ONAL HURRICANE RESEARCH PROJECT

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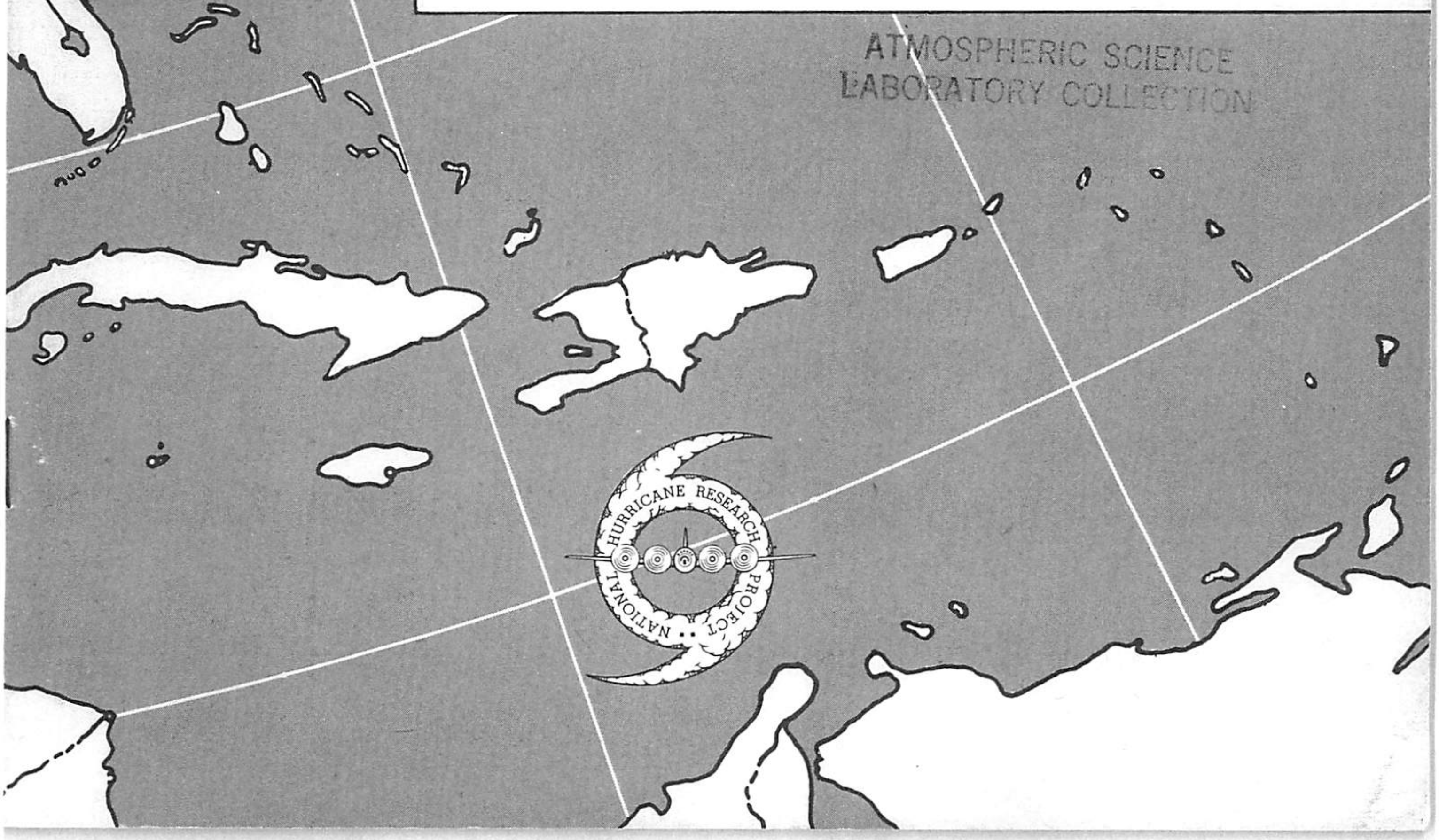

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NATIONAL HURRICANE RESEARCH PROJECT

REPORT NO. 16

Modification of Hurricanes Through Cloud Seeding

by

R. R. Braham, Jr. and E. A. Neil
Department of Meteorology, University of Chicago

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MODIFICATION OF HURRICANES THROUGH CLOUD SEEDING

R. R. Braham and E. A. Neil

EXPLORATORY EXPERIMENTS VERSUS SYSTEMATIC STUDIES

In considering cloud seeding experiments within hurricanes one must, from the outset, distinguish between what the authors choose to call "exploratory experiments" and "systematic studies." Exploratory experiments are those carried out in order to "see what will happen." When one is concerned about a problem with very little known, exploratory studies may help establish a level of "tentative knowledge" upon which one can base a program of more penetrating inquiry. The value of exploratory experiments depends primarily upon the ingenuity of the experimenter and the flexibility of the experiment.

On the other hand, after a general knowledge of the subject is at hand, it inevitably becomes necessary to test the validity of early concepts to separate cause and effect from coincidence. At this point it becomes necessary to undertake a group of systematic studies. The success of such studies also depends upon the ingenuity of the designer of the experiment, but they differ significantly from the exploratory experiments in that they are much less flexible and, in general, do not permit change in design from one experiment to the next.

It is well to bear in mind the role of both types of experiments in the matter of seeding clouds to increase precipitation over restricted areas. The early experiments of Langmuir and Schaefer and of Bowen and collaborators, fall into the first category. These experiments very quickly pointed out areas of fruitful investigation. But it has only been after long and carefully designed experimentation that meteorologists are able to state the degree of effect which can be attained by cloud seeding - and even this is possible only for relatively few cloud types and meteorological conditions.

The early experiments of Langmuir and Schaefer were successful because they were based upon principles of physics and chemistry which were well known and were demonstrable in the laboratory. The experiments which were most successful were those which involved the nucleation of subcooled stratus clouds with dry ice or silver iodide smokes. The physics of this process was reasonably well understood before the experiments were undertaken. The experiments which thus far have not permitted evaluation on a sound basis are those involving energy transformations within clouds, a matter very poorly understood.

In the case of seeding hurricanes one is interested, not in producing precipitation as an end product (the nucleation problem which is understood and demonstrable), but in so modifying the storm as to reduce its intensity or to cause it to move in a direction away from habitation. In other words, the desired effect is to produce profound changes in the energy or energy distribution within the storm.

It appears to the writers at this time that the hurricane is so poorly described and that there is so little known about the thermodynamic and hydrodynamic processes which govern its growth and decay, it is not possible to set down a rational argument linking any known effect of seeding to predicted changes in the behavior of the storm.

This must inevitably mean that initial seeding experiments in hurricanes must be of an exploratory nature with the view that it is unlikely that any definitive conclusions will come from them, but with the hope that they will reveal certain aspects of the storm makeup which then may be studied at length. In this frame of reference, seeding experiments in hurricanes may prove to be of great value; but the investigator must be prepared to find nothing.

ANALYSIS OF CLOUD SEEDING EXPERIMENTS

The natural variability of clouds, the fact that two seemingly identical clouds at time t_1 may be totally different at time t_2, or the fact that rain falls from one cloud and not from another which is outwardly very similar, makes assessment of most cloud seeding experiments very difficult. In the case of seeding subcooled stratus the effect is so striking and the natural variability so slight that only a few experiments were necessary to establish as fact the modification of such a cloud. However, assessment of the degree to which stratus can be modified has been more difficult.

In the case of cumulus clouds, the natural variability is so large that it has required over one hundred experiments to permit the conclusion that it is possible to cause effects through seeding. As yet, however, it is not possible to do more than guess at the magnitude of these effects. Several hundred experiments will be required for this. This is true in spite of the fact that the knowledge of the ways in which the seeding should produce an effect is at hand.

Although considerable effort has been made by the Weather Bureau and New York University researchers (ACN Projects), at this time there is no acceptable evidence that one can modify large cloud systems and/or the weather pattern which they accompany. This does not mean that such effects are not possible, it only reflects that the natural variability in these storms is so large, and our techniques so crude, we have not been able to find the effects if they exist.

To our knowledge, there has been only one attempt at hurricane modification through cloud seeding. In 1947 a group from Project Cirrus flew into a hurricane located off the coast of South Carolina. Into this storm they dispensed about 180 pounds of dry ice. The subsequent movement of the storm has been cited as evidence that the seeding had a marked effect. This, of course, is not acceptable inasmuch as previous and subsequent storms have undergone equally erratic changes in path without the help of seeding.

To put hurricane seeding attempts on a firm scientific basis, it will be necessary to select one or more parameters characterizing (describing) the storm, which can be used as the test statistic. The experiment then consists of comparing this test statistic in treated and untreated hurricanes, in order to determine what, if any, changes are brought about by the seeding. It is very important that a good and sufficient means be available for determining the magnitude of this test statistic. The greater the margin of uncertainty in determining the test statistic, the poorer the power of test. In view of the great internal variation in the clouds, precipitation, etc., from place to place within the hurricane, it seems as though the test statistic will have to involve some aspect of the storm as a whole; e.g., some feature of the energy or energy distribution, or perhaps the motion of the storm. Another alternative might be to consider some feature of the upper outflow or low level inflow, averaged over the entire storm. Unfortunately, the parameters easiest to measure at one point are likely to differ most widely from point to point within the storm and therefore present the greatest difficulties in an attempt to obtain a single "average" applicable for the storm. Conversely, the parameters likely to be most useful for test purposes, i.e., parameters which characterize the entire storm as a single unit, are the most difficult to measure with present techniques. (A possible exception is the wind pattern.)

Whatever the details of any hurricane seeding trials carried out under the National Hurricane Research Project, it is considered to be of greatest importance that these tests be very carefully planned with the help of a competent statistician knowledgeable in the design of meteorological experiments.

TECHNOLOGY OF CLOUD SEEDING

The technology of cloud seeding has developed to the point where it would be impossible to cover it in this report - nor is such a discussion in order here. Instead, an effort will be made to summarize some of the principles involved and some of the facts and figures pertaining to present techniques for the help of those planning possible seeding trials in hurricanes.

Cloud seeding hypotheses. - All modern seeding attempts are aimed at artificially modifying the liquid phase of the cloud in such a way as to permit natural processes to proceed toward a more desirable end product. Precipitation inducement trials are aimed at broadening the cloud particle distribution in order to increase the likelihood of precipitation. This might be done by artificially introducing ice-forming particles in subcooled clouds wherever there is a natural shortage of such particles, or it might be done by introducing particles which will aid in the formation of droplets large enough to initiate rain through coalescence alone. From the standpoint of the ratio of theoretical return to initial effort, the introduction of ice-forming particles (assuming that they are needed in nature) is by all odds the most attractive of these two possibilities and most effort has gone into this approach. Interestingly enough, however, the seeding trials that have revealed the most statistically significant effects are ones involving the second approach.

Attempts to create widespread changes in storm conditions, to reduce hail or lightning, etc., are essentially aimed at changing the energy of the system through the addition of latent heat of sublimation. In these tests the precipitation is viewed as a secondary consideration, although some people hope that it might be possible to simultaneously accomplish both ends.

In the matter of seeding hurricanes, it appears that the only consideration is to produce changes in the energy balance of the storm which in turn will cause desirable changes in the storm as a whole. This suggests that these trials should try to attain the maximum release of latent heat of sublimation at points within the storm where it can be expected to produce the maximum desired effect. This means, obviously, that the only interest is in ice-forming nuclei, released in subcooled clouds having a shortage of such nuclei. There are several ways in which this might be accomplished.

Dry ice seeding theory. - The physics of dry ice seeding are thought to be well understood, although many of the steps in the process have not been subjected to rigid laboratory scrutiny.

The essence of this process is that the latent heat of evaporation of the CO_2 cools small parcels of air. This cooling causes condensation of water vapor upon the many natural condensation nuclei present. In some parts of the cooled parcels of air, the temperature drops below the homogeneous nucleation temperature for water drops with the result that the many small droplets freeze spontaneously. These small spheres of ice thus are presumed to grow by sublimation into small ice nuclei.

It is possible to make reasonable estimates of the number of nuclei which should be produced by such a process as outlined above. In doing this, we are aided by the results of certain laboratory experiments and theoretical deductions. From these independent sources we know:

1. The spontaneous nucleation temperature for small water droplets is in the neighborhood of -40°C.

2. When a small pellet of CO_2 is dropped into a cold box, the cloud of small droplets produced initially scatters in the blue and hence must be approximately 0.5 μ in diameter.

Consider the result of evaporating one gram of dry ice in air saturated at -10°C. and 450 mb. The saturation mixing ratio at -10°C. is 4 gm./kg. and at -40°C. is 0.25 gm./kg. The L_f of CO_2 at -40°C. is about 80 cal./gm. The c_p for dry air is 0.24 cal.gm.$^{-1}$ deg.$^{-1}$, for water vapor, 44 cal.gm.$^{-1}$ deg.$^{-1}$ and L_s of water at -40°C. is 678 cal.gm.$^{-1}$.

Under these conditions about 7.5 gm. of air will be cooled to -40°C. and about 2.8×10^{-2} gm. H_2O will be converted to ice crystals. This will produce about 2×10^{12} crystals of the size indicated by point (2) above.

The calculations assume that the process is 100 percent efficient, which is highly improbable. These values are about three orders of magnitude smaller than those given by Langmuir, et al. [1] who apparently used slightly different assumptions or initial conditions.

It is important to note that only CO_2 evaporation in the subcooled regions of the cloud can be effective in this process. Theoretically one could produce ice nuclei in the cooled wake of CO_2 pellets at the above freezing temperature, but these could not grow into ice crystals and could play no role in the physics of the cloud.

Number and distribution of nuclei produced. - In dry ice seeding in field tests, crushed CO_2 is released from airplanes into subcooled portions of a cloud or cloud system. The pellets of CO_2 have appreciable falling speeds (depending on size) and therefore fall as they evaporate. Since it is the released latent heat of evaporation of the CO_2 which is responsible for the ice crystal formation, it is of importance to examine the relationship between size of CO_2 pellets, their falling speed, and their fractional evaporation in falling through a given height interval.

Both Langmuir [1] and Squires and Smith [2] have considered the problem of pellet size versus falling speed. With this basic information it is possible to plot a graph of distance a pellet will fall in evaporating from any initial size to any other final size. From this one can compute the fractional evaporation of dry ice pellets as they fall through any given height interval. Table 1 gives the percent of pellet evaporated as a function of falling distance and initial pellet size. This chart was prepared from data which assume a pressure of 800 mb. and a temperature of -10°C.

It is to be noted that pellets smaller than 1 mm. diameter are evaporated in the first 500 feet of fall. This implies a rapid evaporation and suggests that seeding materials should be screened to exclude such small sizes inasmuch as they will tend to evaporate inside the airplane and dispensing equipment before they can be useful.

On the other hand, pellets larger than 7 or 8 mm. diameter fall so far before evaporating that it is unlikely that they could be used effectively; i.e., in most operations the seeding will probably be limited to a height of 5000 to 7000 feet above the freezing level. Seeding with pellets which fall through the freezing level before evaporating represents a needless waste of airplane facilities.

The space distribution of ice crystals immediately following seeding depends primarily on the size and number of ice pellets released and the slipstream characteristics of the airplane used for the seeding. Further dispersion will depend primarily upon turbulent conditions inside the clouds.

Based upon what we know about airplane-induced turbulence, slipstream effects, etc., it would seem reasonable that the dispensed dry ice might be mechanically spread as a sheet of about 200 feet in width and extending downward as far as the zero isotherm unless the pellets evaporate prior to reaching that level. Further spreading will depend upon turbulent diffusion. This problem can be approached through turbulence theory but in any event the

Table 1. - Percent of dry ice pellet evaporated in falling through various distances

Initial pellet size (cm.)	Distance fallen after release (ft.)										
	500	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
1.0	7%	13%	26%	37%	47%	57%	66%	74%	81%	87%	92%
.9	7	15	29	42	54	62	74	83	89	95	97
.8	10	18	35	51	64	75	85	92	96	99	100
.7	12	24	44	61	76	87	94	98	99+	100	
.6	16	29	54	73	86	95	99	100			
.5	20	38	67	85	95	100					
.4	23	47	78	95	100						
.3	35	62	95	100							
.2	40	96	100								
.1	100	100									

spreading time will be small compared with the life of the hurricane and thus is of secondary interest in hurricane seeding.

Methods of dry ice seeding. - Dry ice seeding methods are relatively easy and straightforward. Pellets of dry ice are released continuously, or in small packets, from an airplane flying through or above the clouds to be seeded. It is advisable to pre-crush and sieve the dry ice to avoid most of the "fines." These small particles have a tendency to pick up water and freeze the crushed dry ice into one solid mass. The pre-crushed ice is given another crushing at the time of dispersal to break up clumps and insure an even dispersal. The initial pellet size should be governed by the planned height above the freezing level of the dispersal. Table 1 will be useful in determining proper sizes - only under exceptional circumstances would pellets larger than about 1 cm. diameter be advisable.

The only technical problem involved in dispensing dry ice from the Hurricane Project airplanes is one concerning the pressurized cabin. Since almost all of the carrying space of the B-50 is pressurized, it appears that it would be necessary to install remote feeding, crushing, and dispensing equipment. In principle this should not be difficult although there is no readily available equipment which could be used for this purpose. It would probably be necessary to design and fabricate these equipments as a part of the research program.

Silver iodide seeding theory. - The early cold box studies of Vonnegut and Schaefer established the fact that a subcooled cloud of water droplets could be nucleated to the ice state through the introduction of any one of a large number of foreign substances. The degree of effectiveness and the temperature at which the material becomes effective differ, in general, for every substance tried; however, very few substances show effectiveness at temperatures warmer than about -20°C. There is some debate among physical chemists concerning the way in which these substances accomplish the nucleation. The two most likely suggestions seem to be epitaxy (oriented overgrowth) and surface polarization. To date most of the theoretical papers on the subject have considered the process to be one of oriented overgrowth.

Of all the substances tried in the laboratory, silver iodide smoke appears to be the most effective. That is, it appears to produce the most crystals per unit mass and to be able to do this at a temperature warmer than for any other substance (excepting dry ice). It is presumed that the reasons for this are that the internal structure and lattice spacings of silver iodide are very similar to those of water ice. Since, in general, the effectiveness of the materials tried varies with the degree to which the lattice approaches that of water, the overgrowth hypothesis has received considerable support.

Number and distribution of nuclei produced in AgI seeding. - Unlike the action of dry ice pellets, silver iodide nuclei act directly in nucleating the subcooled water droplets to the ice state. According to the theory, at any temperature colder than about -4°C. a small surface of a silver iodide crystal containing some sort of defect is capable of holding water molecules which arrange themselves in the ice lattice. Aided by the forces at the surface of the silver iodide crystal, the water molecules may be held long enough for the ice kernel to grow to a size which is stable and can continue to grow.

The theoretical attack on the problem of the number of effective nuclei produced by AgI seeding has proceeded slowly, largely because it is one of rather involved surface chemistry. However, there has been a great amount of experimental work aimed at establishing these data. These studies have been of two types: (1) studies of the number of nuclei per unit mass of material, and (2) studies of the action of sunlight, burner temperature, temperature, pressure, etc., in reducing the effectiveness of the nuclei.

Studies by Vonnegut [3] show that silver iodide smokes produced in a low temperature flame will produce between 10^{13} and 10^{16} active ice nuclei per gram of silver iodide. These figures have been confirmed by other investigators. Thus silver iodide smokes are capable of producing two to four orders of magnitude more ice particles per unit mass of material than can be produced by dry ice.

It is important to consider the levels of effectiveness of silver iodide smokes as compared with dry ice. Dry ice is theoretically capable of nucleating, and subcooled water cloud values as warm as -1°C. have been cited as the threshold. Silver iodide smoke, on the other hand, has a threshold temperature of about -4°C. and does not reach full activity (10^{13} - 10^{16}/gm.) until temperatures of -10°C. to -20°C. are reached. The degree of activity as a function of the degree of subcooling apparently has not been fully investigated. Table 2 is illustrative of the ranges of values usually found.

As silver iodide particles are usually dispersed from an airplane, the initial distribution in the seeded cloud is as a long, thin trail behind the seeding plane. The particles are much too small to have appreciable falling speeds and they depend upon mechanical turbulence to disperse them through the cloud, after they emerge from the generator on the airplane. Turbulence induced by the airplane is capable of spreading the particles as a horizontal cylinder about 200 to 300 feet in diameter. Further spreading must be due to eddy diffusion.

Deactivation of silver iodide smokes. - It has been established beyond all reasonable doubt that silver iodide particles released into free air may lose their nucleating ability with time. Smokes released in daylight conditions, and in particular those released in bright sunlight, lose their nucleating ability at a rapid rate. The initial experiments on this problem, by Reynolds et al., showed losses at the rate of two orders of magnitude per 30 minutes exposure to sunlight. Similar rates have been measured by other investigators. It has been conjectured that the process is one of photolytic reduction of the silver. At the present time there is no known way of preventing this effect for daytime releases.

Recent experiments in Australia have been pointed toward finding ways around the matter of deactivation. They have found that smokes prepared in a hydrogen flame deactivate faster than those produced in a kerosene flame, presumably because of the higher flame temperature. They have also shown that smokes released at night are subject to little, if any, deactivation (Smith and Heffernan [4]).

Other studies at the Geophysics Research Directorate of Air Force Cambridge Research Center have indicated that silver iodide smokes may also be affected by the absorption of water vapor and other substances in the atmosphere. This point is poorly understood at this time. (Refer to Birstein [5], [6]).

Methods of producing AgI smokes for seeding. - Silver iodide smokes are produced by heating silver iodide in some sort of flame. Because of the very low solubility of AgI in most solvents, it is usually complexed with another substance such as NaI and the mixture burned in a flame. The flame may be of almost any kind. In some cases charcoal or string have been impregnated with the solution and these burned to produce the silver iodide particles.

The most usable generators for cloud seeding involve spraying silver iodide solution into a flame of hydrogen (propane, kerosene, etc.). In the flame the solution is vaporized and burned. The silver iodide, sodium iodide evolves as some sort of a mixed crystal which has nucleating ability. The nature of this crystal is largely unknown although the British group under Mason is currently working in this area. It seems likely that generators of this type can be made much more effective once the chemistry of the smokes is understood.

A second, but little used, method for releasing silver iodide smokes from an airplane is through the use of a charcoal burner. In this device, charcoal is impregnated with silver iodide solution and allowed to dry. The charcoal is then burned in a small vessel within or below the airplane and ice-forming silver iodide particles are evolved. Apparently there are no thorough studies of the effectiveness of this method in the published literature.

A third approach to the silver iodide seeding problem is represented in the impregnated string burner. In this device a string or light rope, which has been impregnated with silver iodide solution, is automatically fed into a flame. The most careful check on this device that has been reported was made by a working group from the Advisory Committee on Weather Control. According to their study, the outputs from the string burner and the coke burner are roughly similar to a single propane flame generator burning about 0.5 gm. of silver iodide in solution per second. Unfortunately it is not possible to make a comparison of the amount of the materials used.

Optimum seeding rates. - The question as to the most effective seeding rate has been the subject of considerable speculation and controversy during the past several years. For the most part, the reason for debate lies in our inadequate knowledge concerning the number of natural ice-forming nuclei, the effectiveness of seeding materials, and the failure to recognize that the most effective ice crystal concentrations are directly related to the objectives of the experiments.

The number of natural ice-forming nuclei in the atmosphere is known to differ widely from time to time and from place to place. It is known that there are many times when there are too few nuclei for effective precipitation from clouds whose tops lie in the 0 to -10°C. temperature range. At other times, measurements show large numbers of nuclei to be active in this same temperature interval. The causes for these variations, the chemical nature of the active substances, and the manner in which they get into the air are largely unknown. Also largely unknown is the degree to which the atmosphere may be "nuclei poor" in the levels above the -10°C. isotherm. In the interval warmer than -10°C., nuclei measurements generally agree with the observed characteristics of clouds. At colder temperatures, cloud studies suggest that there are more active nuclei in the air than can be accounted for by the conventional nuclei measurements.

The field effectiveness of seeding materials has been the subject of several studies in recent years. In general they indicate that fewer ice crystals are produced in the field than one would expect from laboratory and theoretical considerations. The University of Chicago studies in cumulus clouds suggest that the number of ice crystals produced by dry ice seeding is smaller by a factor of ten than would be expected theoretically. No similar studies using AgI have yet been made.

The goal of the seeding experiment is one of the most important factors in seeding considerations. In hurricane studies, it seems very unlikely that the goal will be the augmentation of precipitation, therefore one is not concerned with obtaining an optimum number of ice particles from that point of view. Rather, it seems likely that the goal of hurricane seeding will be to introduce an artificial source of energy at a critical point of the storm's dynamics. The great amount of energy per unit volume in the active part of a hurricane suggests that it would be desirable to make the artificial energy source as large as possible. In other words, it appears advantageous to seed the clouds to the maximum capability of the operation. It is believed that this is the only way to maximize the probability of detecting an effect from the seeding.

Using data from available published reports for the capability of a silver iodide generator and assuming the validity of the theoretical values for dry ice seeding efficiency, we can compare the relative capabilities of the two methods, table 2.

It is obvious from table 2 that the decision concerning the proper seeding material for hurricane research must be based upon some information as to the levels of operation and the natural nuclei count. If it is suspected that the levels of concern are warmer than about -8°C., then dry ice is recommended. If the levels of concern are colder than about -12°C., silver iodide is the best. At intermediate levels the choice must be based primarily upon factors dealing with cost and convenience of installation.

<u>Other seeding materials</u>. - There is no shortage of suggestions of seeding materials. In general only dry ice and silver iodide have shown consistent results and they have been treated in detail above. Of special interest to the Weather Bureau is the possibility of seeding with tank nitrogen. As a special problem, cloud physics personnel were asked to make a series of computations in an effort to predict the performance of nitrogen seeding. These computations were originally reported in abbreviated form and are repeated here in detail.

Table 2. - Relative capabilities of silver iodide and dry ice seeding

Temperature (°C.)	No. ice crystals per gram of material AgI	AgI solution*	CO_2**
- 8	10^{10}	5×10^{8}	10^{12}
-10	10^{12}	5×10^{10}	10^{12}
-12	2×10^{13}	10^{12}	10^{12}
-14	10^{14}	5×10^{12}	10^{12}
-16	4×10^{14}	2×10^{13}	10^{12}
-18	2×10^{15}	10^{14}	10^{12}
-20	6×10^{15}	3×10^{14}	10^{12}

* For logistics purposes it is necessary to consider the mass of the acetone used in addition to the mass of AgI dispensed. An additional allowance should be made for the fuel burned. However this may vary depending upon the type of burner used.

** Based upon theory and University of Chicago field trials.

Nitrogen, in tanked form, might be useful for seeding because of the cooling produced when the material is released. This might be of two forms - evaporational cooling as liquid nitrogen is evaporated, and adiabatic expansion of tank nitrogen gas.

Normal commercial N_2 gas is tanked under 2200 p.s.i. The adiabatic cooling, if 100 percent efficient, would cool the expanding gas to about 65°K. If we could use this heat sink to 100 percent efficiency, it would be about half as efficient as dry ice. There are other problems such as freeze-up, but these are probably no worse than similar problems for dry ice.

Liquid nitrogen has a temperature of -196°C. and a latent heat of 47.6 cal./gm. Considering the latent heat and sensible heat, liquid nitrogen is just about equal to dry ice, pound for pound, in its cooling power. For example, from dry ice we can realize an effect of 96 cal./gm. and for liquid nitrogen, 85 cal./gm.

There are several dispersal problems in connection with liquid nitrogen. One is the hypsometric effect. Because of the change of boiling point with pressure, one-seventh of the liquid must be evaporated in adjusting the temperature of the liquid to the pressure as the airplane flies from 1000 to 500 mb. This means a loss of material and, additionally, a vent problem to prevent the tank from exploding at high altitudes.

Chicago producers of nitrogen state that it would be fairly easy to engineer a dispensing system for releasing liquid nitrogen spray. The biggest drawback to liquid nitrogen is the cost and the heavy containers. Nitrogen liquid is about five times as expensive as dry ice in the Chicago area. The container used commercially for handling liquid nitrogen is almost as heavy as the nitrogen itself. Because of these factors, it is not recommended as the seeding agent to be used in hurricane flights.

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