	SI ground & DI air seeding
113	08/24	Schoharie Valley	Observing ground seeding
114	09/01	Schoharie Valley	Observing ground seeding
115	09/02	Schoharie Valley	Observing ground seeding
116	09/06	Schoharie Valley	Observing ground seeding
117	09/20	Schoharie Valley	Observing ground seeding--tie-in Ground Operation #13
118	09/23	Schenectady	Testing vortex thermometer
119	09/26	Schenectady	Testing vortex thermometer
120	09/27	Schenectady	Testing vortex thermometer--tie-in Ground Operation #16
121	09/28	E of Schenectady	DI seeding; Ground Operation #17
122	10/12	Schenectady	Temperature sounding; Ground Operation #24-25
123	10/13	Schenectady	Instrument testing; Ground Operation #26
124	10/18	Schenectady	Observation
125	10/17	Rome	Temperature soundings; Ground Operation #34
126	10/24	Albany	Observation
127	11/01	Schenectady	Temperature soundings; Ground Operation #34
128	11/10	Schenectady	Observation; GO-39
129	11/16	---	GO-41
130	11/17	---	GO-42
131	11/16	Schenectady	Instrument test; GO-41
132	11/30	Schenectady	Instrument test; GO-46
133	11/30	Schdy-Indianapolis	Instrument test & weather observation
134	12/01	Indianapolis-Schdy	Instrument test; GO-47-48
135	12/13-14	Schenectady	Calibrating vortex thermometer; GO-53-54
136	12/15	Schenectady	Snow replicas; vortex thermometer; GO-55
137	12/16	Cape Cod	DI seeding; joint with MIT
138	01/04/50	Mt. Washington	SI detection; GO-63
139	01/20	Schdy-Mt. Washington	Instrument check; DI seeding
140	01/30	Schenectady	Snow replicas; GO-71
141	01/30	Schenectady	Calibrating vortex thermometer;GO-71
142	02/03	Schenectady	DI clear-air seeding

FLIGHT NUMBER	DATE	LOCATION	OPERATION
143	02/06	Schenectady	Snow replicas; vortex thermometer
144	02/10	Schenectady	Photos; snow replicas
145	02/20	Schenectady	Clear-air seeding
146	02/28	Schenectady	DI seeding; snow replicas
147	02/28	Schenectady	DI seeding; snow replicas
148	03/03	Schenectady	Attempted vapor trails
149	03/17	Schenectady	Instrument calibration
150	03/20	Schenectady	Snow replicas
151	03/21/50	Schdy-Dayton, Ohio	Weather reconnaissance
152	03/22	Dayton-Schenectady	Weather reconnaissance
153	04/10	Schenectady	Snow replicas
154	04/12	Schdy-Amsterdam	SI seeding; GO-83
155	04/18	Schenectady	Observation
156	04/19	Schenectady	SI seeding
157	04/25-26	Schdy-Boston-Bangor-Massena-Rochester-Schdy	SI seeding
158	05/08	Mt. Washington	SI seeding
159	05/23	N of Schenectady	DI clear-air seeding
160	06/06	E Troy & Albany	DI seeding
161	06/23	Albuquerque, NM	DI cumulus seeding
162	06/26	Albuquerque, NM	DI cumulus seeding
163	06/27	Albuquerque, NM	DI cumulus seeding
164	06/27	Albuquerque, NM	DI cumulus seeding
165	06/28	Albuquerque, NM	DI cumulus seeding
166	06/29	Albuquerque, NM	DI cumulus seeding
167	06/30	Albuquerque, NM	DI cumulus seeding
168	07/01	Albuquerque, NM	DI cumulus seeding
169	07/05	Albuquerque, NM	Tracing ground SI; DI seeding
170	07/06	Albuquerque, NM	Tracing ground SI; DI seeding
171	07/07	Albuquerque, NM	DI seeding
172	07/08	Albuquerque, NM	DI & SI seeding
173	07/11	Albuquerque, NM-Burbank, CA	Gathering weather data
174	07/12	Burbank-Gt. Falls, Ont.	Gathering weather data
175	07/13	Gt. Falls-Schdy	Gathering weather data
176	10/26	Mt. Washington	DI seeding (joint)
177	05/15/51	Mt. Washington	SI seeding (joint)
178	04/08	Schenectady	SI & DI seeding
179	04/24	Schenectady	Observation
180	05/09	Schenectady	DI, liquid CO_2 & SI seeding
181	05/15	Schenectady	DI & SI seeding

APPENDIX 4

PROJECT CIRRUS GROUND OPERATIONS

NUMBER	DATE	LOCATION	OPERATION
1	03/08/49	Schdy Co. Airport	Cloud photography (still)
2	03/23	Schdy Co. Airport	Cloud photography (still)
3	04/06	Schdy Co. Airport	Cloud photography (still)
4	06/06	Schdy Co. Airport	Cloud photography (still)
5	07/02	Schdy Co. Airport	Time lapse movies
6	07/24-29	Albuquerque, NM	
7	08/23	Schoharie Valley	SI seeding
8	08/25	Schoharie Valley	SI seeding
9	08/30	Schdy Airport	SI seeding
10	08/31	Schoharie Valley	SI seeding
11	09/07	Schoharie Valley	SI seeding
12	09/08	Schoharie Valley	SI seeding
13	09/20	Schoharie Valley	SI seeding--tie-in Flight #117
14	09/21	Schoharie Valley	SI seeding
15	09/22	Schoharie Valley	SI seeding
16	09/27	Schoharie Valley	SI seeding--Flight #120
17	09/28	Schoharie Valley	SI seeding--Flight #121
18	09/29	Schoharie Valley	SI seeding
19	10/04	Schoharie Valley	SI seeding
20	10/05	Schoharie Valley	SI seeding
21	10/05	Schdy Airport	Time lapse movies
22	10/06	Schoharie Valley	SI seeding
23	10/11	Schoharie Valley	SI seeding
24	10/12	Schoharie Valley	SI seeding--Flight #122
25	10/12	Schdy Airport	Time lapse movies
26	10/13	Schoharie Valley	SI seeding--Flight #123
27	10/18	Schoharie Valley	SI seeding--Flight #124
28	10/19	Schoharie Valley	SI seeding
29	10/20	Schdy Airport	Time lapse movies
30	10/20	Schoharie Valley	SI seeding
31	10/25	Schoharie Valley	SI seeding
32	10/26	Schoharie Valley	SI seeding
33	10/27	Schoharie Valley	SI seeding--Flight #127
34	11/01	Schoharie Valley	SI seeding
35	11/02	Schoharie Valley	SI seeding
36	11/03	Schoharie Valley	SI seeding
37	11/08	Schoharie Valley	SI seeding
38	11/09	Schoharie Valley	SI seeding
39	11/10	Schoharie Valley	SI seeding--Flight #128
40	11/15	Schoharie Valley	SI seeding
41	11/16	Schoharie Valley	SI seeding--Flight 129, 131
42	11/17	Schoharie Valley	SI seeding--Flight #130
43	11/22	Schoharie Valley	SI seeding
44	11/23	Schoharie Valley	SI seeding
45	11/29	Schoharie Valley	SI seeding
46	11/30	Schoharie Valley	SI seeding--Flight #132, 133
47	12/01	Schoharie Valley	SI seeding--Flight #134
48	12/01	Schdy Airport	Time lapse movies
49	12/02	Schdy Airport	Time lapse movies
50	12/06	Schoharie Valley	SI seeding
51	12/07/49	Schoharie Valley	SI seeding
52	12/08	Schoharie Valley	SI seeding
53	12/13	Schoharie Valley	SI seeding--Flight #135
54	12/14	Schoharie Valley	SI seeding--Flight #135
55	12/15	Schoharie Valley	SI seeding--Flight #136
56	12/20	Schoharie Valley	SI seeding
57	12/21	Schoharie Valley	SI seeding
58	12/22	Schoharie Valley	SI seeding
59	12/27	Schoharie Valley	SI seeding
60	12/28	Schoharie Valley	SI seeding
61	12/29	Schoharie Valley	SI seeding
62	01/03/50	Schoharie Valley	SI seeding
63	01/04	Schoharie Valley	SI seeding--Flight #138

NUMBER	DATE	LOCATION	OPERATION
64	01/05	Schoharie Valley	SI seeding
65	01/10	Schoharie Valley	SI seeding
66	01/11	Schoharie Valley	SI seeding
67	01/12	Schoharie Valley	SI seeding
68	01/16	Schdy Airport	Time lapse movies
69	01/25	Schoharie Valley	SI seeding
70	01/26	Schoharie Valley	SI seeding
71	01/30	Schdy Airport	Still photos; Flight #140,141
72	01/31	Schoharie Valley	SI seeding
73	02/01	Schoharie Valley	SI seeding
74	02/02	Schoharie Valley	SI seeding
75	02/07	Schoharie Valley	SI seeding--Flight unnumbered
76	02/08	Schoharie Valley	SI seeding
77	02/09	Schoharie Valley	SI seeding
78	02/14	Schoharie Valley	SI seeding
79	02/16	Schoharie Valley	SI seeding
80	02/21	Schoharie Valley	SI seeding
81	03/07	Schdy Airport	Time lapse movies
82	---	---	---
83	04/12	Schdy Airport	Time lapse movies; Flight #154
84	04/24	Schdy Airport	Still photos

APPENDIX 5

PROJECT CIRRUS REPORTS

Note: These reports were prepared by members of the Project Cirrus staff and were widely distributed. Most of them were subsequently published as papers in scientific journals.

1. "Meteorological Research"

   I. General Summary of Cloud Studies Project
      Vincent J. Schaefer

   II. Summary of Results Thus Far Obtained in Artificial Nucleation of Clouds
      Irving Langmuir

   III. Techniques for Seeding Clouds with Ice Nuclei
      Vincent J. Schaefer

   IV. Instrumentation Developments for the Cloud Study Project
      Raymond E. Falconer

   V. Nucleation of Ice Formation by Silver Iodide Particles
      Bernard Vonnegut

   VI. Typical Data Obtained from Photographs of a Seeded Area
      Raymond E. Falconer

   VII. Proposed Flight Plans for Cloud Studies
      Irving Langmuir, Vincent J. Schaefer, and Bernard Vonnegut

2. "Meteorological Research", Supplement to Section V, General Electric Progress Report on Meteorological Research. This portion of the report, by Bernard Vonnegut, dealing with various techniques for generating silver iodide smokes, was originally given the classification of Confidential but was later declassified.

3. Occasional Report No. 1: "The Production of Rain by a Chain Reaction in Cumulus Clouds at Temperatures Above Freezing", Irving Langmuir, W-36-039-SC-32427, 15 April 1948.

4. Occasional Report No. 2: "A New Plane Model Cloud Meter", R. E. Falconer, V. J. Schaefer, W-36-039-SC-32427, 15 May 1948.

5. Occasional Report No. 3: "Some Experiments on the Freezing of Water", Robert Smith-Johannsen, W-36-039-SC-32427, 1 June 1948.

6. Occasional Report No. 4: "Smoke from Smelting Operations as a Possible Source of Silver Iodide Nuclei", Raymond E. Falconer, Bernard Vonnegut, W-36-039-SC-32427, 15 July 1948.

7. 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

   Bernard Vonnegut, W-36-039-SC-32427, 15 September 1948.

8. Occasional Report No. 6: "Variation with Temperature of the Nucleation Rate of Supercooled Liquid Tin and Water Drops", Bernard Vonnegut, W-36-039-SC-32427, 15 October 1948.

9. Occasional Report No. 7: "Observations on the Behavior of Water Drops at Terminal Velocity in Air", Duncan C. Blanchard, W-36-039-SC-32427, 1 November 1948.

10. Occasional Report No. 8: "A Method for Obtaining a Continuous Record of the Type of Clouds in the Sky During the Day", Raymond E. Falconer, W-36-039-SC-32427, 1 March 1949, RL-145.

11. Occasional Report No. 9: "The Detection of Ice Nuclei in the Free Atmosphere", Vincent J. Schaefer, W-39-039-32427, 1 February 1949, RL-138.

12. Occasional Report No. 10: "Studies of the Effects Produced by Dry Ice Seeding of Stratus Clouds", Irving Langmuir, W-39-039-32427, 1 February 1949.

13. Occasional Report No. 11: "The Possibility of Modifying Lightning Storms in the Northern Rockies", Vincent J. Schaefer, W-36-039-SC-38141, 1 February 1949, RL-134.

14. Occasional Report No. 12: "Report on Cloud Studies in Puerto Rico", Vincent J. Schaefer, W-36-039-SC-38141, 1 April 1949, RL-190.

15. Occasional Report No. 13: "Silver Iodide Smoke, Bernard Vonnegut, W-36-039-SC-38141, 1 July 1949, RL-227.

16. Occasional Report No. 14: "Vortex Thermometer for Measuring True Air Temperatures and True Air Speeds in Flight", Bernard Vonnegut, W-36-039-SC-38141, 1 September 1949, RL-247.

17. Occasional Report No. 15: "The Distribution of Raindrops in Natural Rain", Duncan C. Blanchard, W-36-039-SC-38141, 15 November 1949, RL-283.

18. Occasional Report No. 16: "The Use of Sooted Screens for Determining Raindrop Size and Distribution", Duncan C. Blanchard, W-36-039-SC-38141, 15 November 1949, RL-284.

19. Occasional Report No. 17: "Experiments with Water Drops and the Interaction Between Them at Terminal Velocity in Air", Duncan C. Blanchard, W-36-039-SC-38141, 15 December 1949, RL-285.

20. Occasional Report No. 18: "Some Correlations Between Variations in the Atmospheric Potential Gradient at Schenectady and Certain Meteorological Phenomena", Raymond E. Falconer, W-36-039-SC-38141, 1 December 1949, RL-287.

21. Occasional Report No. 19: "Continuous Recording Condensation Nuclei Meter", Bernard Vonnegut, W-36-039-SC-38141, 1 January 1950, RL-300.

22. Occasional Report No. 20: "The Occurrence of Ice Crystal Nuclei in the Free Atmosphere", Vincent J. Schaefer, W-36-039-SC-38141, 15 January 1950, RL-308.

23. Occasional Report No. 21: "Progress in Cloud Modification by Project Cirrus, Irving Langmuir, W-36-039-SC-38141, 15 April 1950, RL-357.

24. Occasional Report No. 22: "Cause and Effect Versus Probability in Shower Production", Irving Langmuir, W-36-039-SC-38141, 15 July 1950, RL-366.

25. Occasional Report No. 23: "A Gamma Pattern Seeding of Stratus Clouds, Flight 52 and a Racetrack Pattern Seeding of Stratus Clouds, Flight 53, Charles A. Woodman and Irving Langmuir, W-36-039-SC-38141, 1 June 1950, RL-363.

26. Occasional Report No. 24: "Results of the Seeding of Cumulus Clouds in New Mexico", Irving Langmuir, W-36-039-SC-38141, 1 June 1950, RL-364.

27. Occasional Report No. 25: "Study of Tropical Clouds", Irving Langmuir, W-36-039-SC-38141, 1 July 1950, RL-365.

28. Occasional Report No. 26: "Periodic Fluctuations in the Ohio Basin Moisture Balance, LTJG W. E. Hubert, H. J. Wells, AGC, U. S. Navy, W-36-039-SC-38141, 15 January 1951, RL-485.

29. Occasional Report No. 27: "Seven-Day Periodicity in Upper Air Temperatures Induced by Localized Silver-Iodide Seeding", LTJG W. E. Hubert and H. J. Wells, AGC, U. S. Navy, W-36-039-SC-38141, 15 January 1951, RL-486.

30. Occasional Report No. 28: "Concentration of Ice Crystal Nuclei Under Various Weather Conditions", LTJG W. E. Hubert and H. J. Wells, AGC, U. S. Navy, W-36-039-SC-38141, 15 June 1951, RL-541.

31. Occasional Report No. 29: "Detection and Measurement of Aerosol Particles by the Use of an Electrically Heated Filament", Bernard Vonnegut and Raymond Neubauer, W-36-039-SC-38141, 1 September 1951, RL-555.

32. Occasional Report No. 30: A Vortex Whistle", Bernard Vonnegut, DA-36-039-SC-15345, 1 November 1951, RL-599.

33. Occasional Report No. 31: "Spray Nozzle Type of Silver Iodide Smoke Generator for Airplane Use", Bernard Vonnegut and Kiah Maynard, DA-36-039-SC-15345, 15 February 1952, RL-635.

34. Occasional Report No. 32: "A Continuous Cloud Chamber for Studying Small Particles in the Atmosphere", Vincent J. Schaefer, DA-36-039-SC-15345, 1 March 1952, RL-654.

35. Occasional Report No. 33: "The Formation of Ice Crystals in Ordinary and Nuclei-Free Air", Vincent J. Schaefer, DA-36-039-SC-15345, 1 March 1952, RL-655.

36. Occasional Report No. 34: "Thin Films of Supersaturated Solutions for Detecting, Counting, and Identifying Very Small Crystalline Particles", Bernard Vonnegut, DA-36-039-SC-15345, 15 April 1952, RL-677.

37. Occasional Report No. 35: "The Concentration of Ice Nuclei at the Summit of Mt. Washington", Vincent J. Schaefer, DA-36-039-SC-15345, 1 August 1952, RL-722.

38. Occasional Reports Nos. 36 and 37: "Production of Monodisperse Liquid Particles by Electrical Atomization", Bernard Vonnegut and Raymond L. Neubauer; "Multiple-Stage Dilution of Aerosols by Use of Aspirators", Bernard Vonnegut, Myer Geller, and Kiah Maynard, DA-36-039-SC-15345, 1 October 1952, RL-747.

39. Occasional Reports Nos. 38 and 39: "Counting Sodium-Containing Particles in the Atmosphere by Their Spectral Emission in a Hydrogen Flame", Bernard Vonnegut and Raymond L. Neubauer; "Effect of Halogens on the Production of Condensation Nuclei by a Heated Platinum Wire", Bernard Vonnegut, DA-36-039-SC-15345, 1 October 1952, RL-748.

40. Occasional Report No. 40: "Variations in the Concentration of Condensation Nuclei in the Atmosphere", Raymond E. Falconer, Kiah Maynard, and B. Vonnegut, DA-36-039-SC-15345, 15 April 1953, RL-825.

INDEX