NASA SP-212

PROGRESS OF NASA RESEARCH ON WARM FOG PROPERTIES AND MODIFICATION CONCEPTS

A symposium held at
NASA HEADQUARTERS
WASHINGTON, D.C.
February 6, 1969

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FOREWORD

Warm fog frequently has been the cause of aircraft takeoff and landing delays and flight cancellations. The delays and cancellations are costly to the aircraft operators and passengers alike. The NASA initiated a research program in 1962 to obtain further knowledge on the physical and electrical characteristics of warm fog. The research was carried out by the Cornell Aeronautical Laboratory under NASA contract. The primary aim of the research was to accumulate a sound understanding of warm fog characteristics and the related atmospheric environment. The hope was that a sound understanding would shed light on a practical way to modify warm fog for improved visibility and subsequent increased airport utilization.

During these past several years, theoretical analyses and laboratory experiments were used to explore various warm fog modification concepts and catalogue the noteworthy aspects of each concept. The results of these earlier Cornell Aeronautical Laboratory research efforts have been released in NASA Contractor Reports CR-72, CR-368, CR-675 and CR-1071. Based on these earlier results, the seeding concept using sized hygroscopic nuclei was developed and tested in fog chamber experiments. The small amounts of the seeding material needed to significantly modify the fog and greatly increase visibility in these experiments were encouraging. This prompted field tests to assess the effectiveness of the technique on natural fogs in the airport environment.

This Symposium was in the nature of a progress report, recognizing that there is work yet to be done before warm fog will no longer be an obstacle to routine aircraft operation. One objective of this Symposium was to provide results of recent warm fog seeding field experiments at the Chemung County Airport, Elmira, New York, and laboratory experiments at the Cornell Aeronautical Laboratory facility to evaluate several seeding materials. Another objective was to provide a forum for others to present and discuss their fog research programs and for aircraft users to define the operational needs of a practical fog modification system for airports. We feel the results are significant and should be made available, especially to those contemplating field seeding programs. Hopefully the information will permit determination of the promise and limitations of this seeding concept according to the user's needs.

The NASA wishes to thank the authors who presented the technical papers and those who participated in the General Discussion period, thereby adding to the information source and objectives of the Symposium.

William A. McGowan
Chairman
NASA Headquarters

CONTENTS

Page

I. A REVIEW OF PROJECT FOG DROPS

By
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Project Fog Drops is now in its Sixth Contract Year. Because of time limitations this review of project activities must be limited to a few of the high points of the program.

The purpose of the project has been two-fold: to investigate basic warm fog properties and dynamics, and to evaluate suggested methods for suppression of warm fog.

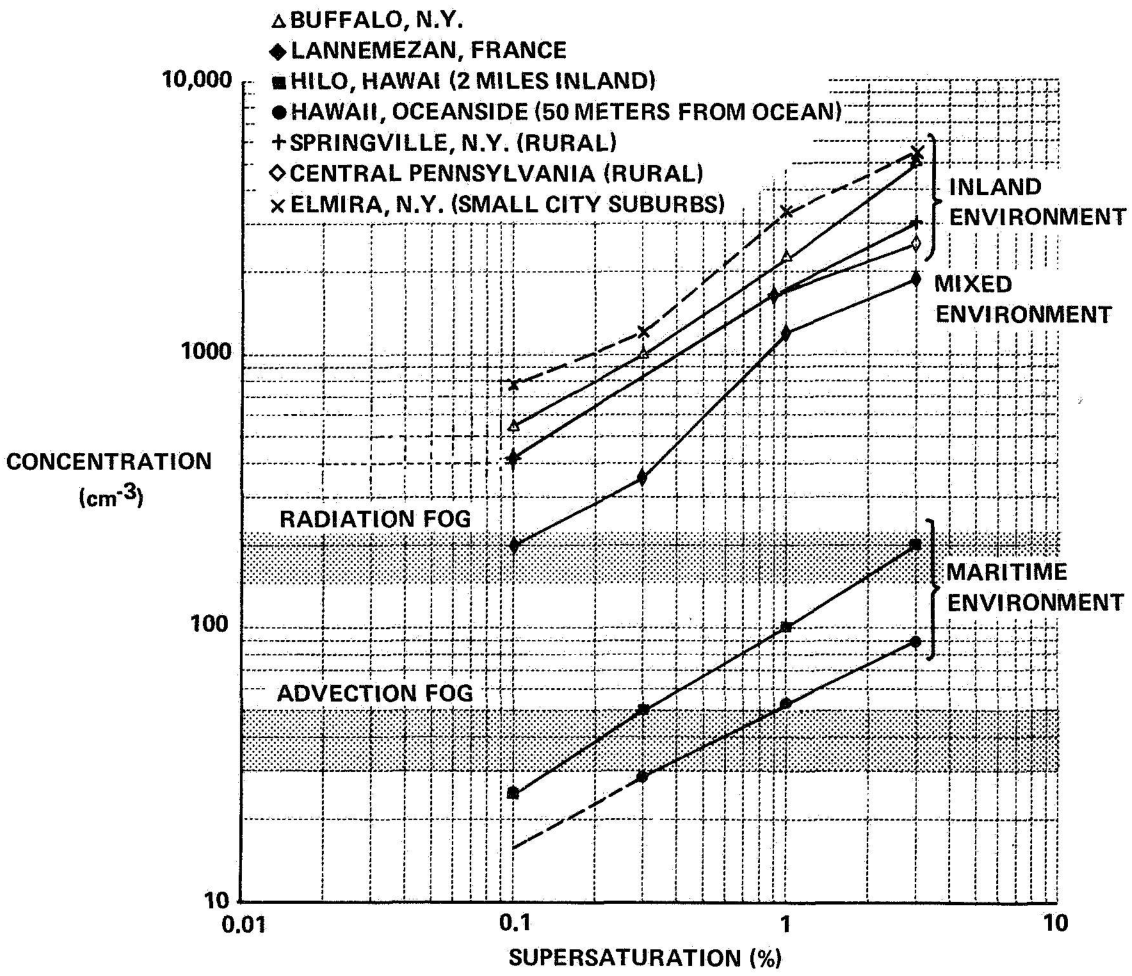
Our investigations of basic fog properties included such activities as literature studies, fog modeling, fog climatologies, experimental investigations aimed at the description of fog, and studies of condensation nuclei that are activated to droplet growth in fog. These studies were all aimed at the development of a better understanding of what fog is, how it forms and why it creates a problem. Much of the information that we have obtained will be presented in later discussions. I want to touch on three topics now.

Concentrations of Fog and Haze Nuclei

One of our most interesting and rewarding activities has been an investigation of the concentration of condensation nuclei that are active at very low supersaturations. The measurements were made in seven locations throughout the world with a thermal diffusion chamber of CAL design. Averages of the data obtained in each location are shown in Figure 1. The curve for Elmira, N. Y. is dashed because we suspect that the data may have been contaminated by a local source of pollution. The points that I would like to

Figure 1

AVERAGE CONCENTRATION OF NUCLEI AS A FUNCTION OF SUPERSATURATION



make are as follows: The data are easy to acquire with relatively simple, inexpensive equipment; yet very few workers are making such measurements. I urge others to begin similar investigations. The information obtained will certainly improve our understanding of the processes of cloud and fog formation.

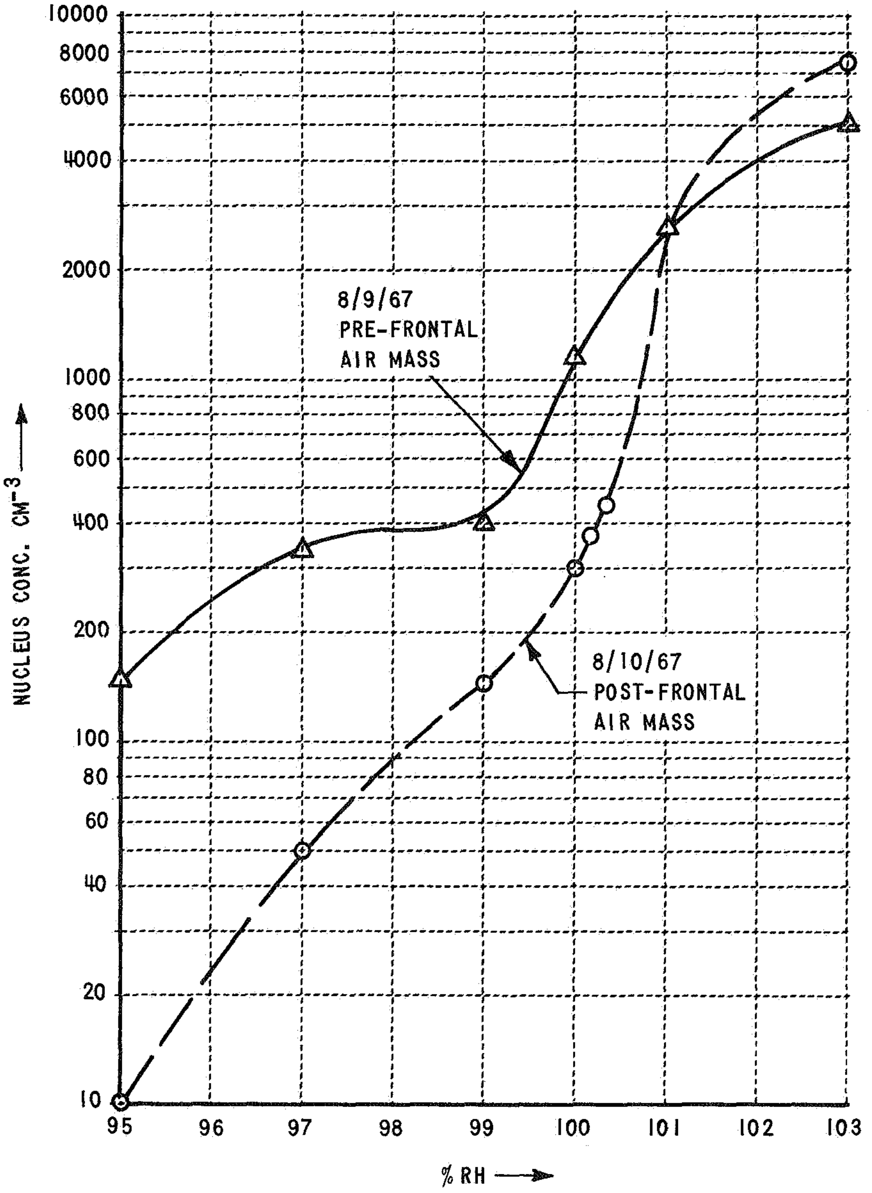
From data taken in inland environments it appears that the concentrations of nuclei active at 0.1% supersaturation always exceed the concentration of droplets found in typical inland fogs. Supersaturations of a few hundreths of one percent seem sufficient, therefore, to produce radiation fog. In maritime environments, on the other hand, we found that supersaturations between 0.1 and 1.0% were required to activate sufficient nuclei to produce the concentrations of droplets typical of maritime fogs. One of the more significant differences between the inland radiation fog and the maritime advection fog is the relative cleanliness of the two atmospheres in which the fogs form.

If a thermal diffusion chamber is modified by replacing the pure-water surfaces with saturated solutions of some water-soluble chemical, it is possible to produce accurately controlled, very slightly subsaturated conditions by controlling the temperature of the surfaces. In such atmospheres, hygroscopic nuclei deliquesce and grow to solution droplets of dimensions determined by the nature and size of the nuclei and the relative humidity within the chamber. These solution droplets are primarily responsible for wet haze. The modified diffusion chamber can be used to study the concentration of "haze nuclei" that grow to minimum detectable size (for a given instrument) as a function of relative humidity.

We wet the upper and lower surfaces of our haze chamber with a saturated solution of KNO_3 which is in equilibrium with the environment at 94% relative humidity. By controlling the temperature of the two surfaces we are able to produce controlled humidities ranging from 94% upward. With our optical system the minimum detectable droplet diameter is approximately one micron. Illustrative results are shown in Figure 2. We have not yet acquired sufficient data to speak in terms of averages or typical conditions for our area.

Figure 2

NUCLEUS SPECTRA BEFORE AND AFTER A FRONTAL PASSAGE



The main reason that I am presenting these results is to call the technique to your attention and suggest that other investigators begin making similar measurements. To our knowledge, our group is the only one making observations of nuclei at subsaturated humidities.

The other two topics concerning fog properties that I'd like to discuss come straight from the literature and are presented as background information for the remainder of the symposium.

Descriptive Models of Fog

From an extensive literature search performed early in the program we developed physical models of typical radiation and advection fog. They are presented in Table I. These descriptions of "typical fogs" have been extremely useful throughout the program. We used the numbers for most of our preliminary calculations and attempted to duplicate the indicated values when producing laboratory fogs.

TABLE I

PHYSICAL FOG MODELS

Fog Parameters at the Surface	Radiation (Inland) Fog	Advection (Coastal) Fog
1. Average Drop Diameter	10μ	20μ
2. Typical Drop Size Range	5-35μ	7-65μ
3. Liquid Water Content	110 mg/m^3	170 mg/m^3
4. Droplet Concentration	200 cm^{-3}	40 cm^{-3}
5. Vertical Depth of Fog		
a. Typical	100 m	200 m
b. Severe	300 m	600 m
6. Horizontal Visibility	100 m	300 m

Visibility in Fog

The final topic that must be mentioned before entering into a discussion of specific fog dispersal concepts is the basic expression for visual range in fog. For this purpose I'd like to present the visibility equation as derived by Trabert in 1901.

$$V = \frac{c}{\omega} \frac{\Sigma n_r r^3}{\Sigma n_r r^2} \approx K \frac{\bar{r}}{\omega}$$

where ω = liquid water content, n_r = number of drops of radius r, c = constant, and K = constant. The conclusion is: To increase visibility two choices are available; either increase the average droplet radius $\bar{r}$ or decrease the liquid water content ω. These principles, or combinations of these principles, have formed the basis for all serious efforts to suppress fog.

The techniques available for fog suppression are:

1. Cause droplets to evaporate to decrease ω. The FIDO System caused evaporation by heating the air. Houghton and Radford (1938), whose work we've extended on this project, caused evaporation by desiccation of the fog laden air with hygroscopic materials.

2. Cause droplets to precipitate to decrease ω. Sonic agglomeration techniques are based on this principle.

3. Capture the droplets to decrease ω. Electrostatic precipitation techniques and the "Fog Broom" now used experimentally on New Jersey highways are examples of this concept.

4. Cause preferential growth of a few droplets at the expense of others to increase $\bar{r}$, (i.e., try to redistribute all of the water into a few large droplets rather than a large number of small droplets).

Now I'd like to review very briefly some of the concepts for fog suppression that we have investigated in the laboratory and, in so doing, indicate the experimental techniques used for these investigations and state the conclusions that we drew from the investigations.

Inhibition of Droplet Growth

Before Project Fog Drops began we were intrigued by evaporation retardation experiments in which monolayers of heavy alcohols were spread on water reservoirs and droplets to reduce the evaporation coefficient (Bradley, 1955, Eisner et al., 1958). We wondered if the same materials might be used on water droplets to reduce the condensation coefficient and thereby retard droplet growth. We reasoned that, if the diffusional growth of some of the droplets in a population could be retarded, more water would be available for growth of the untreated droplets and the average drop size in the fog would increase. As a result of this process visibility would improve.

When the project began Dr. James Jiusto, now of SUNY at Albany, and Mr. Paul Brown, now of NCAR, studied the effects of two classes of materials on diffusional growth rates of droplets.

It was found that the heavy alcohol monolayers, notably octadecanol and hexadecanol, decreased droplet growth rate by factors exceeding 500 if the surface layer was properly compressed. Typical results are illustrated in Figure 3. The conclusion is that the materials could be effective for fog suppression if a suitable method could be found for treating a large fraction of the droplets in a fog during fog formation. At the present time we are not aware of such methods.

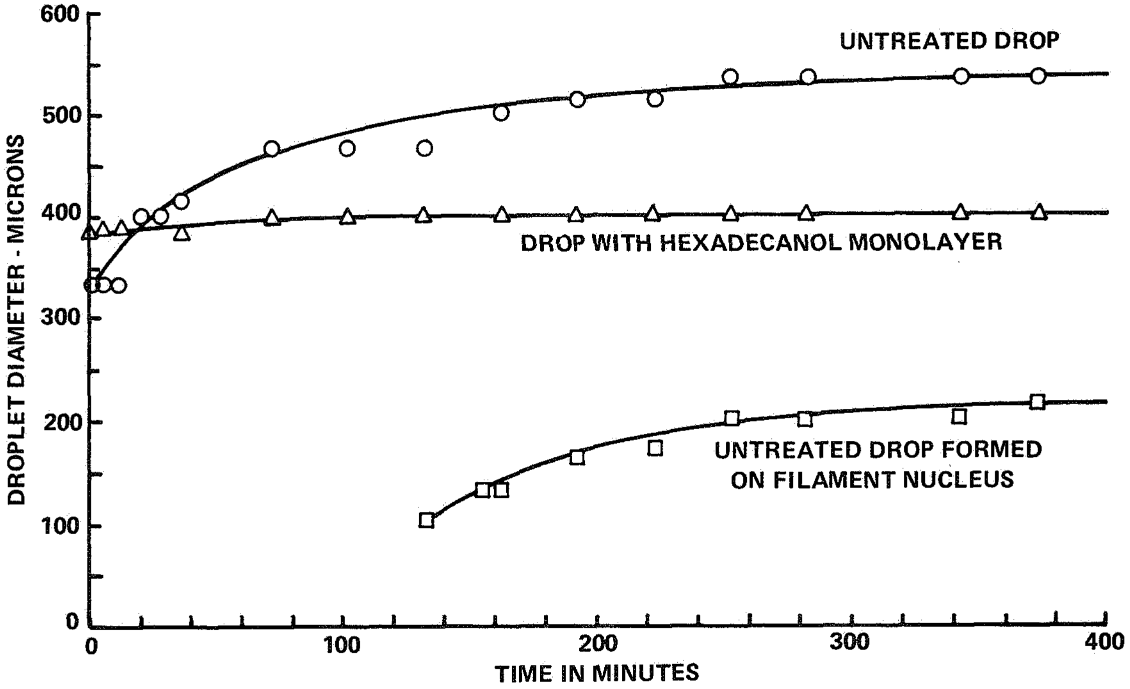
In related experiments, treatment of droplets with ionic surfactants produced no observable changes in growth rates.

With the success in decreasing growth rates of droplets we thought that the same methods might be used to deactivate nuclei to keep them from participating in fog formation. While we did show that it is possible to decrease the deliquescence rate of nuclei we could not prevent droplet formation on the treated particles. Once droplets formed on the nuclei, however, the growth rate of the droplets was significantly retarded.

This concept may be of some value in minimizing the effectiveness of nuclei in industrial effluents particularly in processes where very active nuclei are formed, such as in the paper industry.

Figure 3

GROWTH OF DROPLETS IN CHEMICAL-GRADIENT DIFFUSION CHAMBER



Investigation of Effects of Ionic-Surfactants on Coalescence

Several investigators, e.g., Elton (1953) and Benton et al. (1958), have suggested that ionic-surfactants could be used to promote droplet coalescence. Ionic surfactants are compounds that separate into ionic components when dissolved in water. Ions of one polarity migrate preferentially to the surface of water and those of the other polarity distribute themselves uniformly throughout the volume of the liquid. Even though the net charge on a droplet treated with such materials is zero it was suggested that the presence of the surface charge might affect coalescence.

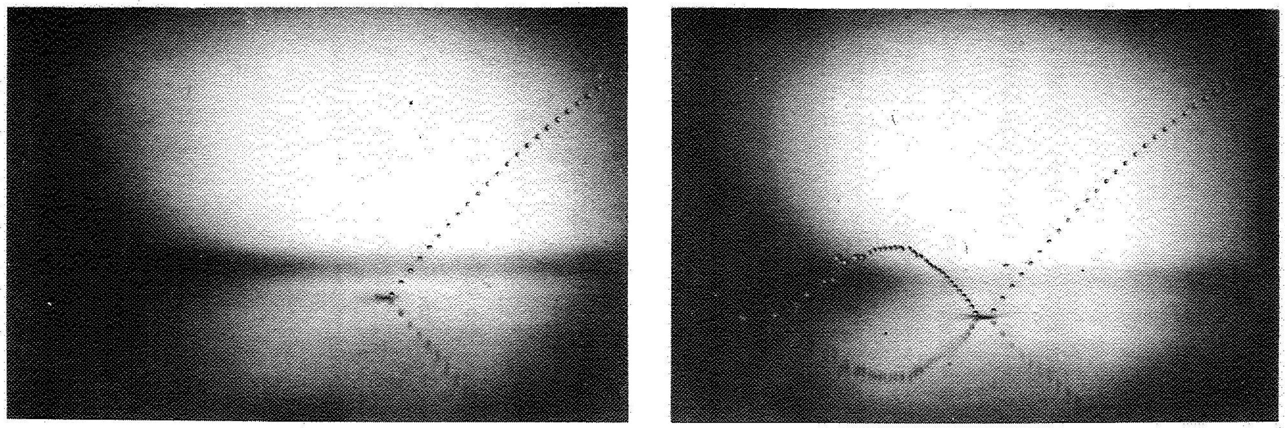
To test this concept we set up an experiment similar to those performed by Mason et al. (1963) in which we caused droplets of water to bounce off of a plane surface of water. To generate a reproducible stream of droplets we used a vibrating hypodermic needle technique used by several other investigators in the past. Then, we added a very small quantity of surfactant (1 part in 10^5) to the water forming the plane surface. We expected the droplets to coalesce with the plane surface if the surfactants worked as suggested. Instead, the droplets bounced several times, and even skidded across the surface. Indications were that the surfactants were inhibiting coalescence.

We therefore reversed the experiments, i.e., caused every droplet to coalesce with the plane surface of pure water and then added the surfactant. The results of typical experiments with cationic (positive surface), nonionic and anionic (negative surface) surfactants are illustrated in Figures 4, 5, and 6 respectively. In every case the surfactants decreased the probability of coalescence. Similar effects were produced with monolayers of the heavy alcohols.

Figure 7 is an enlargement of the second photograph in Figure 6. It is included to show details of the collision. Note that the crater produced in the plane surface by the droplets is about three times larger than the droplets themselves and that several drops, some formed by coalescence of eight to ten of the impacting droplets, are skidding across the surface without coalescence with the underlying treated surface.

Figure 4

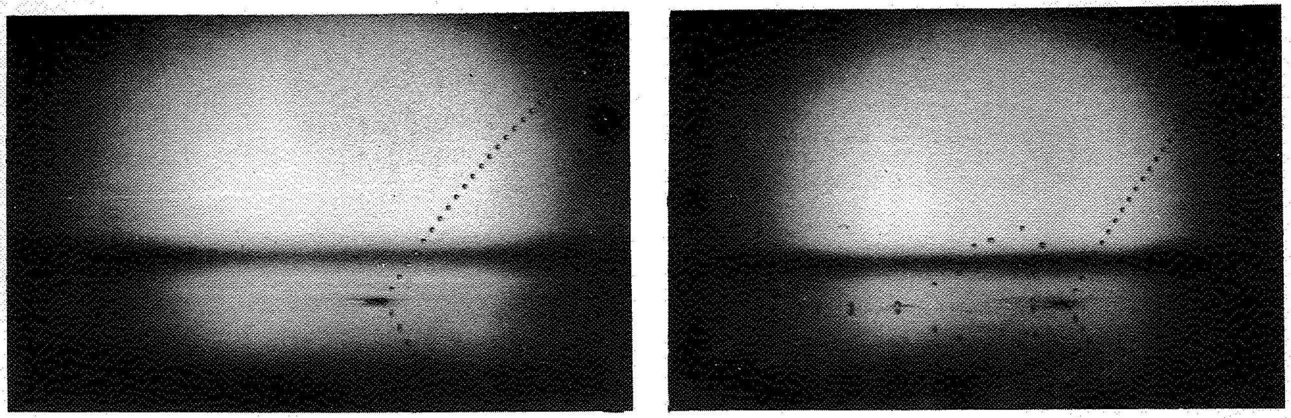
300 μ RADIUS WATER DROPS IMPACTING AT 105 CM/SEC ON A PLANE WATER SURFACE BEFORE AND AFTER TREATING THE WATER SURFACE WITH CATIONIC SURFACTANT (1 HYDROXYETHYL - 2 HEPTADECENTYL GLYOXALIDENE)



(BEFORE) (AFTER)

Figure 5

300 μ RADIUS WATER DROPS IMPACTING AT 100 CM/SEC ON A PLANE WATER SURFACE BEFORE AND AFTER TREATING THE WATER SURFACE WITH NON-IONIC SURFACTANT (A TYPE OF NONYL PHENYL POLYETHYLENE GLYCOL ETHER)

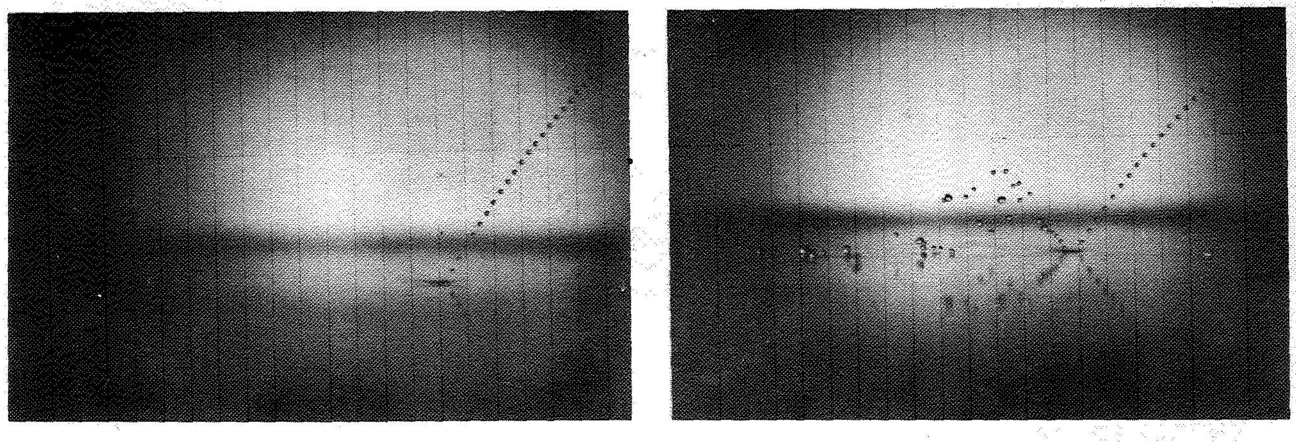


(BEFORE)

(AFTER)

Figure 6

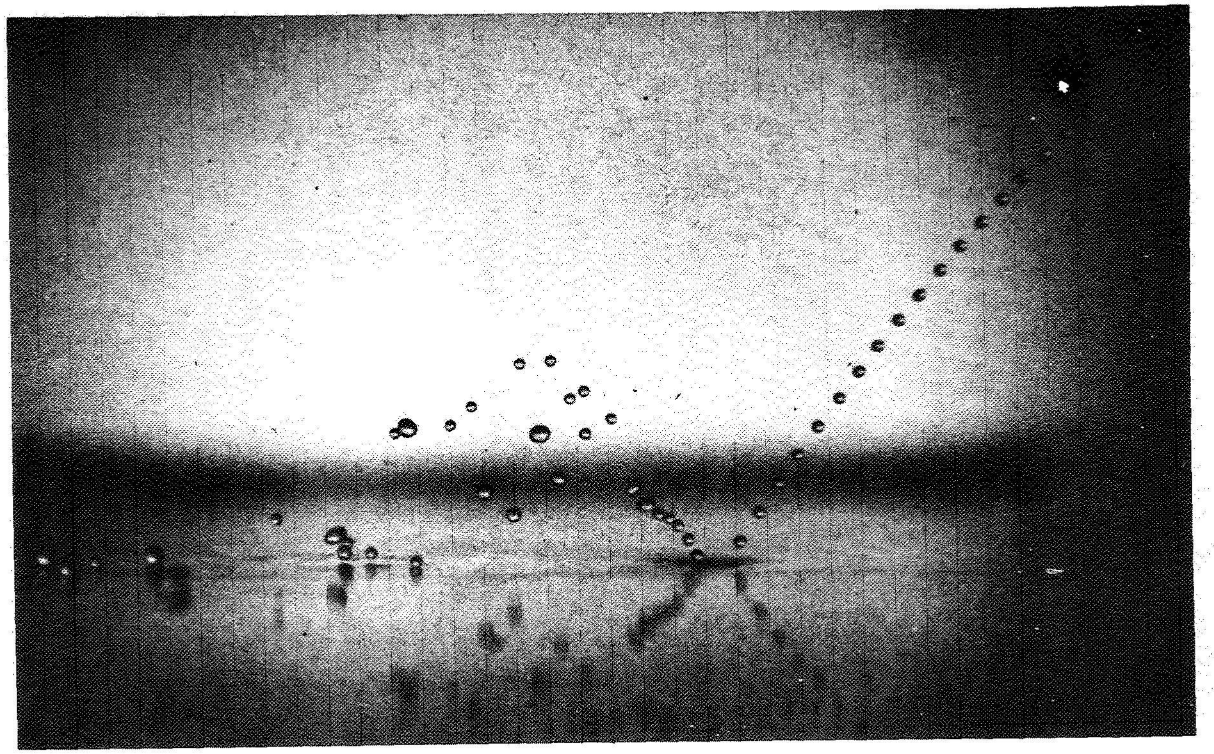
300 μ RADIUS WATER DROPS IMPACTING AT 95 CM/SEC ON A PLANE WATER SURFACE BEFORE AND AFTER TREATING THE WATER SURFACE WITH ANIONIC SURFACTANT (SODIUM TETRADECYL SULFATE)



(BEFORE) (AFTER)

Figure 7

ENLARGED PHOTOGRAPH SHOWING DROPS IMPACTING
AND BOUNCING ON A TREATED WATER SURFACE. AT IMPACT, DROPS
FORM A CRATER ABOUT THREE DROP DIAMETERS WIDE.



To prove that the effect was one of bouncing rather than splashing we doped the water forming the plane surface with ink and then collected the bouncing droplets in a small vial. Comparisons with equal quantities of the doped water revealed no evidence of ink in the bouncing droplets.

We concluded that ionic surfactants inhibit coalescence of drops with a plane water surface; they do not promote coalescence.

We also attempted to observe the effects of surfactants on drop-drop coalescence. In these experiments we were never able to detect any significant change in the coalescence behavior of treated and untreated drops.

Investigation of Electrical Means for Fog Dispersal

Many investigators have demonstrated, both theoretically and experimentally, that electrical forces are important in promoting coalescence. Naturally, the suggestion is frequently made that artificial electric forces be used to disperse fog.

The thought of artificially charging fog droplets to promote coalescence keeps popping up. In our investigation we tried to examine the magnitude of the forces that might be produced by artificially charging droplets in an electric field.

The literature shows that droplets already existing in the atmosphere can be artificially charged by subjecting them simultaneously to an electric field and an atmosphere with a conductivity that is dominated by ions of one polarity. Consider the geometry in Figure 8 which shows a droplet subjected to an ambient electric field E_a. The field at the droplet surface due to E_a is $3E_a$. In the case illustrated, positive ions will be forced onto the droplet by the ambient field until the surface field E_q due to the charge on the droplet is equal and opposite to the driving field.

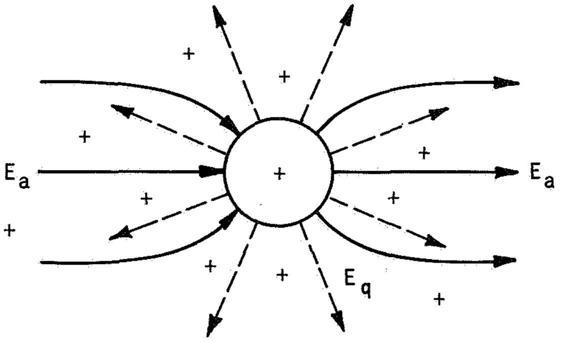


Figure 8

$$E_q = \frac{q_{max}}{4\pi \varepsilon_o r^2} = 3\, E_a$$

$$q_{max} = 12\pi\varepsilon_o E_a r^2$$

A simple method for forcing conductivity to be dominated by ions of one polarity is the corona discharge. In addition it is easy to produce an electric field of 10^4 V/m over distances of 1 meter and possible, with difficulty, to produce such fields over 10 meters. However 10^5 V/m over 10 meters requires 10^6 volt sources and we consider such a field stretched along a mile of runway, to be completely impractical. Therefore, we based our calculations and experiments on a practical value of 10,000 V/m over one meter.

To maximize forces we considered adjacent regions of charged droplets, as illustrated in Figure 9. We reasoned that with such a configuration two types of forces might promote coalescence. 1) Forces due to all charge present on droplets that exist at the point of tangency might cause droplets to move with high relative velocities and thereby promote coalescence and 2) forces due to opposite charge on adjacent droplets might pull the droplets together and cause coalescence.

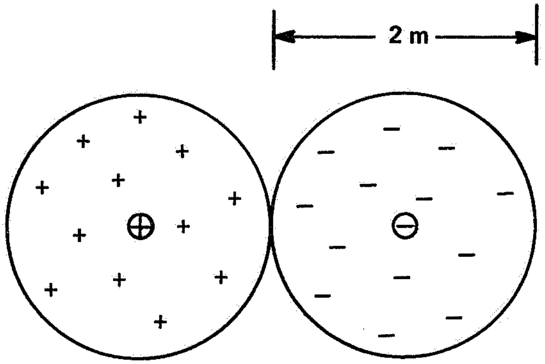
Calculations were based on the following parameters:

$E = 10^4$ V/m, $r = 5\mu$, $n = 200/\text{cm}^3$, $q_{max} = 10^{-16}$ coulombs $\approx$ 600 electrons/droplets

The type 1) forces are $\approx$ 10% of the droplet weight, so that relative terminal velocities due to these long range electrical forces are negligible.

To estimate the type 2) forces it is necessary to consider separations between a droplet and its nearest neighbors. If $n = 200\ \text{cm}^{-3}$, each droplet occupies an average of 5 mm^3. On the average, therefore, the separation between a droplet and "all" neighboring droplets is of the order of one millimeter. On this basis the electrical attraction between adjacent oppositely charged droplets is <u>eight</u> orders of magnitude smaller than droplet weight. Certainly this is negligible.

Figure 9



$E = 10^4$ V/m

$r = 5\,\mu$

$n = 200/\text{cm}^3$

$q_{max} = 10^{-16}\,\text{C} \simeq 600e$

$F = E\,q_{max}$

Geometry considered in electrostatic calculations

Even though the radius of the average volume available to a droplet is a millimeter, the probability is almost unity that a droplet will be closer than this to one of its neighbors. The question is: How much closer? Reduction in the separation by factors of 10 to 100 still leaves extremely small forces, but with such short distances the overall effect is difficult to estimate. We thought it best to observe the effect of a practical droplet charging mechanism experimentally. We therefore set up the experiment illustrated in Figure 10.

The cloud chamber, approximately one meter on an edge, was constructed of aluminum and lined with wet blotting paper. A fog formed about one half hour after a sample of outside air was drawn into the chamber. The sliding aluminum panel was then lowered into the position shown and the corona wires energized to charge droplets in one-half of the chamber volume negatively and, in the other half, positively. (Using the expression for space-charge-limited current in a cylindrical configuration, the electric field was estimated to be of the order of 10^4 V/m. In previous experiments we had determined that the average charge per droplet was approximately 10^{-16} coulombs which is consistent with theory.) After the droplets were charged we measured droplet concentration with the collimated light beam and camera and observed 90° scattered light with a phototube (not shown). Typical droplet concentrations were 200 cm^{-3}. We then lifted the sliding panel to expose the oppositely charged droplets to one another. As predicted, no mixing of the droplets due to electrical forces could be observed. Furthermore, even after mechanically mixing the oppositely charged droplets, no changes in droplet concentration or scattered light (compared with control experiments in which droplets were not charged) could be observed.

We believe, therefore, that we have demonstrated experimentally as well as theoretically that fog suppression by electrically charging the existing droplets is <u>not practical</u>.

We do not imply that electrical forces are not important to coalescence. With larger droplets and/or larger electric fields (such as occur in thunderstorms), or with different charging mechanisms, electrical forces are

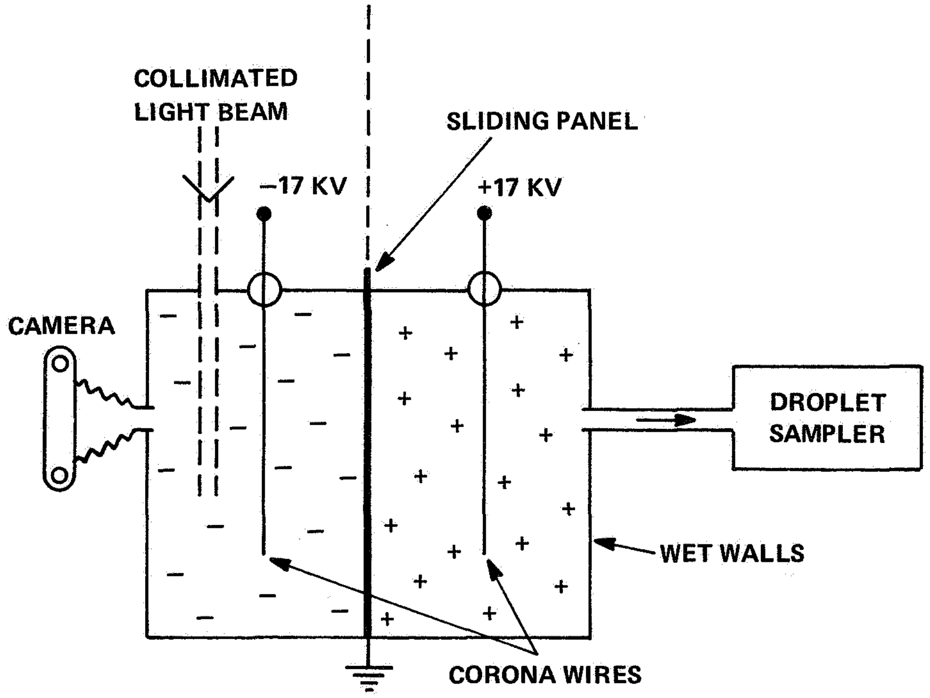


Figure 10

Schematic of apparatus used in droplet charging experiments certainly important. We conclude only that it is not practical to produce the required intense electric fields over the large distances necessary to open a fogged-in airport.

Investigation of a Method for Prevention of Dense Radiation Fog

When we were in the process of designing our thermal diffusion chamber (Figure 11) we studied the effect on nucleation behavior of changes in distance between the two water surfaces. We found, for example, that for very small distances between surfaces the concentration of activated nuclei was independent of separation. Under these conditions, when those nuclei that were activated within about five seconds after being placed in the chamber had settled to the lower surface, the chamber remained clear. For separations greater than about two centimeters, however, the concentration of nuclei activated at a given temperature difference was roughly inversely dependent on separation. Once the first-activated nuclei settled to the lower surface, new nuclei were activated so that the concentration of droplets in the chamber decreased very slowly with time for periods as long as 15 minutes.

It was obvious to us that the first nuclei that promoted droplet growth were extracting water at a rate equal to the rate at which water was being made available by diffusion and that the air within the chamber never achieved the supersaturation indicated by the temperature difference between the water surfaces. When these droplets settled out, the rate of extraction of water decreases, so that supersaturation increased slightly and new, slightly less active nuclei began to grow. This process continued. The important point, however, was that the concentration of droplets remained low.

The thought occurred to us that if a few giant hygroscopic nuclei could be added to the atmosphere before fogs formed, they might extract enough of the available water to prevent activation of small, less-hygroscopic natural nuclei. The result would be a fog consisting of a small number of large droplets rather than one consisting of a large number of small droplets as would occur naturally. With V proportional to $\overline{r}$, visibility should be improved.

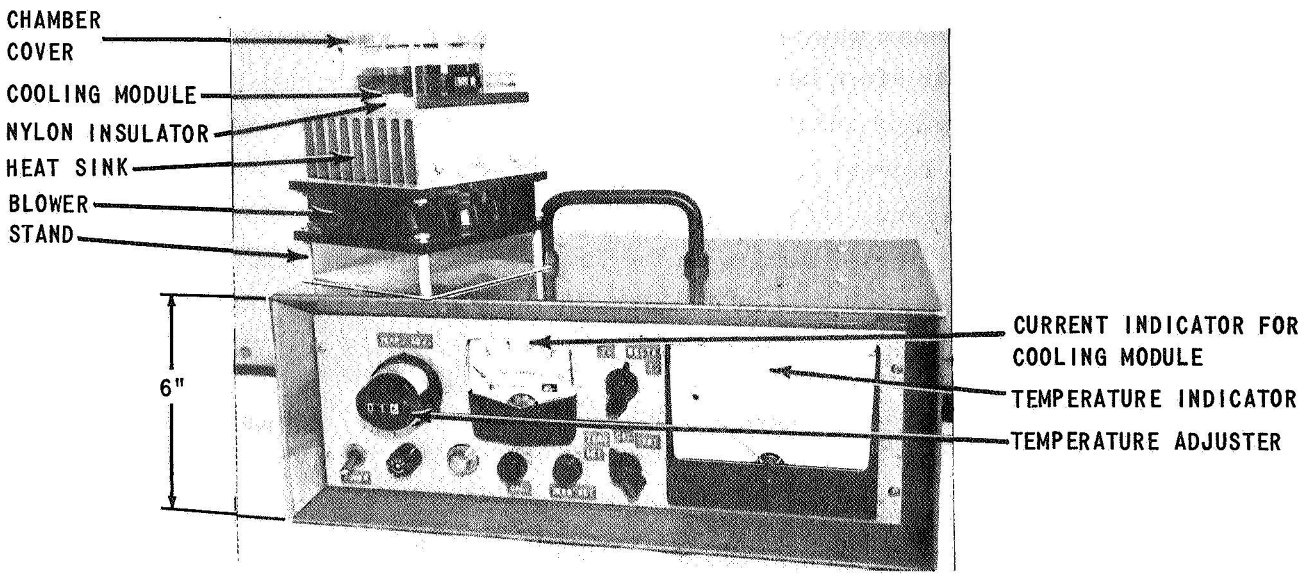


Figure 11 CAL THERMAL DIFFUSION CHAMBER AND TEMPERATURE CONTROL UNIT

Calculations indicated that two 8-micron diameter NaCl particles per cubic centimeter would be sufficient to account for all water made available for condensation at a cooling rate of $1^{o}C/hr$. The visibility in a fog consisting of two droplets per cubic centimeter would be about five times greater than that in a natural fog of the same liquid water content.

This was a concept worth testing and, indeed, it proved effective in the laboratory.

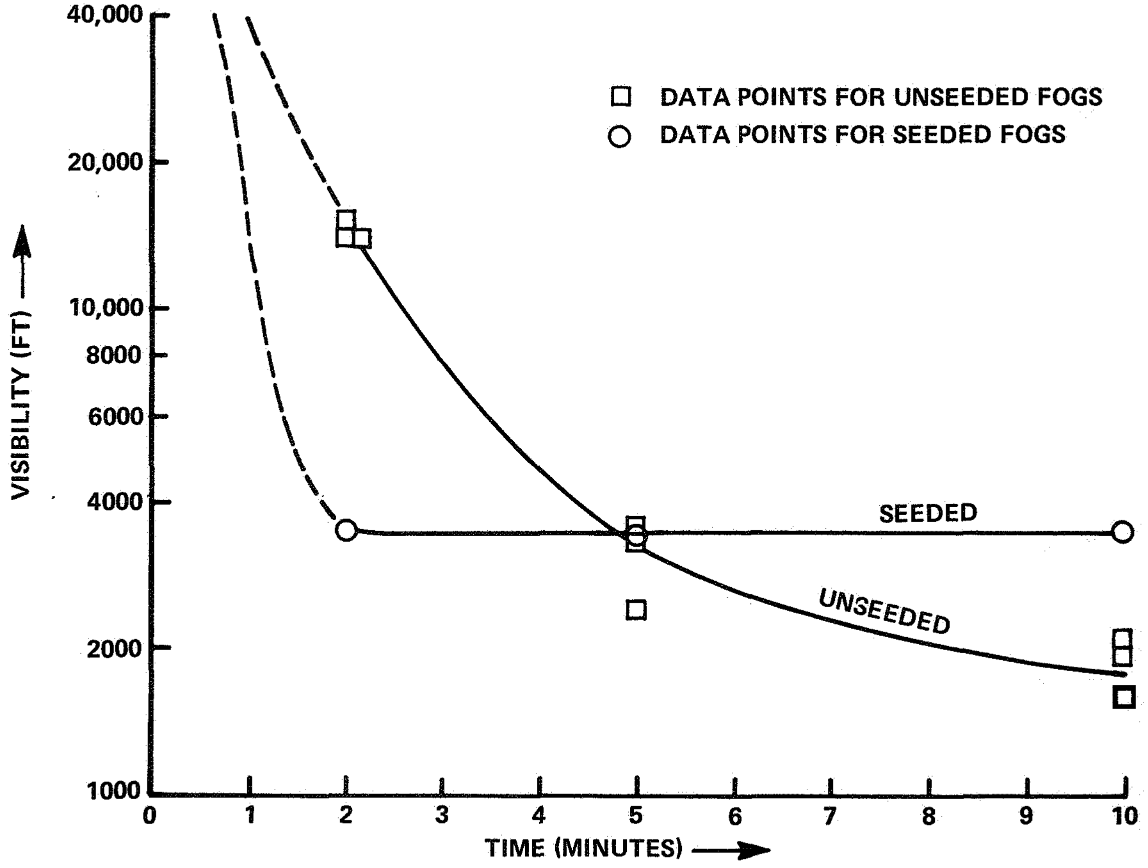
The experimental apparatus consisted of a fog chamber, one square foot at its base and eight feet high. Three sides were lined with wet blotting paper to provide the needed water vapor. Outside air was drawn into the chamber and within ten minutes a dense fog formed. Visibility was measured with a transmissometer having a folded path. Droplet concentration was measured with the collimated light beam and camera and drop size distribution was determined from samples collected on gelatin coated slides.

We would usually form three control fogs on natural nuclei. If these fogs were similar we would bring in a fourth air sample and introduce the properly sized nuclei (4 to 10μ diameter salt particles) as the air entered the chamber. Typical results are shown in Figure 12. Note that, as expected, the visibility degraded more rapidly in the seeded air mass than in the unseeded air but after reaching a given level, remained approximately constant at a value that was better than typical landing minimums. In the unseeded fogs the visibility continued to degrade with time to below landing minimums. Drop concentrations were typically an order of magnitude smaller in the seeded fog than the unseeded fogs; diameters ranged from 2 to 25μ as compared with 2 to 5μ in the unseeded cases.

In most cases a maximum improvement factor of between two and three was observed. The difference between experiment and theory can be explained by our inability to provide proper concentrations of nuclei having the correct size. With these experiments behind us it took almost no time to ask, "What would happen if existing fogs were seeded with hygroscopic nuclei of carefully controlled size distribution?" The answer to that question is the principal subject matter of the remaining papers of today.

Figure 12

COMPARISON OF SEEDED AND UNSEEDED FOGS IN 8 FT^3 CHAMBER



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II.

SOME PRINCIPLES OF FOG MODIFICATION WITH HYGROSCOPIC NUCLEI

By

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Abstract

Calculations and experiments indicate that the visibility in warm fog can be substantially improved by seeding with giant salt (NaCl) particles. By absorbing water vapor from the air, the larger saline drops grow at the expense of the natural fog droplets. In order to avoid impractical salt mass requirements, particle size and concentration must be carefully prescribed. Calculations indicate that, for typical radiation fogs, 5 to 10μ-radius salt nuclei in concentrations of a few mg m^{-3} of air are desired. Excessive drying of the air (i.e., more than a per cent or two lowering of the relative humidity) is neither desirable nor practical. In advection fogs with strong winds, thereby dictating large payloads, the technique appears to be of limited value.

The choice of hygroscopic material is less dependent on small variations in water absorbing capacity than on milling (sizing), agglomeration, cost and corrosion factors. Of the salts, sodium chloride appears to be the best choice. Its only potential deficiency--a possible but as yet undetermined corrosion problem at airports--suggests that substitutes continue to be investigated.

Introduction

Efforts to abate fog have intrigued cloud physicists and would-be weather modifiers for over three decades. Certain cold fogs can be dissipated reasonably well with freezing agents such as dry ice and silver iodide that capitalize on the colloidal instability of supercooled droplets. Warm fogs, unfortunately, have been reluctant to reveal a comparable energy reservoir to tap.

Over the years there has been periodic interest in the possibility of modifying fogs with hygroscopic materials. The usual intent has been to extract a portion of the water vapor from the saturated air so that evaporation of the fog droplets can occur. The most notable and rigorous efforts of this type--and one that achieved limited success--was performed by Houghton and Radford (1938). In their now classic work, clearing of modest size volumes (up to 10^6 m^3) was obtained by seeding with droplets of calcium chloride solution. The experiments were designed to reduce the ambient relative humidity to approximately 90% with clearing rates of 2000 $m^3 sec^{-1}$. In general, solution spray rates of about 5 liters sec^{-1}, or approximately 2.5 gm of seeding material per cubic meter of fog, yielded the desired result.

Extrapolation of the above numbers to air volumes characteristic of present-day airport runways leads to rather discouraging results. Our attempts to relax the stringent mass requirement have invoked the use of dry salt particles of prescribed size and only slight reductions in ambient relative humidity. Principles that must be considered in order to achieve as efficient an approach as is possible are reviewed herein. A more detailed treatment of some of these topics was given elsewhere (Jiusto, et. al., 1968).

Basic Principles

a. Fog Seeding Concept

Giant hygroscopic particles introduced into fog absorb water vapor from the saturated air and lower the ambient vapor pressure. The natural fog droplets thereby commence to evaporate at the expense of the growing saline drops, as illustrated in Figure 1.

In principle, improvements in fog visibility can be effected by shifting the drop size distribution to larger but far fewer drops, or by decreasing the liquid water content of the fog. These conclusions can be drawn from a form of the visibility equation derived by Trabert (1901), i.e.,

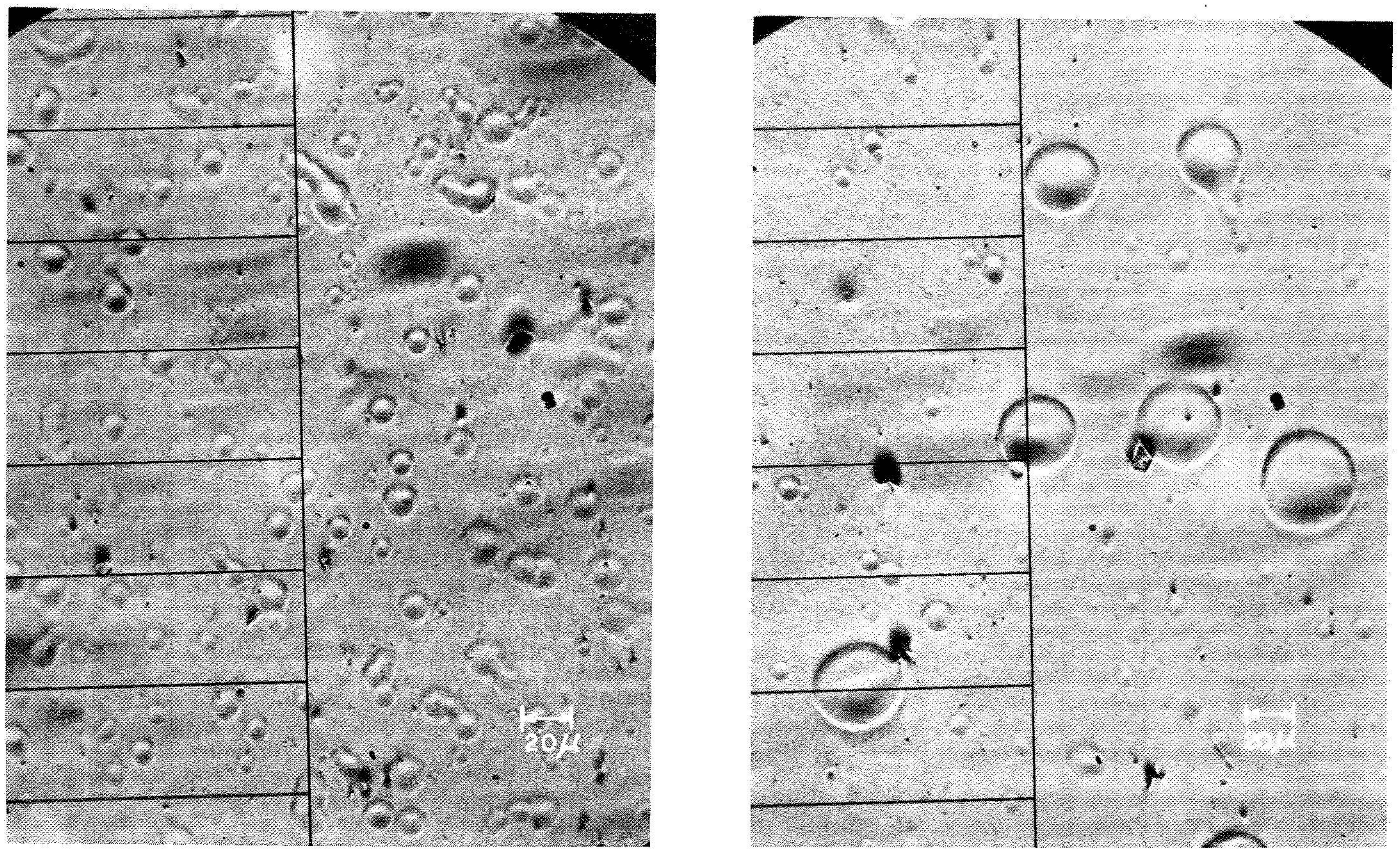
$$V = \frac{C \Sigma N_i r_i^3}{\omega \Sigma N_i r_i^2} \cong 2.6k\frac{\bar{r}}{\omega}, \qquad (1)$$

where V is the visibility in a cloud, N_i the concentration of droplets of radius r_i, ω the liquid water content, C a numerical scattering factor (2.6), $\bar{r}$ the linear-mean droplet radius, and k an empirical value (1-2, typically) varying with the width of the drop size distribution.

Hence, modification concepts that show promise of altering drop size distributions are appealing. Techniques that also incorporate the potential for decreasing fog water content are, of course, most advantageous.

b. Salt Particle Size

The most crucial parameter in developing an efficient fog-modification concept is the salt particle size. If submicron particles are used for seeding, the resultant saline drops will be undesirably small, often leading to increased scattered light and even poorer visibility. On the other hand, if excessively large salt particles are introduced into the fog, more favorable light scattering may be obtained but salt mass requirements soon render the scheme impractical.



CONTROL FOG

SEEDED FOG

Figure 1 DROPLET REPLICAS IN CONTROL FOG AND SIMILAR FOG 8 MINUTES AFTER SEEDING WITH GIANT SALT (NaCl) NUCLEI.

Figure 2, based on equations given in section 3, shows the growth of sodium chloride (NaCl) nuclei of 1 to 50μ radius after falling through a cloud 1 km thick. The curves give the final drop size and dwell time involved. Note the drop sizes represent lower limits since the effects of coalescence and cloud supersaturation are ignored.

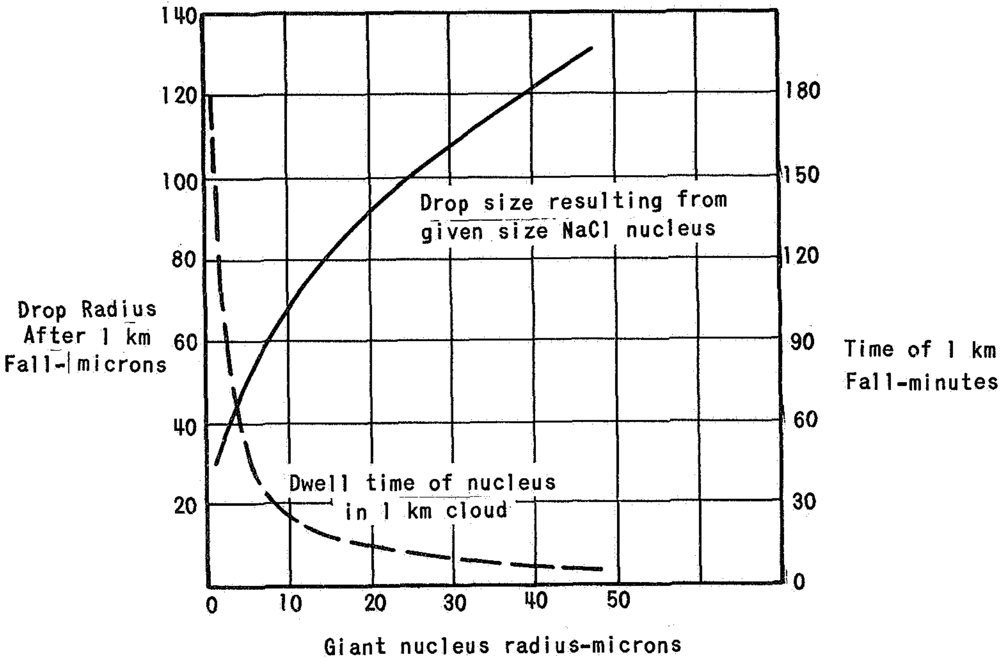


Figure 2 Approximate growth and dwell time of giant salt nuclei in cloud. (NaCl, T = 20C, H = 1km)

Referring to the diagram, it is evident that a 20μ-radius salt particle will grow by diffusion to approximately 90μ radius during a fall time through the 1 km cloud of 15 minutes. A 5μ radius particle will grow to approximately 50μ in 45 minutes. While smaller particles are more efficient in terms of mass of water absorbed to mass of nucleus, their fall time can become prohibitively long.

Choice of desired particle size depends on given fog conditions--principally fog thickness, wind speed, and liquid water content. As subsequent tabulations will suggest, salt nuclei of 5 to 10μ radius are generally most suitable for a broad range of fog conditions.

c. Relative Humidity Reduction

If a modest amount of salt can decrease ambient relative humidity slightly and cause the natural fog droplets to commence evaporating, one might legitimately ask whether a much larger quantity of salt isn't even better. Ironically, the answer is no under most circumstances. Surely a drier environment will speed droplet evaporation. However, the efficiency of the salt in absorbing water decreases markedly as humidity lowers, such that larger salt nuclei are required; payloads increase ominously.

For example, to reduce ambient relative humidity to 99% requires about 3 times as much salt as is required to absorb the fog liquid water (say 0.2 gm^{-3}) while leaving the environment near saturation (100% R.H.). To dry the air to 96% R.H., requires about 30 times as much hygroscopic material! Thus excessive drying of the environment is generally not desirable from a physics standpoint nor practical in an operational sense.

A key question remaining is, will droplet evaporation rates be significant at slight subsaturations (or at 100% R.H.)? Numerical calculations of droplet evaporation as a function of ambient relative humidity were made using the diffusion equation given by Fletcher (1962):

$$r \frac{dr}{dt} = G \left(S - \frac{a}{r} + \frac{b}{r^3}\right), \tag{2}$$

where r is drop radius, t is time, G accounts for condensational heating, S supersaturation (subsaturation here), a/r Kelvin curvature effect, and b/r the nucleus solubility effect. It was assumed that the fog drops had initially condensed on representative 0.1μ radius NaCl nuclei. The times required for given size droplets to evaporate, i.e., reach small equilibrium sizes, are plotted in Figure 3.

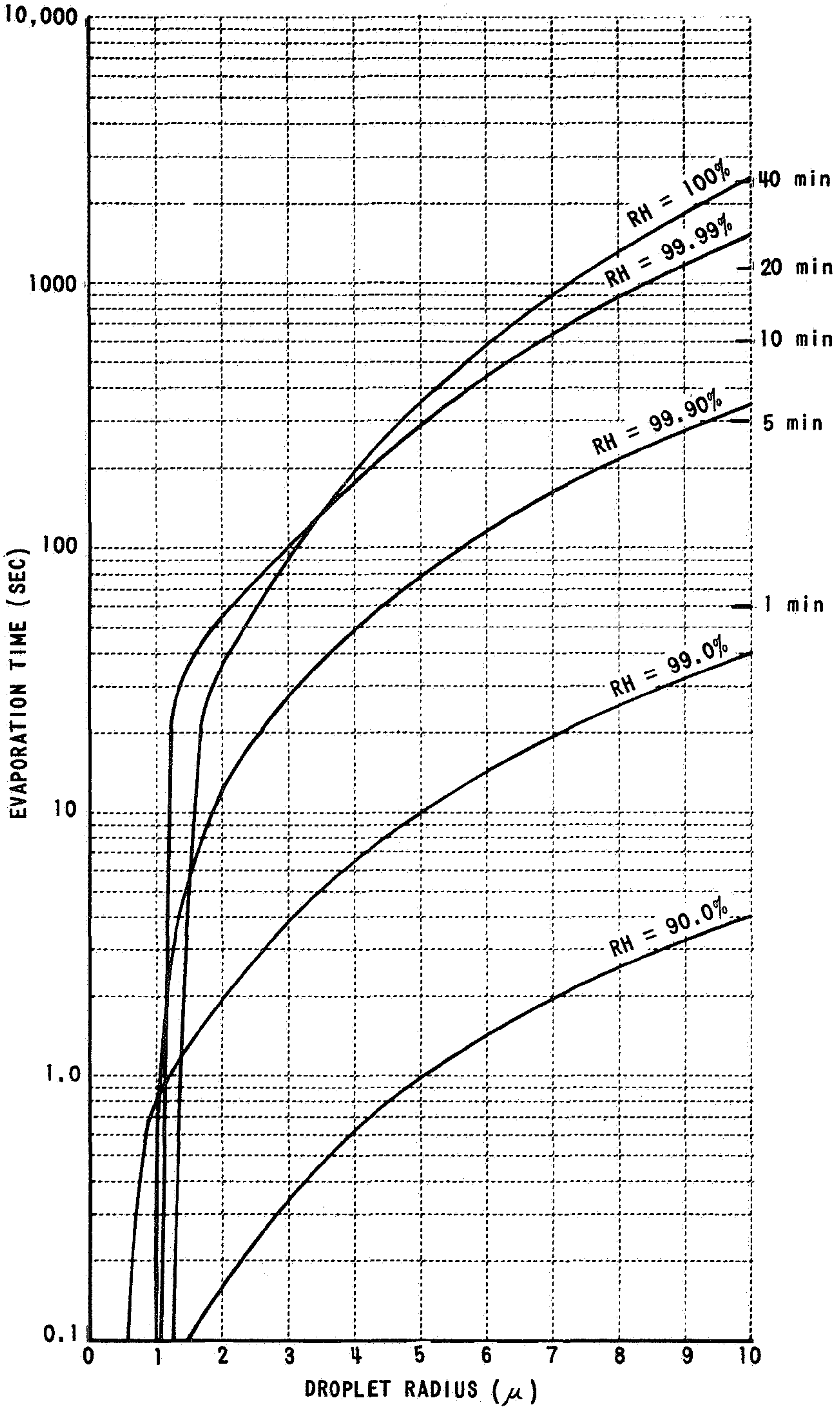


Figure 3 EVAPORATION TIMES OF DROPLET vs RELATIVE HUMIDITY
(ASSUMED DROPLET NUCLEI - 0.1 RADIUS NaCl PARTICLES)

The speed with which small droplets (typical inland fog sizes shown) evaporate is rather revealing and encouraging in terms of the fog seeding objective. Fog droplets of 5μ radius will evaporate in 10 sec. at a relative humidity of 99%, 1.3 min. at 99.9% and 6 min. at 100%. Hence, substantial drying of the atmosphere, which leads to prohibitively large salt masses, does not appear essential. An optimum ambient humidity to strive for, recognizing that such control is not generally possible in practice, is approximately 99.5%.

d. Type of Hygroscopic Nuclei

Sodium chloride was used in many of the fog experiments performed to date. There is a natural reaction to turn from this common substance and explore more hygroscopic materials in anticipation of large improvements in mass requirements. To date, such expectations have not been realized.

While lithium chloride starts to absorb water at 15% R.H. and calcium chloride at 35% R.H. versus a deliquescence point of 75% R.H. for NaCl, the total water absorbed by the time the relative humidity reaches 100% is quite similar for each of the three nucleus types (of common size). Junge (1963) has shown experimentally that this is true for a broad class of salts and acids.

Alternately one may examine the nucleus solubility term b in equation (2),

$$b \cong 4.3\, m_s\, (i/M) \qquad (3)$$

where m_s is mass of nucleus, i the van't Hoff ion-dissociation factor, and M the molecular weight of the hygroscopic nucleus. One would like this (i/M) ratio to be as large as possible. For the more common salts, at least, the ratios do not differ a great deal and NaCl lies toward the top of the rather narrow range.

Conversely, materials that deliquesce at lower relative humidities become progressively more difficult to work with. Handling, storage, and particle agglomeration problems become severe. Thus the selection of hygroscopic materials for fog work is perhaps better dictated by:

(1) capability of being readily milled to desired sizes,
(2) handling ease or resistance to agglomeration,
(3) cost,
(4) corrosion qualities.

So far NaCl still seems to be the best compromise choice. Its "Achille's Heel", perhaps, is item (4) - corrosion potential. For this reason, other materials such as certain organic fertilizers are under investigation by various groups.

Calculations of Fog Modification Requirements

a. General Approach

Approximate expressions were derived for the size achieved by giant hygroscopic particles after falling through a given depth of fog and for the fall time involved. Essentially, this involves combining three equations: a form of the equation for droplet growth by diffusion, the general velocity equation, and Stokes expression for the terminal velocity of spheres.

Drop growth:
$$r\frac{dr}{dt} = G\left(S - \frac{a}{r} + \frac{b}{r^3}\right) \simeq G\frac{b}{r^3} \qquad (4)$$

Stokes law:
$$v = \frac{2}{9}\frac{(\rho_o - \rho_a)}{\eta} g\, r^2 \approx \frac{2}{9}\frac{\rho_o g r^2}{\eta} \qquad (5)$$

Velocity eqn.:
$$dh = v\,dt \qquad (6)$$

Substituting Equations (4) and (5) into (6) and integrating yields the size r_H achieved by droplets growing on nuclei of characteristic b after falling distance H in a fog at 100% relative humidity, i.e.,

$$H = \frac{2}{63}\frac{\rho_o g}{\eta G b}\left(r_H^{\,7} - r_o^{\,7}\right), \qquad (7)$$

For sodium chloride particles, $b \simeq 0.147\ m_s$. Assuming further that temperature $T = 20C$, saline drop density $\rho_o = 1.1$ gm cm^{-3}, and initial drop size $r_o \ll r_H$, the general equation (7) reduces to,

$$r_H = 192\ (m_s H)^{1/7}. \qquad (8)$$

From equation (4),

$$t_H = 1.11 \times 10^{-14}\ r_H^{\ 5}/m_s. \qquad (9)$$

Thus, Equations (8) and (9) yield the resultant size and dwell time of giant salt particles of given mass injected into fogs under the stipulated conditions. While lacking in elegance, these simplified equations permit sound first approximations of fog seeding effects and requirements without the necessity of a computer.

b. Seeding Model

Calculations of salt-seeding requirements were made in preparation for fog experiments conducted in a 600 m^3 test chamber (described elsewhere in this report). The model fog and seeding conditions assumed were as follows:

Fog depth $H = 10$ m (height of facility)
Temperature, 20C
Saturation vapor density, 18 gm m^{-3}
Natural fog drop radii, 5μ
Initial fog liquid water content, 0.2 gm m^{-3}
Salt (NaCl) injected at top of fog

Invoking the above conditions and employing Equations (8) and (9), the final drop size and fall time of droplets in the chamber were calculated as a function of salt nucleus size. It is a straightforward matter to compute the mass of water extracted per giant nucleus and the total concentration and amount of salt needed to fulfill the indicated clearing objective, i.e., to absorb 0.2 gm m^{-3} of fog water. This degree of seeding may be thought of as that just sufficient to evaporate the natural fog droplets and to transfer the vapor to the absorbing salt particles in the times shown. The resulting estimates are shown in Table 1.

Table I

DROPLET GROWTH AND FOG SEEDING REQUIREMENT - 100% R.H.

(MODEL FOG CONDITIONS: T = 20C, FOG DEPTH = 10m, FOG LWC = 0.2 g m^{-3},
DROP RADII = 5μ, WATER ABSORBED BY SALT = 0.2 g m^{-3})

SALT PARTICLE RADIUS (MASS)	FINAL DROP SIZE r_H	FALL TIME t_H	WATER PER PARTICLE m_p	REQUIRED SALT CONC.	REQUIRED SALT MASS (600m^3)	VISIBILITY IMPROVEMENT FACTOR
47.8μ (10^{-6}g)	71.5 μ	21 sec	54.0x10^{-8}g	0.37 cm^{-3}	220g	14
22.4 (10^{-7})	51.5	40	47.4	0.42	25	10
10.0 (10^{-8})	36.8	76	19.9	1.0	6.0	7
4.78 (10^{-9})	26.3	141	7.60	2.6	1.6	5
2.24 (10^{-10})	18.9	270	2.84	7.0	0.42	3.5
1.0 (10^{-11})	13.7	536	1.08	18.5	0.11	2.5
0.48 (10^{-12})	10.0	1110	0.42	47.6	0.024	2

The following conclusions can be drawn from the data presented in Table 1:

1) As salt particle size decreases, the total payload required to absorb 0.2 gm m^{-3} of fog liquid water steadily decreases. Particle fall time in the 10 m high fog undergoes a corresponding increase, with salt nuclei $< 1\mu$ radius being generally impractical.
2) From the Trabert visibility equation, it is apparent that the larger nuclei lead to bigger (fewer) drops and better visibilities. Initially, when liquid water content is essentially constant, the visibility improvement is directly proportional to the final drop size achieved. However, the choice of larger particle size is not unlimited as payloads go up significantly.
3) The optimum salt particle radius, considering final drop size, fall time and total required mass, is approximately 5μ. An acceptable size range appears to be from $2-10\mu$ radius under saturated conditions.

c. Hypothetical Fog Modification at Airports

The foregoing analysis was extended to obtain an estimate of the requirements and feasibility of clearing a hypothetical airport fog. The fog volume considered was 10^8 m^3, equivalent to a zone 500 m wide, 100 m high, and 2000 m long. Model fog conditions, except for height (now 100 m high), were as stipulated previously.

The seeding effects and requirements are indicated in Table 2. Again, 5μ radius salt nuclei appear suitable. As such, 90 kg of material are required for one seeding. With a 3 m sec^{-1} wind speed, about 5 such seedings per hour or 450 kg hr^{-1} would be required for continuous airport operation. Should faster particle fall times prove necessary, the use of say 10μ radius nuclei would dictate corresponding seeding rates of 1600 kg-hr^{-1}. The concept might then be testing the limit of feasibility. (It is of interest to note that on a comparable fog volume basis, this latter requirement is still over 2 orders of magnitude lower than that required by Houghton and Radford (1938) to decrease fog humidity to 90%).

Table II

HYPOTHETICAL FOG CLEARANCE AT AN AIRPORT

MODEL FOG: FOG HEIGHT AT 100 m, 0. 2 gm^{-3} LWC,
5μ RADIUS DROPS, T = 20 C ; RH = 100%

SALT PARTICLE RADIUS (MASS)	FINAL DROP SIZE	FALL TIME t_H	WATER PER PARTICLE MP m_p	REQUIRED SALT CONC.	REQUIRED SALT MASS (10^8 m^3)
47.8 (10^{-6}g)	99.3μ	110 SEC	206. x 10^{-8}g	0.098 cm^{-3}	9720 kg
22.4 (10^{-7})	71.6	210	179.	0.112	1120
10.0 (10^{-8})	51.1	390	61.5	0. 325	325
4.78 (10^{-9})	36.5	730	22.2	0.901	90
2.24 (10^{-10})	26.3	1400	8.36	2.39	24
1.0 (10^{-11})	19.04	2780	3.17	6.31	6.3
0.48 (10^{-12})	13.9	5760	0.887	22.6	2.3

It should be emphasized that the foregoing values represented first-order estimates, subject to more refined modeling and field verification (see subsequent efforts as reported in other papers in this document). Complicating factors such as particle size variations, inhomogeneities in atmospheric salt distribution, complex heating and cooling effects, and turbulent diffusion will all influence field applications. Nevertheless, a reasonable understanding of the processes involved in fog droplet behavior was obtained that enabled a quantitative framework to be developed for subsequent fog modification experiments.

Conclusions

Effective fog clearance with hygroscopic nuclei entails many considerations and compromises between required payloads, drop sizes, and fall times of particles. Calculations indicated that for typical radiation fogs, salt nuclei of approximately 5μ radius in concentrations of 2-3 mg m^{-3} are quite favorable. Under these conditions, substantial improvement in fog visibility can be expected. To minimize the required salt mass, it is desirable to seed with just enough material to promote complete evaporation of natural fog droplets and leave the ambient atmosphere near saturation after the evaporation is complete. A priori information on fog depth, liquid water content, and wind speed must be considered in advance of an operation.

The ability to specify and generate salt nuclei of desired sizes is essential. The choice of hygroscopic nuclei generally is less dependent on water-absorption variations of the material than on handling, cost, and corrosion factors. Without due consideration of all these design factors, fog modification with giant hygroscopic nuclei rapidly enters the unfeasible realm. Even under ideal conditions of nucleus generation and dispersion, strong winds (and turbulence) may render the payload requirements operationally unattractive.

APPENDIX

List of Symbols

a	droplet curvature term ($3.3 \times 10^{-5}\ T^{-1}$)
b	droplet solubility term
C	Mie scattering factor (2.6)
D	diffusivity of water
g	gravitational acceleration
G	thermodynamic function in drop growth equation $G = \frac{D\rho_v}{\rho}\left[1 + \frac{DL^2\rho_v}{R_v T^2 K}\right]^{-1}$
h, H	height
i	van't Hoff factor
k	empirical value for droplet spectrum width
L	latent heat of vaporization of water
m_s	mass of hygroscopic nucleus
M	molecular weight of nucleus
N	drop concentration per unit volume
r	droplet radius
$\bar{r}$	linear-mean droplet radius
r_o, r_H	initial drop radius and final drop radius after falling distance H
RH	relative humidity
S	supersaturation
t	time
R_v	gas content for water vapor
T	temperature
V	visibility
v	velocity
K	thermal conductivity of air
ρ	density of liquid water
ρ_a, ρ_o	density of air and of drop respectively
ρ_v	saturation water vapor density
η	viscosity of air
ω, LWC	liquid water content

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III. VERIFICATION IN LABORATORY SEEDING EXPERIMENTS

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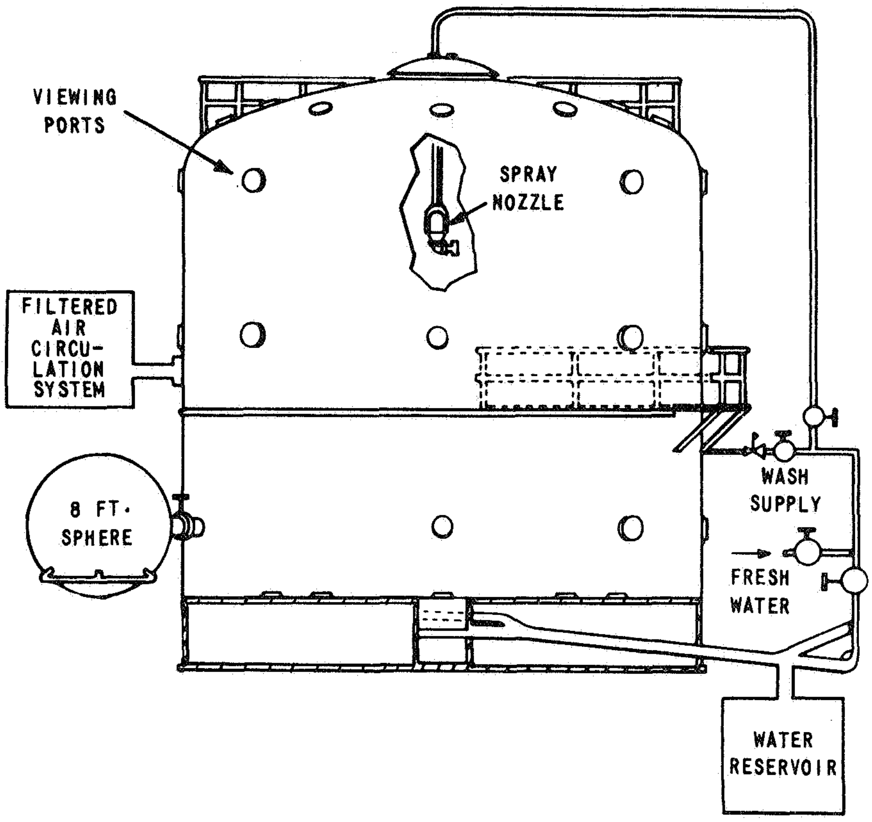
The experiments aimed at laboratory verification of the fog dispersal concepts just discussed by Dr. Jiusto were performed in the CAL Ordnance Laboratory located at Ashford, N. Y. The facility pictured in Figure 1 consists of a cylindrical chamber 30 feet high and 30 feet in diameter that is constructed of 0.5 inch steel plate with an epoxied inner surface. Total volume is approximately 600 m^3. The rotating spray nozzle is designed to thoroughly wet all inner surfaces of the chamber in 1.5 minutes. A blower - circulation system, which is part of the support equipment can be used to either pressurize or evacuate the chamber to approximately 30 cm of water.

To form a fog, the walls are flushed with water and clean air from the rural surroundings is circulated through the chamber. The chamber is then pressurized and the internal air is permitted to approach temperature and humidity equilibrium with the wet walls. The saturated air within the chamber is then vented to the outside at a controlled rate. In essence an adiabatic expansion is produced and fog forms.

Fogs created in the above manner decay within 10 to 15 minutes as droplets evaporate after the chamber pressure reaches equilibrium with the ambient air. However, the fogs can be made to persist at approximately constant visibility for up to an hour, by initiating a secondary expansion after equilibrium has been reached. This is accomplished by slowly evacuating the chamber to produce continuous cooling at a rate of about $4^{o}C\ hr^{-1}$. Visibility in a typical persistent fog as a function of time is illustrated in Figure 2.



THE 600m^3 TEST CHAMBER AT ASHFORD, NEW YORK

Figure 1

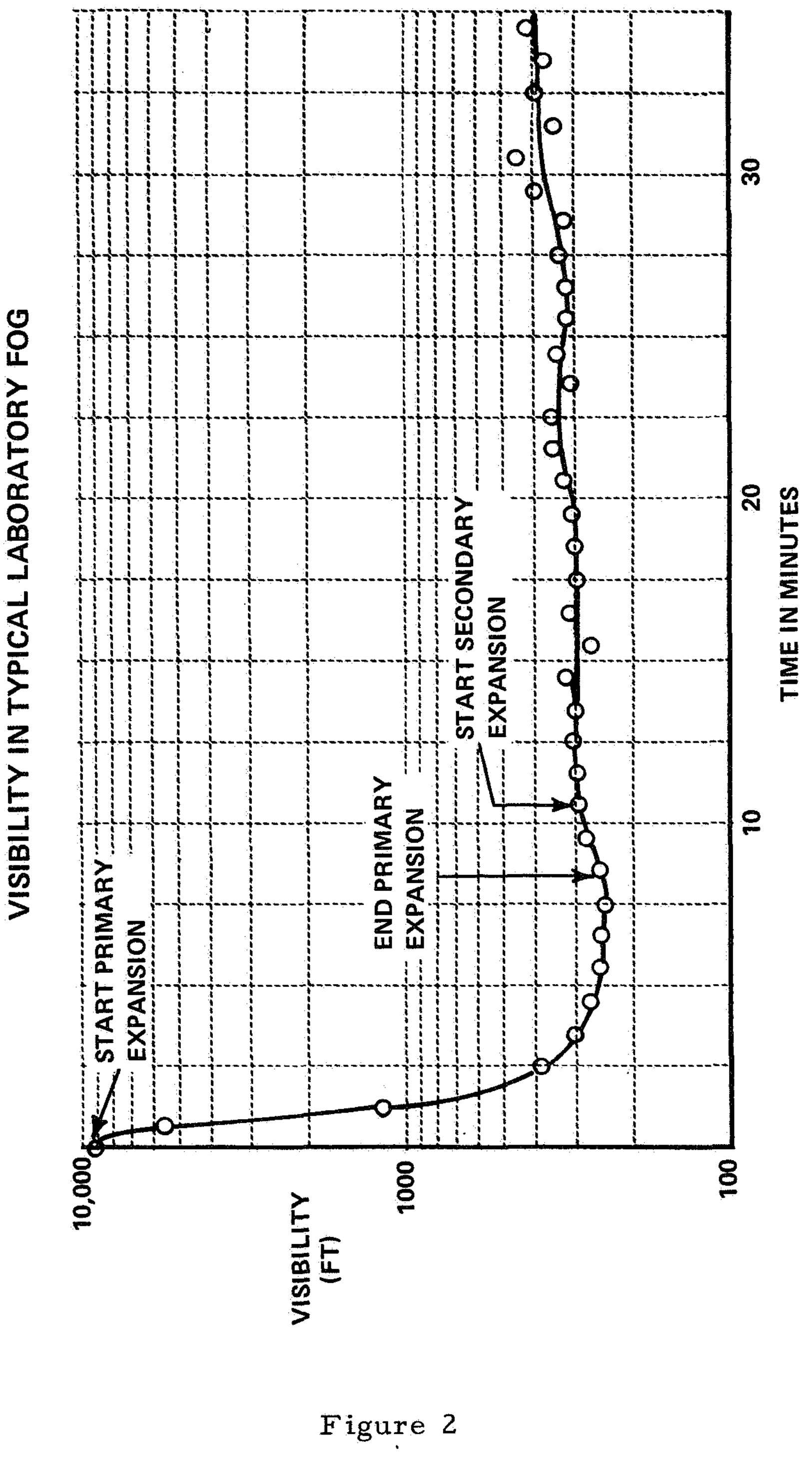

VISIBILITY IN TYPICAL LABORATORY FOG
VISIBILITY (FT)
10,000
1000
100
TIME IN MINUTES
10
20
30
START PRIMARY EXPANSION
END PRIMARY EXPANSION
START SECONDARY EXPANSION

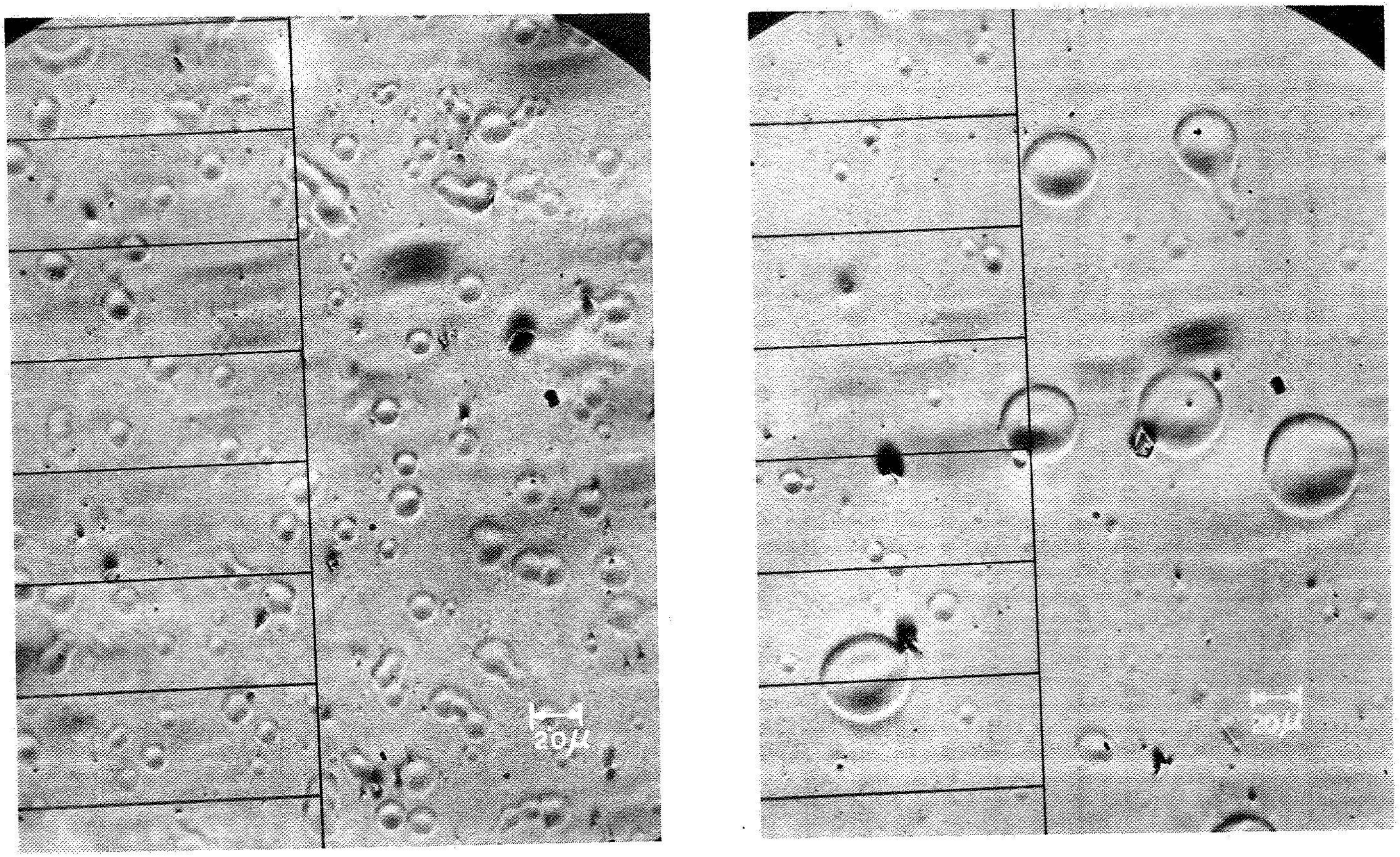
Figure 2

Visibility is monitored with two transmissometers having 60 ft folded path lengths through the fog. The instruments are externally mounted at the viewing ports; one at the 4 foot level and the other at the 15 foot level (above the catwalk in Figure 1). Drop size distributions are obtained from samples collected on gelatin coated slides at the 4 ft level. Typical replicas are illustrated in Figure 3. To assure high collection efficiencies, the slides were cut to 2 mm width and air drawn past them at a minimum of 40 m sec^{-1}. Liquid water content was determined during data analysis by combining transmissometer data with drop size distribution data. A wet and dry bulb psychrometer was located at the four foot level for humidity measurements prior to fog formation and a vertical array of six thermocouples was used for temperature measurement. The G. E. Small Particle Detector and the CAL thermal diffusion chamber were used to monitor condensation nuclei in the chamber prior to fog formation. With this instrumentation we can be assured excellent reproducibility and can monitor fog characteristics quite well.

As shown in Table I the characteristics of the laboratory fog shortly after completion of the primary expansion, t = 10 min, resemble a natural radiation fog quite closely. The $4^{o}C\ hr^{-1}$ cooling rate required to maintain constant visibility causes drops to grow and liquid water content to increase with time so that after about 30 minutes the laboratory fog resembles a typical advection fog. Thus our laboratory fogs are very similar to fogs found in nature.

Seeding is performed with a modified Trost Jet Mill (illustrated in Figure 4) mounted in one of the viewing ports at the top of the chamber. We usually seed with presized material and use the mill only for declumping and dissemination. The two size distributions of sodium chloride particles used in the experiments discussed in this paper are shown in Figure 5. While the 8μ mode distribution is not as narrow as we would like, we feel that the control of size is reasonably good.

Incidently, we used sodium chloride in these experiments because from a theoretical standpoint it appears to be about as good as any chemical and from an experimental standpoint it is relatively easy to handle, i.e., it



CONTROL FOG

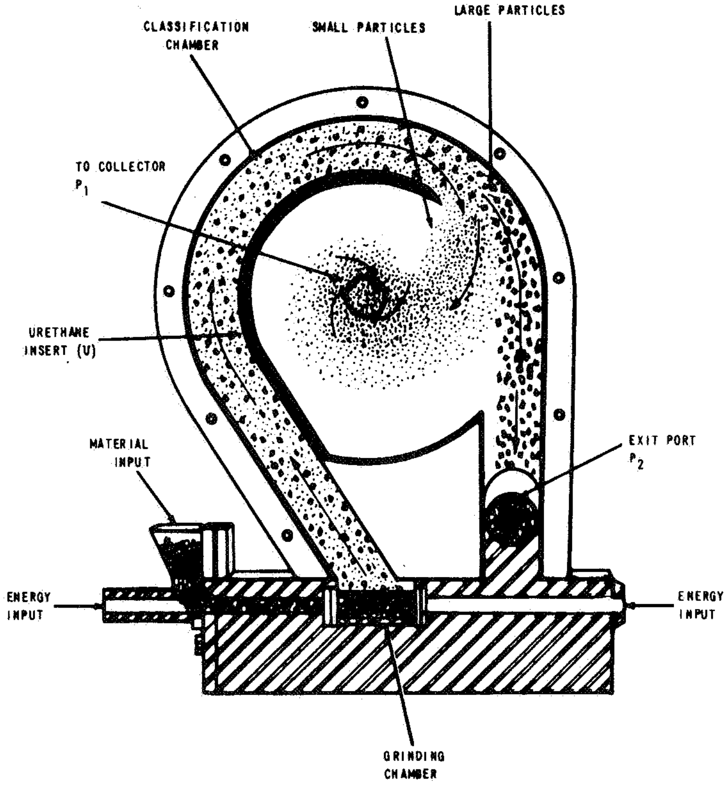
SEEDED FOG

Figure 3 DROPLET IMPRESSIONS OBTAINED AT T = 20 MINUTES IN THE PERSISTENT FOG EXPERIMENT. SCALE SHOWN IS FOR TRUE DROP SIZE.

Table 1

COMPARISON OF FOG CHARACTERISTICS

FOG PARAMETER	NATURAL FOGS		LABORATORY FOGS	
	RADIATION FOG	ADVECTION FOG	t = 10 MIN.	t = 30 MIN.
AVERAGE DROP DIAMETER	10μ	20μ	8 TO 10μ	14 TO 18μ
TYPICAL DROP DIAMETER RANGE	4 TO 36μ	6 TO 64 μ	4 TO 44μ	6 TO 56μ
LIQUID WATER CONTENT	110 mg m^{-3}	170 mg m^{-3}	100 TO 200 mg m^{-3}	150 TO 300 mg m^{-3}
DROPLET CONCENTRATION	200 cm^{-3}	40 cm^{-3}	250 TO 500 cm^{-3}	50 TO 150 cm^{-3}
VISIBILITY	100 m	300 m	200 TO 50 m	200 TO 70 m
DEPTH	100-300 m	200-600 m	10 m	10 m

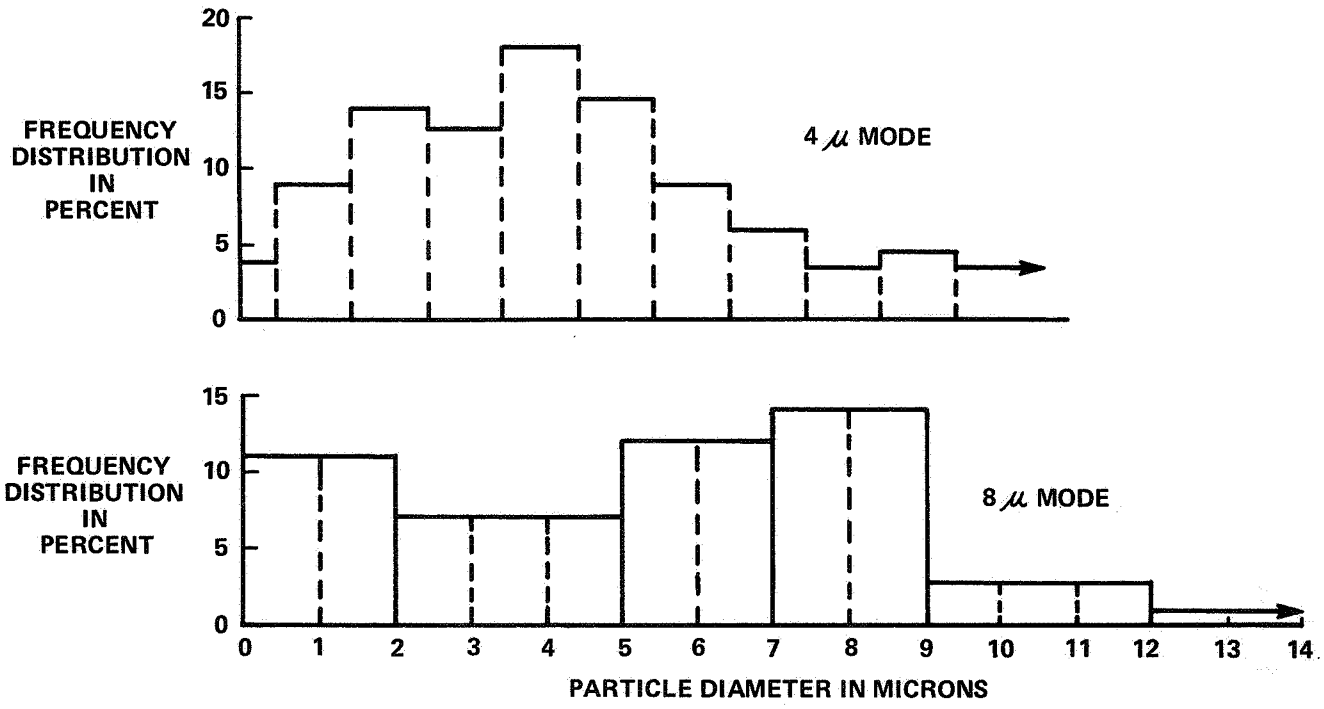


TROST JET MILL WITH MODIFICATIONS

Figure 4

Figure 5

SIZE DISTRIBUTIONS OF NaCl NUCLEI USED
IN SEEDING EXPERIMENTS



can be sized reasonably well and clumping can be controlled with simple storage and handling procedures. Repeated use of NaCl on an operational basis could produce corrosion and cause damage to plant life. We are confident that better materials will become available for operational use and that these problems can be avoided.

Let me now illustrate the results obtained in laboratory seeding experiments. Normally our test procedure was to start with a predetermined set of experimental conditions, form a control fog and observe its behavior for a given length of time. Then, using the same experimental conditions, form a second fog, seed it and observe its behavior for the same length of time. To determine the effects of seeding, the seeded fogs were compared with characteristics of the control fog at the same time after fog formation. Typical visibility improvements are illustrated in Figures 6 and 7. The data in Figure 6 were produced in our first attempt to improve visibility in a persistent fog. The fog was seeded with 8 mg m^{-3} of NaCl having the distribution labeled 4μ mode in Figure 5. Note that the visibility improvement began first and progressed more rapidly at the 15 foot level than at the four foot level. The nuclei simply get to the 15 foot level first. The result is even more evident in Figure 7 in which we used the 8μ mode distribution of salt and increased concentration to 17 mg m^{-3}. In these two experiments, visibility at the four foot level was improved by factors of ~ 3 and 13 respectively, which is representative of the range of improvement that we normally produce in the chamber.

In most of our experiments we seeded the fog only once. As illustrated in Figures 6 and 7 the visibility normally increased to a maximum in five to ten minutes after seeding, remained there for a short time and then began to degrade as the larger droplets, formed on artificial nuclei, fell out. After the solution droplets precipitate out of the chamber the supersaturation due to the secondary expansion causes condensation to occur on natural nuclei for the second time and new fog forms. We demonstrated in several experiments that this degradation in visibility was due to fallout and also that a fog could be effectively seeded more than once. Typical results are illustrated in Figures 8 and 9. Our intent in this experiment was to work with fogs of about 500 foot visibility and to purposely underseed with large particles so that

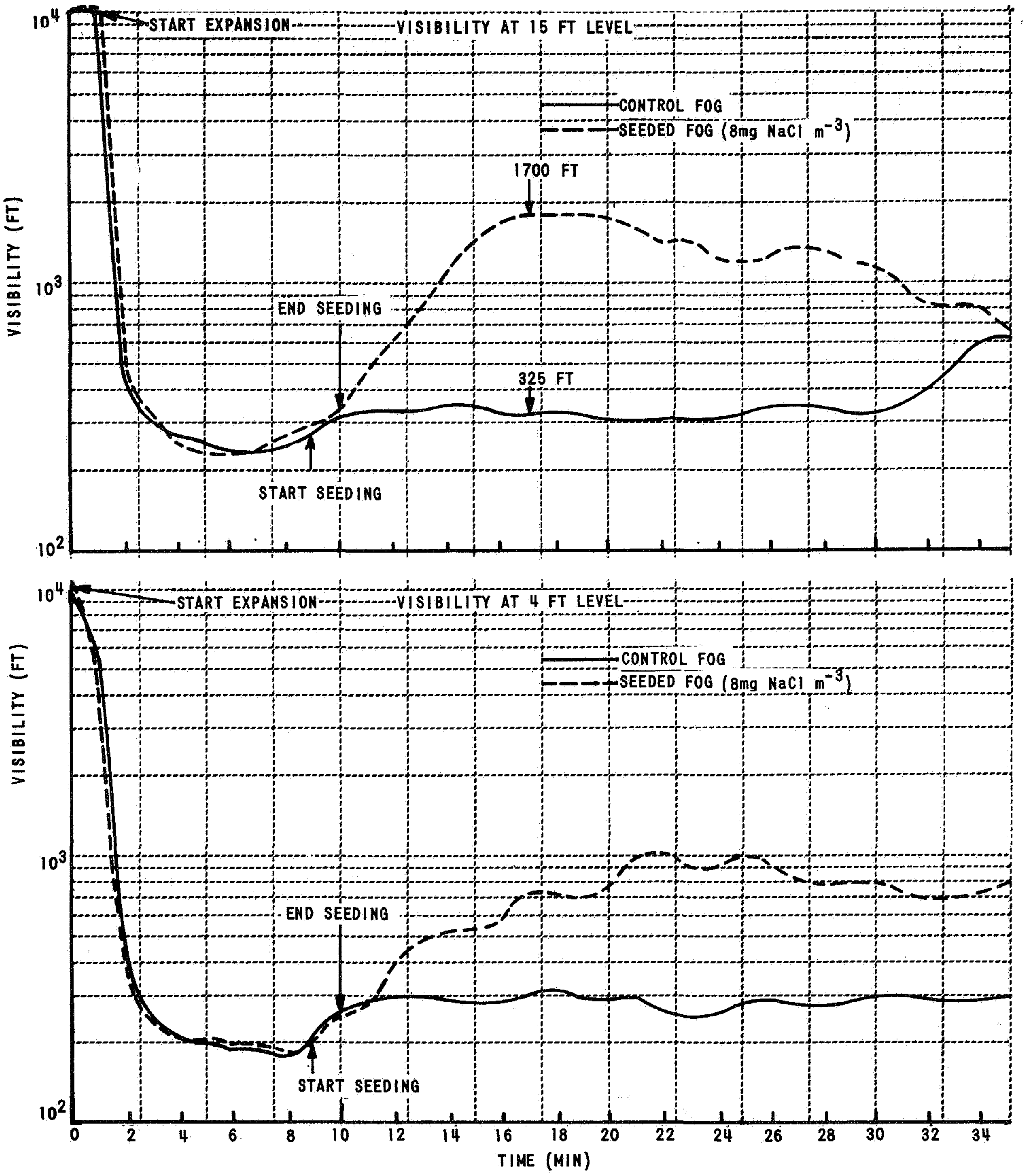


Figure 6 VISIBILITY AS A FUNCTION OF TIME FOR A SEEDED AND CONTROL FOG

Figure 7

VISIBILITY AS A FUNCTION OF TIME FOR A SEEDED AND CONTROL FOG

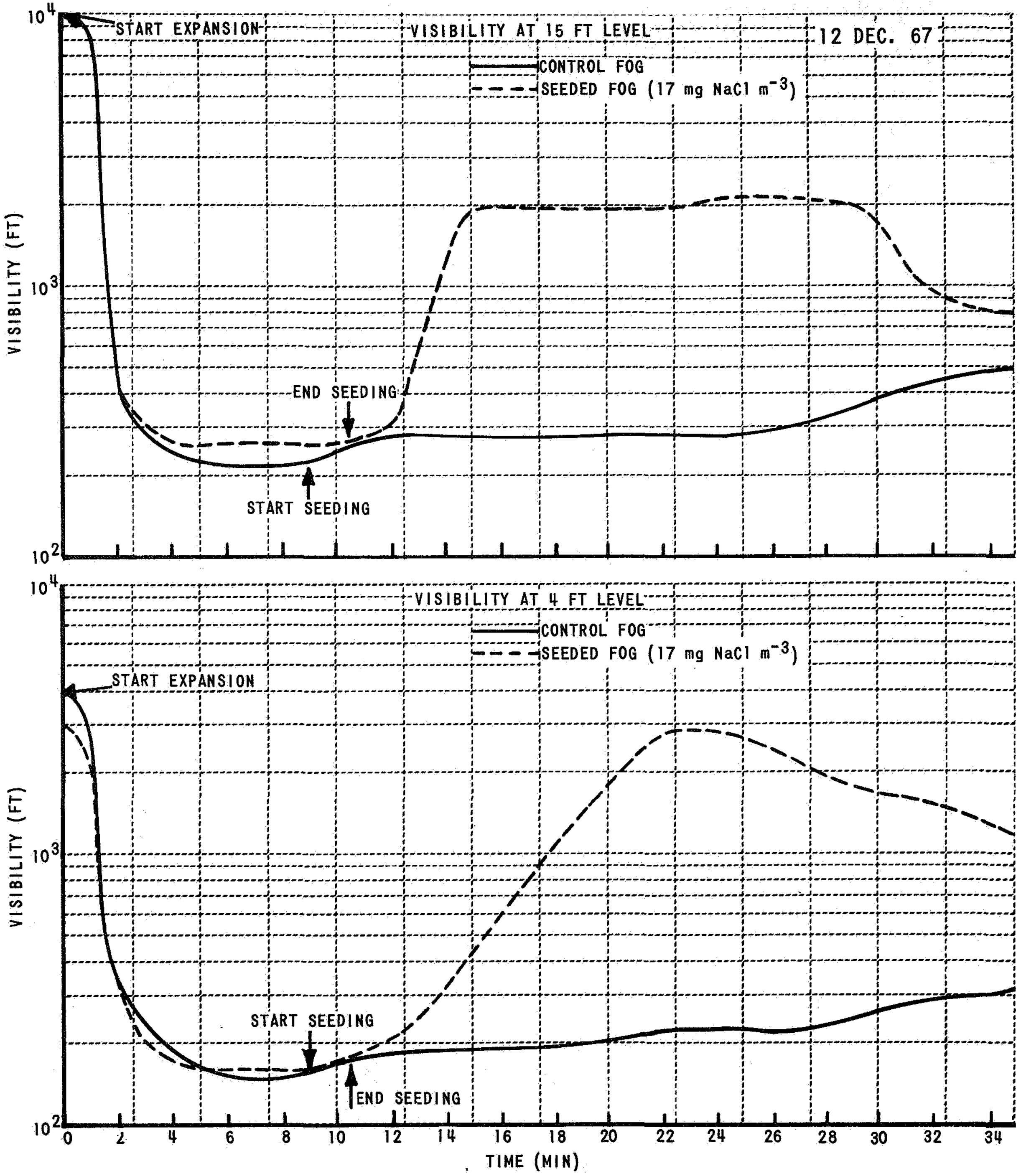


Figure 8

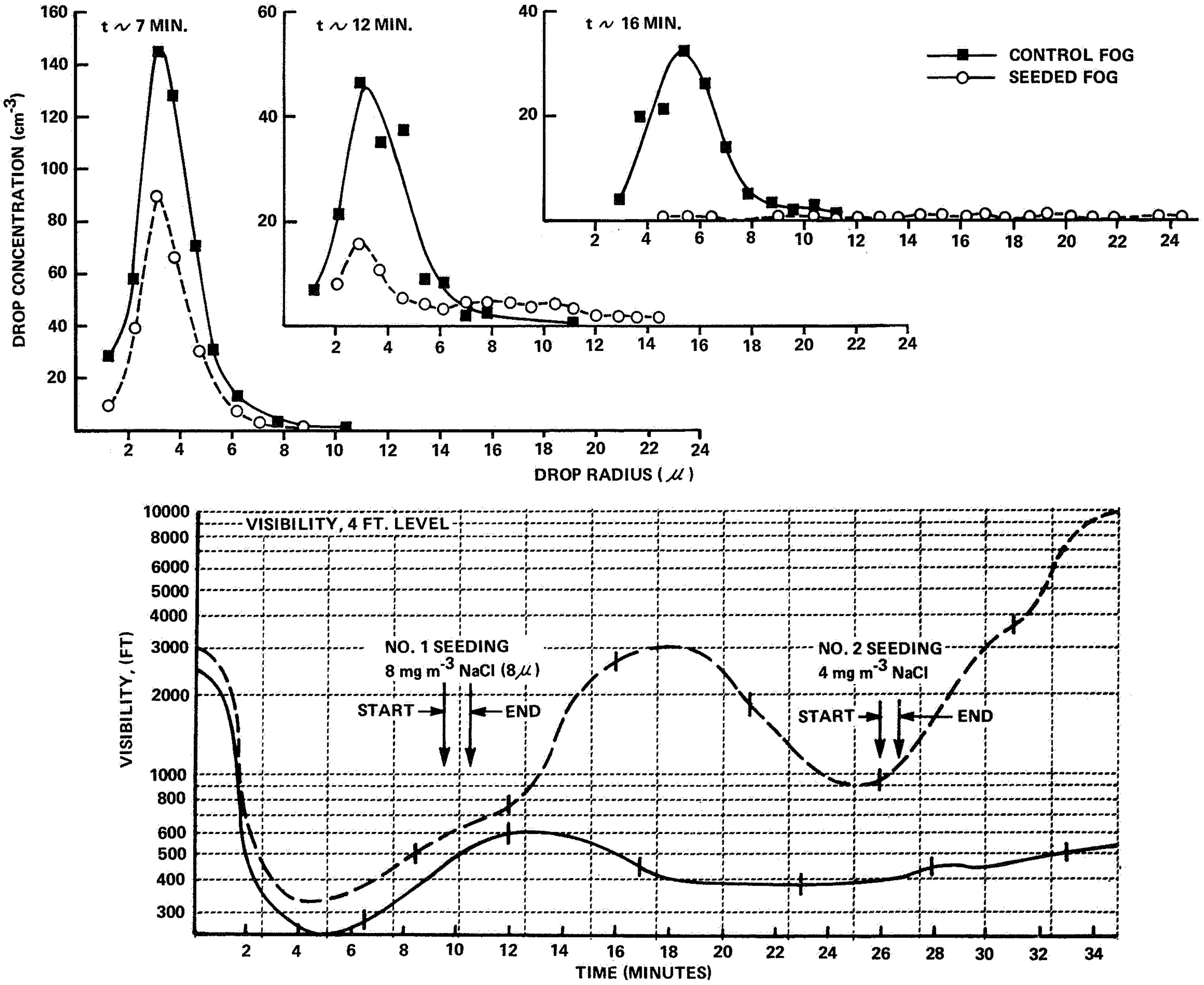
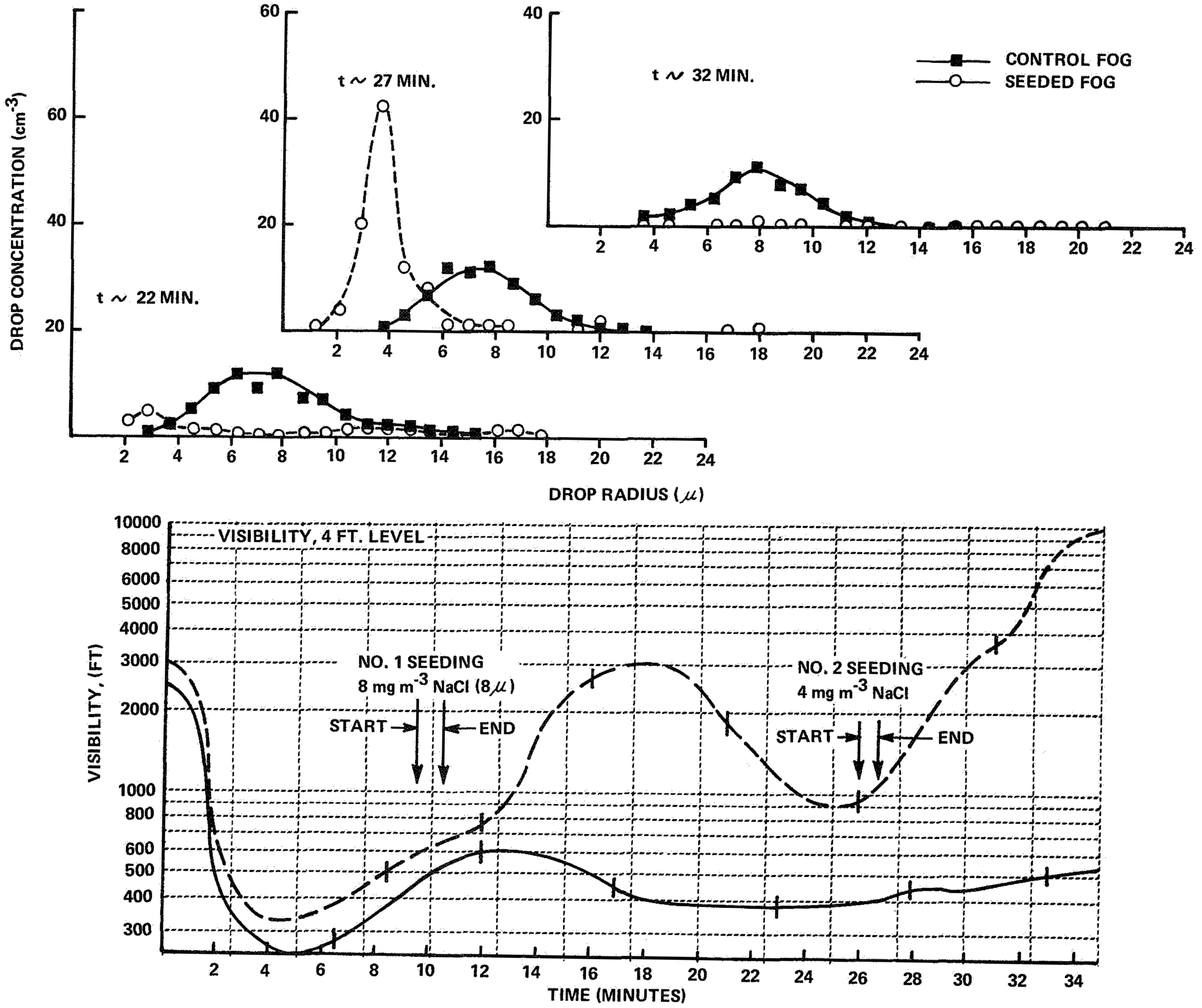

t ~ 7 MIN.
t ~ 12 MIN.
t ~ 16 MIN.
CONTROL FOG
SEEDED FOG
DROP CONCENTRATION (cm^{-3})
DROP RADIUS (μ)
160
140
120
100
80
60
40
20
2
4
6
8
10
12
14
16
18
20
22
24
VISIBILITY, 4 FT. LEVEL
NO. 1 SEEDING
8 mg m^{-3} NaCl (8μ)
START
END
NO. 2 SEEDING
4 mg m^{-3} NaCl
START
END
VISIBILITY, (FT)
10000
8000
6000
5000
4000
3000
2000
1000
800
600
500
400
300
TIME (MINUTES)
26
28
30
32
34

Figure 9



CONTROL FOG
SEEDED FOG
t ~ 22 MIN.
t ~ 27 MIN.
t ~ 32 MIN.
DROP CONCENTRATION (cm^{-3})
20
40
60
2
4
6
8
10
12
14
16
18
20
22
24
DROP RADIUS (μ)
VISIBILITY, 4 FT. LEVEL
NO. 1 SEEDING
8 mg m^{-3} NaCl (8μ)
START
END
NO. 2 SEEDING
4 mg m^{-3} NaCl
START
END
VISIBILITY, (FT)
10000
8000
6000
5000
4000
3000
2000
1000
800
600
500
400
300
TIME (MINUTES)
26
28
30
32
34

fallout would be rapid. We would then have sufficient time to observe the effects of the second seeding.

As shown in the visibility traces, the initial seeding with 8 mg m^{-3} of 8μ mode salt improved visibility to about 3000 ft in eight minutes. During the next eight minutes visibility degraded to about 900 ft and the fog was then reseeded with 4 mg m^{-3} of the same sized salt. The visibility subsequently improved to 10,000 ft. The drop size distributions shown on the two figures were made at the times indicated by the tick marks on the visibility traces and demonstrate the effects of seeding and evolution of the fog quite well. Let us examine them in detail.

The distributions labeled $t \sim 7$ minutes indicate the condition of the fogs prior to seeding. The lower concentration of droplets in the seeded fog is due to two facts: the seeded fog was slightly less dense than the control fog and, more important, the sample of the seeded fog was taken two minutes later in its life cycle than in the control fog. The data for the control fog in Figure 10 illustrate the natural decrease in droplet concentration and the increase in liquid water content that is characteristic of our experiments. The gradual increase in drop size for the control fog is illustrated by the size distributions shown.

At $t \sim 12$ minutes, approximately two minutes after seeding, large solution droplets were beginning to reach the 4 ft level where the drop samples were collected. Visibility had not yet begun to increase, however. As illustrated in Figure 10, the increase in average drop size was compensated for by an increase in liquid water content due to desiccation of the air.

By $t \sim 16$ minutes, virtually all of the natural droplets in the seeded fog had evaporated. (Half circles in the figure indicate less than 0.5 droplet per cubic centimeter.) Almost all liquid water in the fog was in the solution droplets and the total concentration was extremely small; our best estimate was 3 cm^{-3} and virtually all of the droplets were larger than the maximum size in the control fog.

By t ~22 minutes, most of the larger solution droplets had precipitated out of the chamber and those few remaining could not remove the water vapor being made available for condensation by the continued expansion. The drop size distribution suggests that new droplets were being formed for the second time on the natural nuclei that were present in the chamber. Drop concentration was up to 11 cm^{-3} at this time. By t ~ 27 minutes, when visibility reached the second minimum in the seeded fog, the new fog was well developed on natural nuclei and almost all of the solution droplets had fallen out. Droplet concentration was again 100 cm^{-3}. Note in Figure 10 that between t = 16 minutes and t = 26 minutes, while the visibility changed from 2700 feet to 900 feet, the liquid water content remained constant. The entire change in visibility was due to the changes in droplet concentration and size distribution.

The second seeding was initiated immediately after the droplet sample was collected at t = 26 minutes. Between then and t = 32 minutes all natural droplets formed in the second natural fog had evaporated and only solution droplets remained. Total concentration was again down to ~ 3 cm^{-3}. At the same time the concentration in the control fog was approximately 70 cm^{-3}. Note in Figure 10 that solution droplets had begun to fall out of the chamber so that LWC was reduced to ~40 mg m^{-3}. Further improvement in visibility was undoubtedly due to continued precipitation.

Similar analyses have been performed for approximately 40 experiments. Results may be compared with theory as follows:

In Dr. Jiusto's paper, he indicated that the visibility improvement due to the change in drop size distribution alone should be a factor of ~3.5 if 4.5μ diameter salt particles are used. We observed factors between 1.5 and 3.3 experimentally when seeding with the 4μ mode distribution. He indicated that the improvement factor should be ~5 if 9.5μ diameter salt particles were used. With the 8μ mode distribution we have improved visibility by factors ranging from 2.5 to 4 due to redistribution of drop sizes. Visibility improvements beyond these values are attributed to the decrease in liquid water content as illustrated in Figure 10.

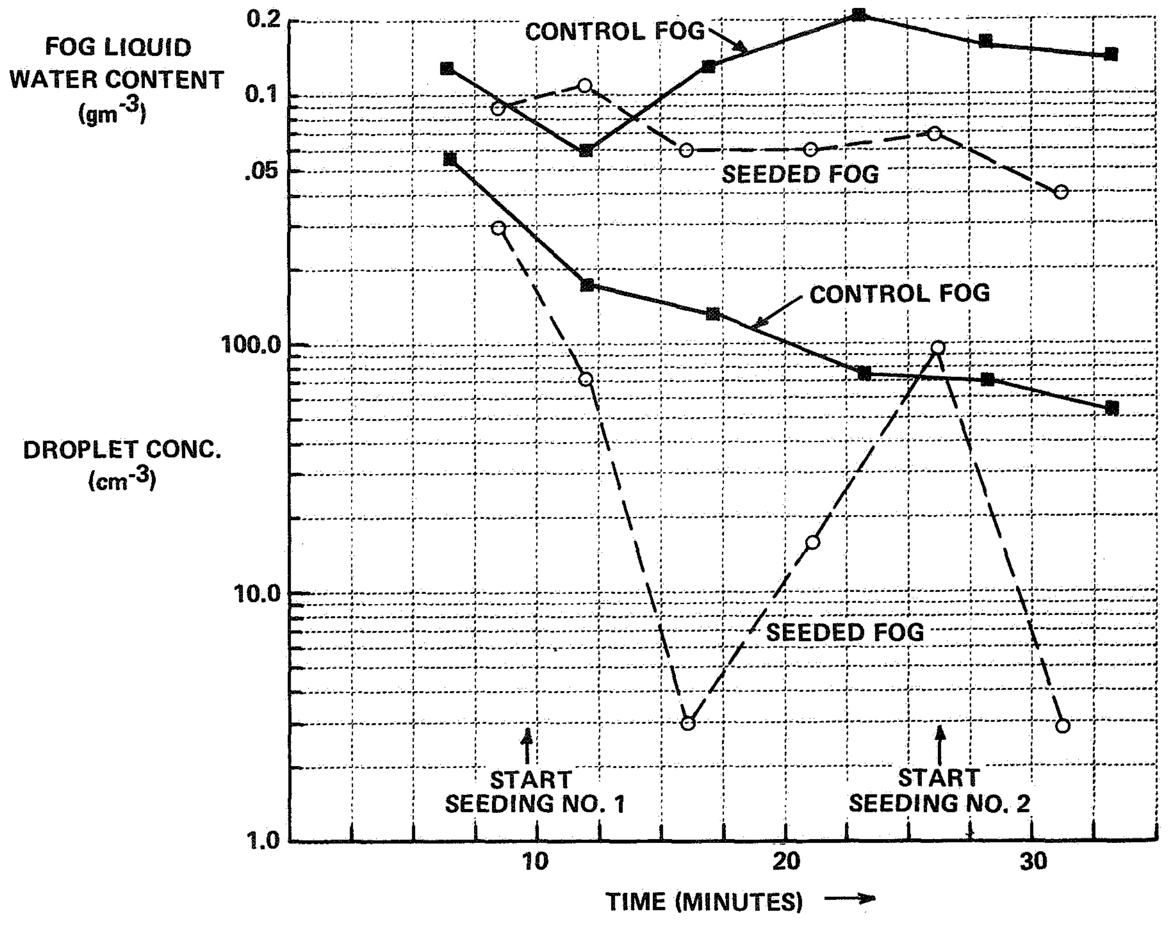

FOG LIQUID
WATER CONTENT
(gm^{-3})
0.2
0.1
.05
CONTROL FOG
SEEDED FOG
100.0
10.0
1.0
DROPLET CONC.
(cm^{-3})
CONTROL FOG
SEEDED FOG
START
SEEDING NO. 1
START
SEEDING NO. 2
10
20
30
TIME (MINUTES) →

Figure 10

Because of the continued cooling associated with the secondary expansion, the concentration of salt required to produce comparable visibility improvement in this type of experiment is 5 to 10 times greater than the theoretical values. In experiments in which we do not use the secondary expansion the experimentally determined requirements are approximately twice the theoretical values. For example, the theoretically required concentration of 4.5μ diameter salt particles is 0.7 mg m^{-3}. Experimentally we have achieved visibility improvements ranging from 4 to 7 times with as little as 1.6 mg m^{-3} of the 4μ diameter mode NaCl, but produce no improvement with 0.8 mg m^{-3}.

These results, while not in perfect agreement, are certainly consistent with theory.

IV. DISSIPATION OF NATURAL FOG IN THE ATMOSPHERE

By

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During the late summer and early fall months of 1968, 31 fog seeding experiments were conducted at the Chemung County Airport near Elmira, N. Y. The primary objective of these experiments was to determine the effects of seeding dense natural fog with carefully sized hygroscopic particles. Our intent was to evaluate the concept by seeding fogs from the ground, and if necessary, perform aerial seeding experiments during the latter part of the fog season. A total of 25 experiments were conducted with ground seeding apparatus during the period May-September 1968. Six aerial seedings of dense valley fog were performed during a three week period in October 1968. Data collected during several of these experiments have now been analyzed and the results are presented here.

Fog Seeding Experiments - Elmira, N. Y.

After reviewing the climatology of several locations, the vicinity of Elmira, N. Y. was selected for fog seeding experiments because of its high fog frequency and relative proximity to the Laboratory. On the average, about 30 dense fogs formed in the Chemung Valley near Elmira between the months of May and October. Most of the fogs appeared to be of the radiation type, forming during cloudless nights between the hours of 12 midnight and 6 AM. The presence of a nearby airfield on one of the adjacent ridges made this site a particularly appealing one for airborne seeding trials.

1. Instrumentation and equipment

Initially, fogs were seeded from the ground using the mobile seeding apparatus pictured in Figure 1.

During operation, hygroscopic nuclei of controlled sizes were fed from within the camper to a nitrogen-driven particle disseminator. The nuclei were then transferred by means of a high-velocity nitrogen stream through copper ducting to a region near the center of, and slightly above, a 9-ft diameter, three-bladed propeller. Here, the particles were injected into the airstream and lifted to altitudes varying from a few feet to several hundred feet depending on the prop speed and atmospheric stability. A protective steel shroud, which also enhanced air flow around the prop, was positioned around the propeller hub assembly. Dry nitrogen, used for transferring nuclei to the prop wash, was stored in large high pressure cylinders mounted on the sides of the rig.

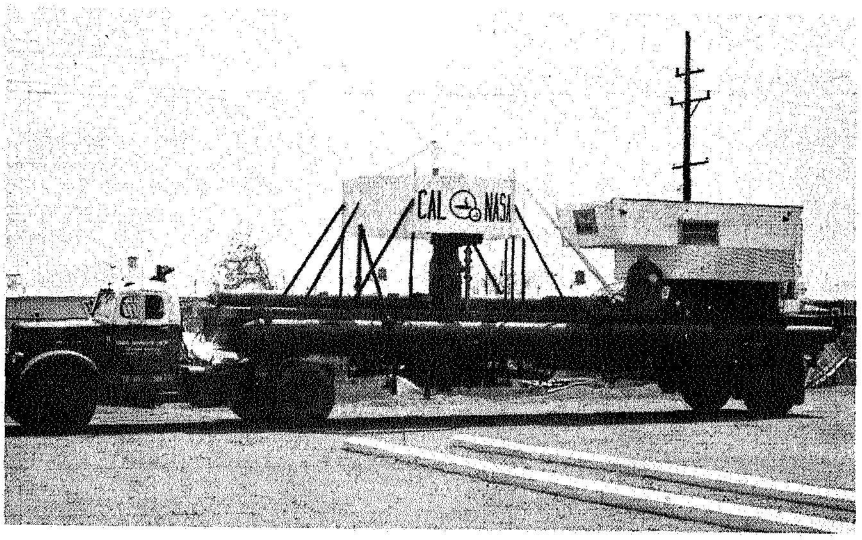

Figure 1 MOBILE SEEDING APPARATUS

Instrumentation for making observations in fog included:

a. A Piper Aztec airplane equipped to measure drop sizes and temperatures at various altitudes in fogs and to provide photo reconnaissance of the seeded area. Photographic equipment consisted of two 70 mm Hasselblad cameras mounted in the fuselage of the aircraft.

b. A mobile van carrying instrumentation for measuring drop sizes, liquid water content, visibility, nucleus concentration and temperature in seeded and unseeded fog.

c. Four transmissometers for measuring visibility at selected locations on the airport grounds.

d. A CAL vehicle for locating the path of the seeding material.

2. Fog characteristics

Prior to seeding experiments, the CAL Piper Aztec was sent aloft through the dense fog to gather data on drop sizes, vertical temperature distribution and fog depth. Supplementary data, which included measurements of visibility, liquid water content, drop sizes, and nucleus concentration were obtained at the ground. In Table I typical physical characteristics of the valley fogs in Elmira, N. Y. are compared with the radiation and advection fog models developed during the first year of this program.* The data for the Elmira fogs represent averages of measurements made four feet above the surface in 13 fogs.

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*James E. Jiusto, Investigations of Warm Fog Properties and Fog Modification Concepts, NASA CR-72, July 1964.

TABLE I
COMPARISON OF FOG CHARACTERISTICS

FOG PARAMETER	RADIATION FOG	ADVECTION FOG	VALLEY FOG - ELMIRA, N.Y.
AVERAGE DROP DIAMETER	10μ	20μ	18μ
TYPICAL DROP DIAMETER RANGE	$4\text{-}36\mu$	$6\text{-}64\mu$	$4\text{-}50\mu$
LIQUID WATER CONTENT	110 mg m^{-3}	170 mg m^{-3}	160 mg m^{-3}
DROPLET CONCENTRATION	200 cm^{-3}	40 cm^{-3}	55 cm^{-3}
VISIBILITY	100 m	300 m	100 m
VERTICAL DEPTH	100-300 m	200-600 m	100-200m

As shown, the data for the valley fogs and the advection fogs are similar. In Figure 2 vertical profiles of several pertinent fog parameters are shown for average data obtained in four Elmira valley fogs. The data were obtained during take off and ascent of the CAL Piper Aztec in the fogs. Values of drop concentration and liquid water content were computed from measured drop distributions assuming a constant visibility throughout the fog volume. (It is recognized that visibility is not constant; however the results of computations are intended to provide an indication of trends in the data rather than absolute measures.) Note the steady decrease in average drop diameter as a function of height above fog base. Accompanying the decrease in drop size is an increase in drop concentration, suggesting that conditions typical of radiation fog (i.e., high concentration of small drops) exist only in the upper portion of the fog. Similarly the liquid water content in the valley fog decreases steadily from a high value near the fog base to somewhat lower values near the top.

In Figure 3, selected drop size distributions are shown for four levels within a representative fog. Also shown for each distribution are the average drop diameter and computed values of drop concentration and liquid water content. Again the rather pronounced shift in drop sizes toward smaller values near the fog top is apparent.

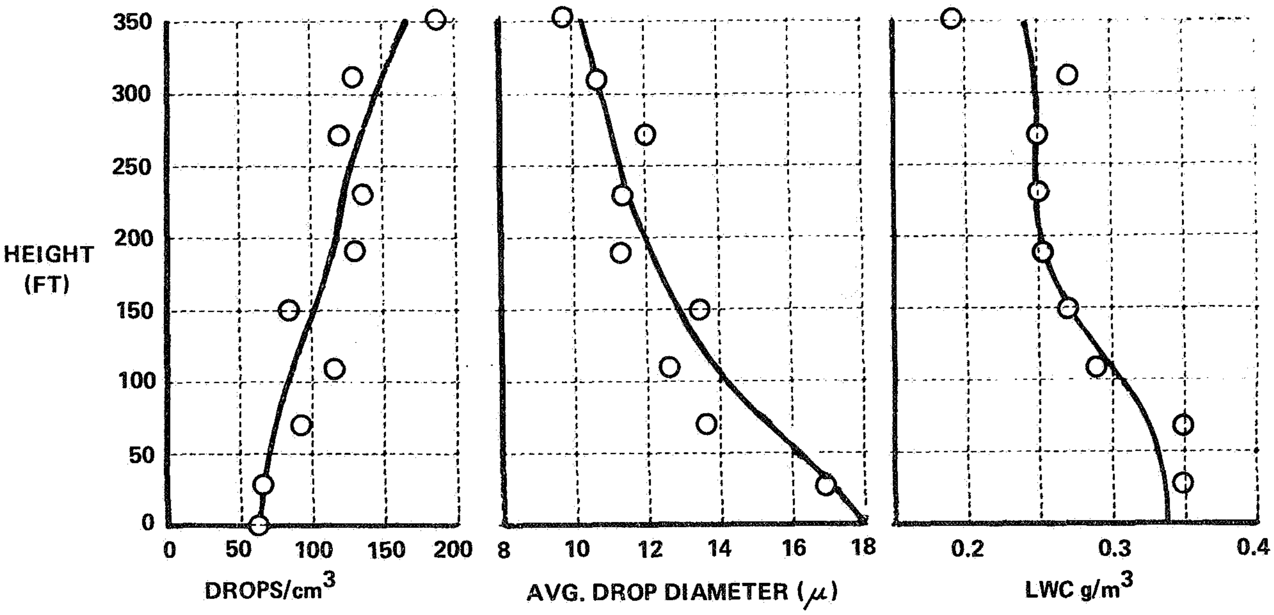

Figure 2 VERTICAL PROFILES OF VALLEY FOG PARAMETERS (AVERAGE DATA FROM FOUR FOGS)

Repeated observations of the formation of fog at our field site suggest that mixing of the nearly saturated layers of air in the valley govern the fog formation process and, as well, shape the drop size distribution and liquid water content of the fog. As always, a variety of other mechanisms involving energy, moisture and heat exchange are also important factors in fog development.

We have noticed that during the early evening, moderate breezes frequently blow across the valley and prevent significant fog formation. As the ambient winds subside, drainage from the hills begins to predominate and surface winds in the valley become aligned with the orientation of the valley. Radiational cooling of the earth's surface and subsequent loss of heat from the lowest layers of air to the ground produce nearly saturated conditions close to the surface. Temperature profiles obtained shortly before fog formation at Elmira have shown that substantial inversions, frequently exceeding 3°C in 100 m, exist in the lowest few hundred feet of air. Once cold air drainage predominates, saturated surface air from the hillside tends to displace the somewhat warmer, nearly saturated air in the valley and, in the process, mixing occurs.

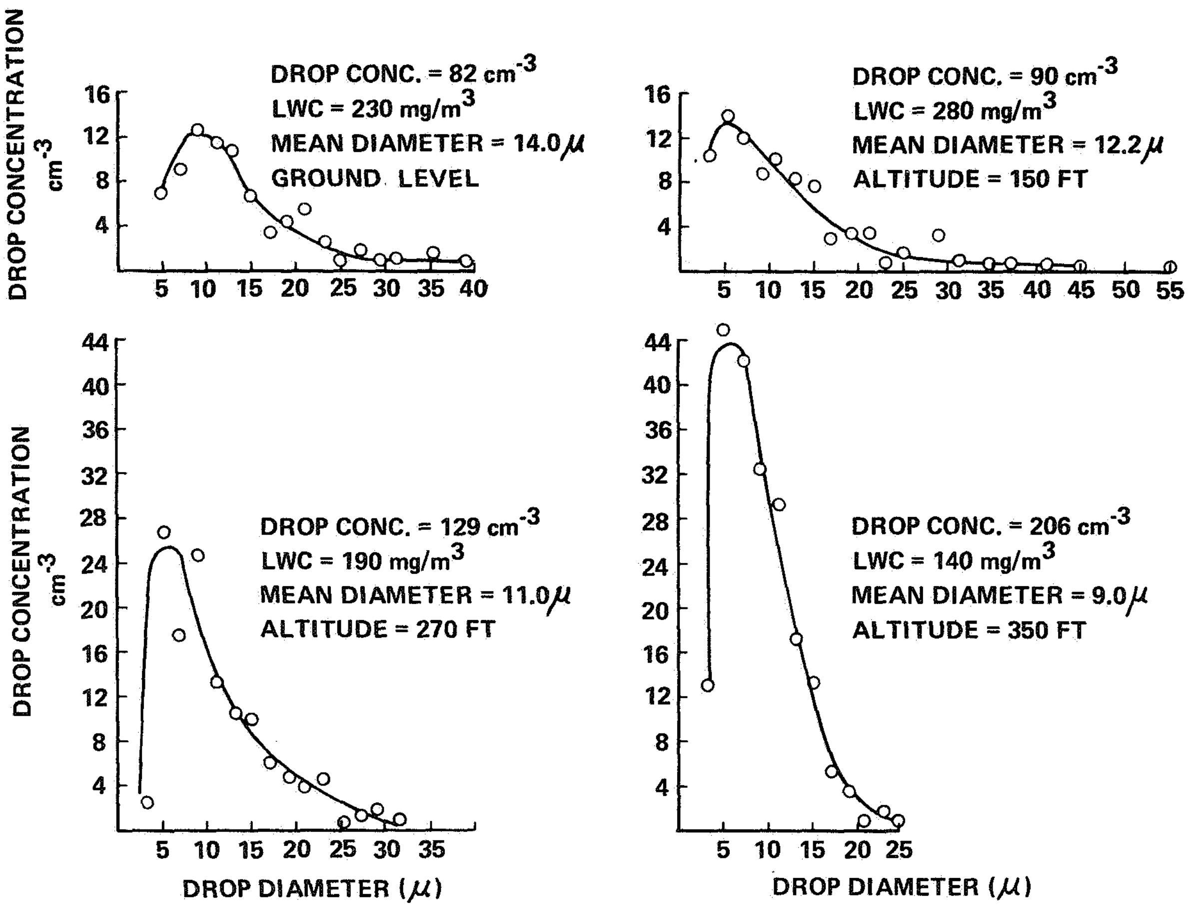

Figure 3 DROP SIZE DISTRIBUTIONS AT FOUR LEVELS IN A VALLEY FOG - ELMIRA, N.Y. 30 AUGUST 1968

In the phase diagram (Figure 4) conditions typical of the valley atmosphere prior to fog formation are illustrated. If, as shown, two parcels of moist air, A and B, having different temperatures and relative humidities are mixed, significant supersaturation will occur and fog will form. The characteristics of the mixture of the two air masses will be represented by some point on the straight line connecting A and B.

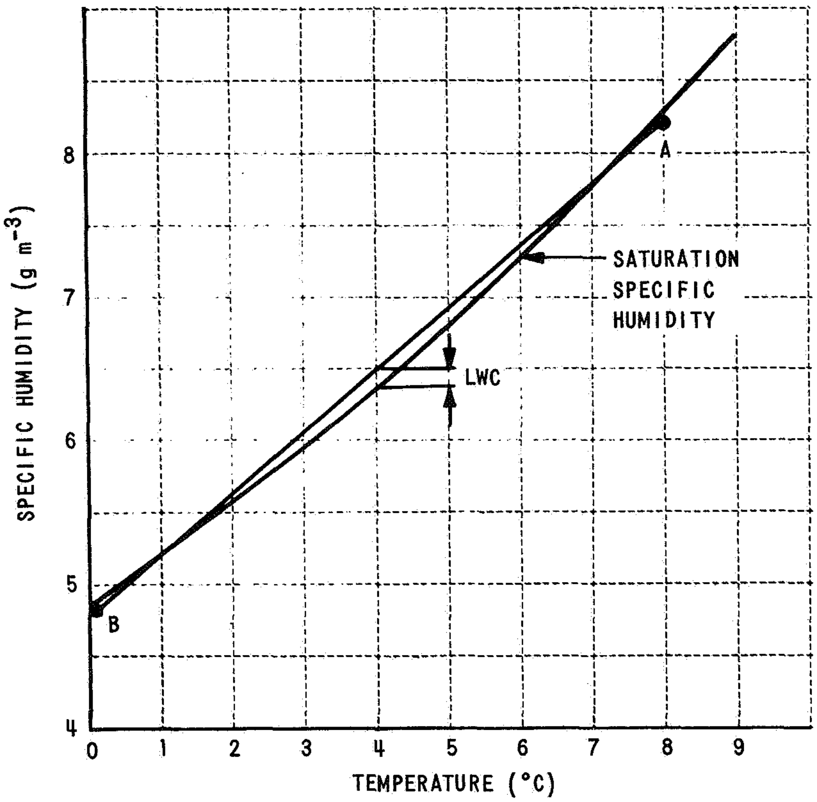

Figure 4 SATURATED SPECIFIC HUMIDITY AS A FUNCTION OF TEMPERATURE

In the formation of valley fog, initial mixing occurs near the base of the hills and fog forms there. As drainage continues, the mixing process persists and the depth of the fog increases. As the ratio of cold air from the hillside (point B) to the somewhat warmer valley air (point A) increases more water is made available for condensation on cloud nuclei and widespread fog develops. Near the fog base, the drops are large and the LWC is high, but the concentration of droplets is depleted because of sedimentation and fallout.

Near the fog top continued radiational cooling of the air results in slight supersaturation and additional fog formation. The continuous formation of new droplets with negligible terminal velocities accounts for the observed high concentration of small droplets near the fog top.

Although other explanations of the manner in which fog forms at the valley site may be plausible, most of our observations suggest that the above reasoning is valid. It is obvious, however, that many additional measurements of the microphysical features of the fog would be needed to define how these changes take place with time. At the present time we are modeling the fog formation process in the computer by assuming various observed nucleus size spectra and producing fog by continuous cooling and also mixing. The results of these studies will be reported in a subsequent report.

3. Fog seeding results - ground seeding

As previously stated, fog seeding experiments were initially performed employing ground based seeding apparatus. A total of 25 ground seeding experiments were conducted, most of which resulted in some observed improvement in visibility. In more than half of the experiments the seeded air mass passed between the instrumentation sites and consequently quantitative data could not be taken. In spite of this difficulty, several reasonably successful seeding experiments were performed in which detailed information was obtained on fog characteristics. Experiments in which a noticeable visibility improvement occurred in the seeded area are typified by results presented below. In this experiment (8 September 1968) the seeded area passed over one of our transmissometers as observations of drop size were being made. Detailed analysis of the relationships between drop sizes, visibility and liquid water content of the fog could therefore be made.

Prior to seeding, the CAL Aztec obtained data on fog characteristics. Fog had formed in the valley about 4:30 AM and by 5 AM airport ground conditions were WOXOF. Following take off, (6:30 AM) the airborne observer reported fog depth to be 100 m. Visibility at the ground was about 100 m and fog liquid water content was 170 mg m^{-3}. As was usually the case, a temperature inversion existed in the fog, amounting in this case to 3.1°C in 100 m. Wind velocity was three knots at 260°

Our initial plan was to seed the fog with 280 lbs of sized NaCl* (5-20μ diameter) at a dissemination rate of about 30 lbs/min. The instrumented van was positioned a short distance from the seeding rig so that drop size data could be collected in the unmodified fog and in the seeded area as the plume moved downwind. Shortly after seeding was started, however, a 60° shift in wind caused the salt plume to drift away from our instrumentation and the airport. The experiment was, therefore, terminated after 4 minutes of seeding (~ 130 lbs of material were expended) and the rig was moved to a more favorable location.

The position of the seeding unit for the second experiment is shown in Figure 5 (the original location of the seeding rig was on the approach end of Runway 10). Also shown in the figure are the locations of transmissometers used in this experiment. The distance from the seeding unit to transmissometer (1) is 0.83 mile.

Seeding with the remaining 150 lbs of material was scheduled for 7:25 AM. Fog density and liquid water content had not changed appreciably during the previous hour. Based on the wind direction and speed (240° at 6 knots) we predicted that particles injected into the fog in the vicinity of Taxiway B would reside in the foggy air approximately 9 minutes before reaching the opposite end of the airport. According to our model, this would be ample time for the salt to have a significant effect on the natural drop size distribution.

Seeding was started at 7:25 AM and completed at 7:30 AM. The 30 lb/min dissemination rate was intended to provide approximately 3 mg of NaCl particles per cubic meter of treated fog. Droplet data obtained by ground observers indicated that the salt plume followed a path similar to that shown in Figure 5. Visibility measurements obtained with transmissometer (1) indicate that visibility increased from about 300' to about 820' between 7:30 and 7:42 AM. No other transmissometer indicated any change in visibility during the same period of time. The improvement in visibility by a factor of 2.5 to 3.0 is typical

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*Particle sizing done by Meteorology Research, Inc., Altadena, Calif.

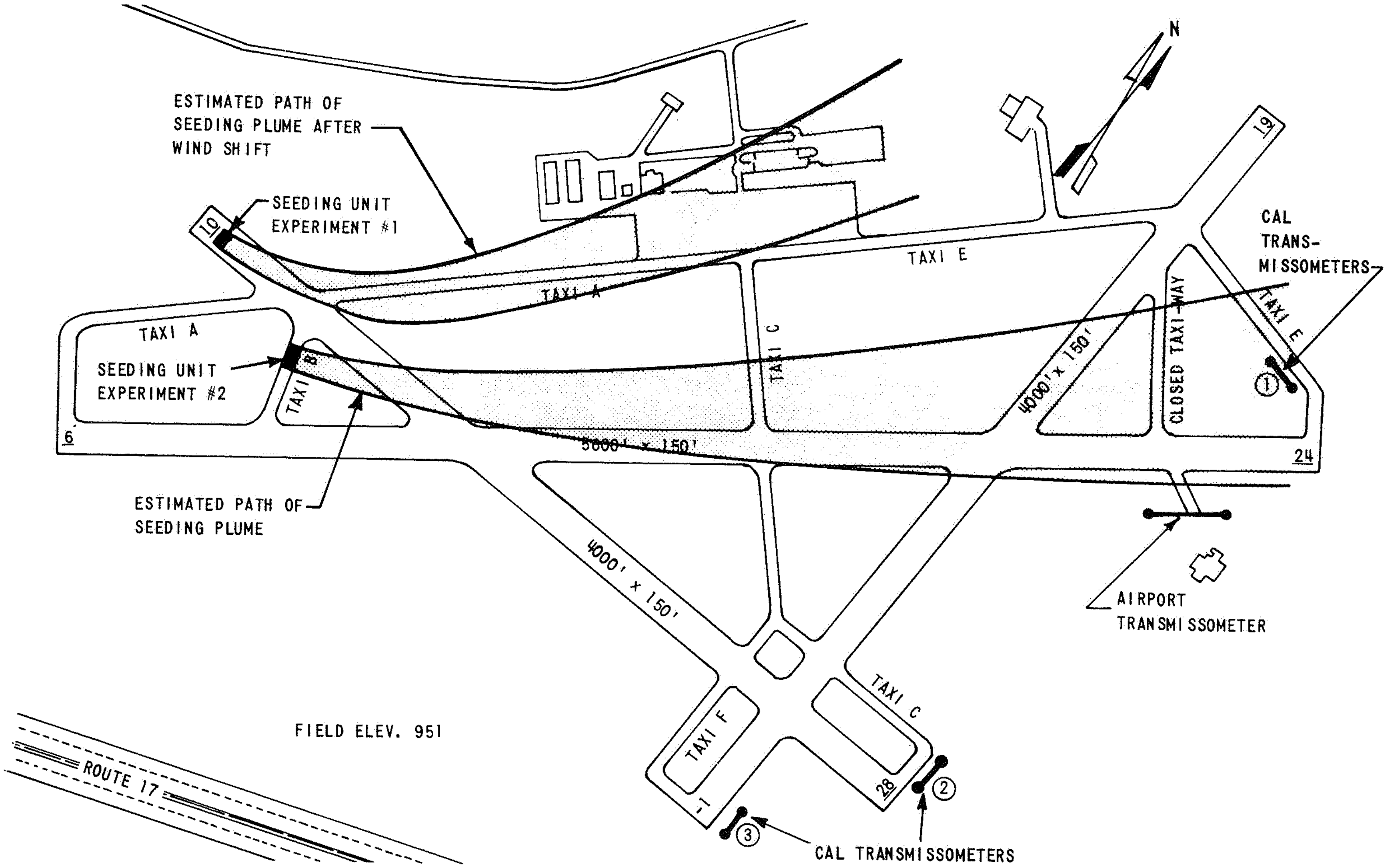

Figure 5 LOCATION OF SEEDING UNIT AND TRANSMISSOMETERS AT EXPERIMENTAL FIELD SITE - CHEMUNG COUNTY AIRPORT, ELMIRA, NEW YORK, SEPTEMBER 8, 1968

of the results obtained in most ground seeding experiments.

Because of the large average drop sizes in the natural fog, the expected visibility improvement was less than we originally predicted. For example, seeding a fog consisting of 5μ radius drops with 10μ radius dry hygroscopic particles could be expected to give a ten fold increase in visibility, according to our model. Seeding a fog consisting of 9μ radius drops, using the same material, could only be expected to give a six-fold increase in visibility due to changes in drop size.

Figure 6 shows the drop size distribution obtained in the seeded portion of the fog at about 7:40 AM. The data were collected alongside transmissometer (1). A drop distribution from the adjacent unmodified fog, taken a few minutes earlier, is shown for comparison. As shown, a significant change had occurred in the drop sizes after seeding. Also shown in the legend of the figure are the computed drop concentrations, liquid water contents and mean volume diameters for the seeded and unseeded fogs. It is perhaps interesting to note that the liquid water content was higher in the seeded region than in the natural fog. All visibility improvement at the time of these measurements therefore resulted from a favorable shift in drop size distribution.

Variations in the calculated liquid water content can be expected, of course, depending on whether large saline droplets are encountered when the sampling is taken. It is frequently difficult to obtain statistically valid drop size distributions, particularly in seeded fog where drop concentrations are low. In spite of these difficulties the data suggest that after seeding, the relative humidity was initially lowered by a few percent, an occurrence which is expected from theory and commonly noted in laboratory experiments. Somewhat later in time, after most of the largest drops settled out of the fog, visibility improvements greater than those measured probably occurred but instrumentation was not suitably located for observation further downstream.

Results from early tests demonstrated that seeding from the ground, using sized hygroscopic nuclei, can be effective in producing visibility improvements. Although ground based seeding did not improve visibility above the landing minimums, the nearly three-fold increase in visual range was encouraging. The principal problem seemed to be that of effectively distributing the seeding material throughout the fog volume. Mixing of unmodified fog with the narrow seeded region from a single seeding unit frequently limited the visibility improvement that could be achieved. Improved methods of particle dissemination must be sought if the ground system is to be adapted to airport use. These limitations prompted us to test aircraft seeding techniques during the latter part of the experimental period.

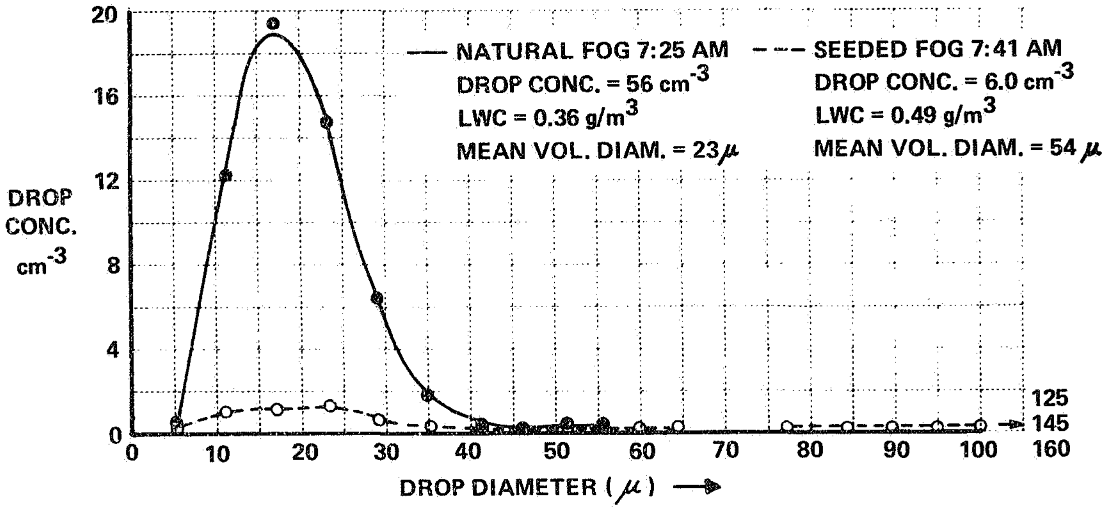

Figure 6 COMPARISON OF DROP SIZE DISTRIBUTIONS FOR NATURAL AND SEEDED FOG SEPT. 8, 68

4. Fog seeding results - aerial seeding

Aerial seedings of dense valley fog were performed during the first three weeks in October, 1968. A Piper Pawnee aircraft, designed for crop dusting, was obtained for the experiments.* A total of six seeding trials were conducted using various aerial seeding methods. Our plan was to seed

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*Rented from EG&G, Boulder, Colorado.

the fog a prescribed distance upwind of the airport (depending on wind speed and direction) and allow the seeded area to drift over the ground instrumentation located near the runways.

On two occasions spiral seeding over the fog top was attempted but difficulties in maintaining the prescribed flight pattern resulted in ineffective seeding. The procedure that produced the most outstanding results involved flying perpendicular to the prevailing wind and disseminating dry particles in "evenly" spaced rows over the fog top. For these experiments the volume to be cleared of fog was approximately 3×10^7 m^3. The results of one seeding trial (16 October 1968) are discussed below in some detail. In this experiment a significant amount of data were collected, both in seeded and unmodified fog.

Prior to seeding, routine procedures were followed in collecting data on fog characteristics. Fog depth was reported as 350 ft with a layer of haze exceeding 1000 ft lying above the fog top. Horizontal visibility measured 300 ft; liquid water content was about 280 mg m^{-3}. Representative drop size distributions at four different levels in the fog prior to seeding are shown in Figure 7. Note the differences in drop concentration and size near the fog top as compared to the values near the base.

Seeding was accomplished with approximately 700 lbs of NaCl* having a size range of 10-30μ diameter. The aircraft completed seeding of the fog top in about 7 minutes, traversing an area approximately 1/2 mile by 1/4 mile. The salt concentration within the fog was therefore about 10 mg m^{-3}. Three photos taken during various stages of the experiment are shown in Figure 8. Note, in the second photo the seeding aircraft and trailing salt plume. Within a few minutes after seeding, narrow paths began to open in the fog, increasing in size until, after 15 minutes, large areas of the fog were completely dissipated. (Visibility in the seeded area improved to approximately 1/2 mile.) The cleared region persisted for about

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*Sized material purchased from Meteorology Research, Inc., Altadena, Calif.

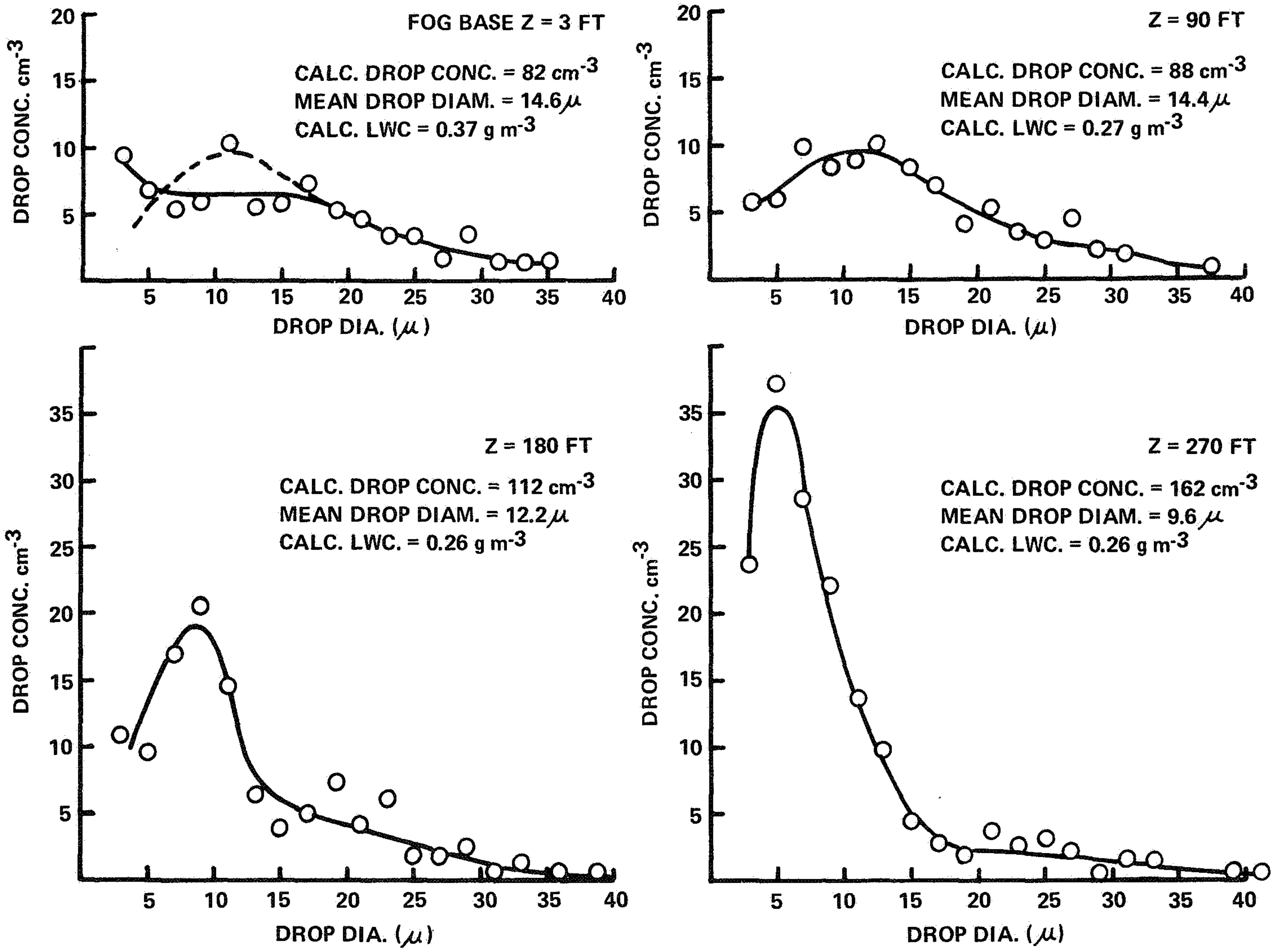
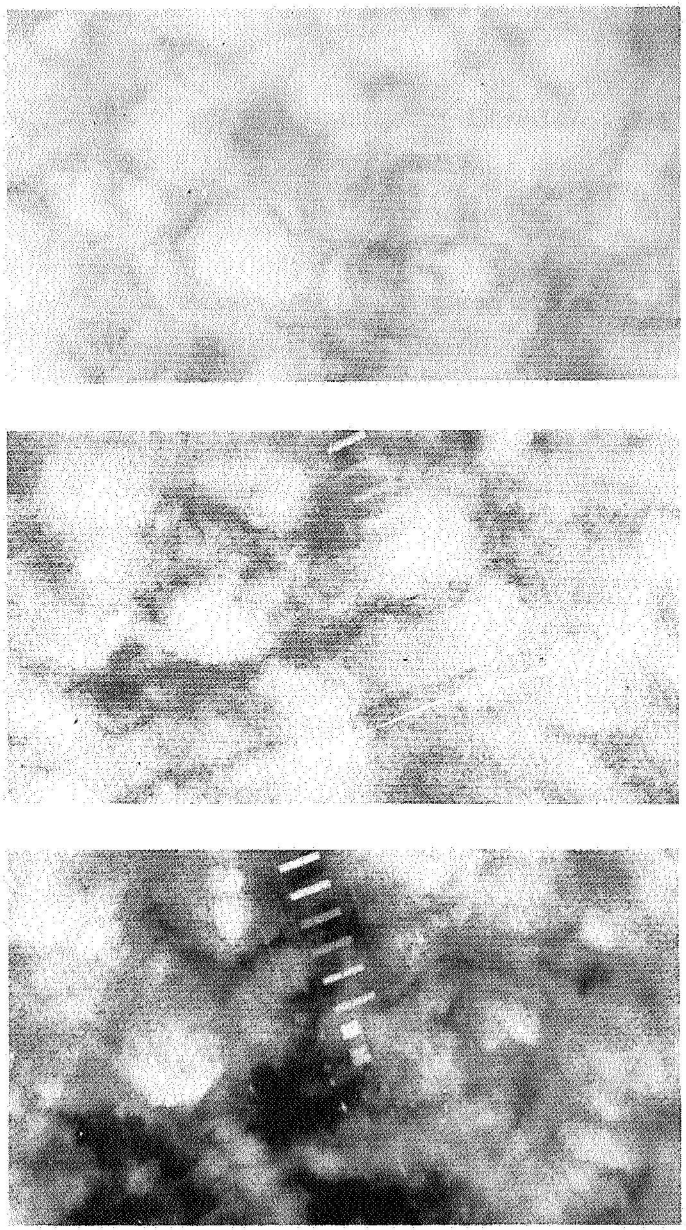


Figure 7 DROP SIZE DISTRIBUTIONS AT FOUR LEVELS IN A VALLEY FOG PRIOR TO SEEDING - ELMIRA, NEW YORK, 16 OCTOBER 1968



TARGET AREA ONE MINUTE PRIOR TO SEEDING.

THE TARGET AREA DURING SEEDING (SALT PLUME AND SEEDING AIRCRAFT ARE VISIBLE).

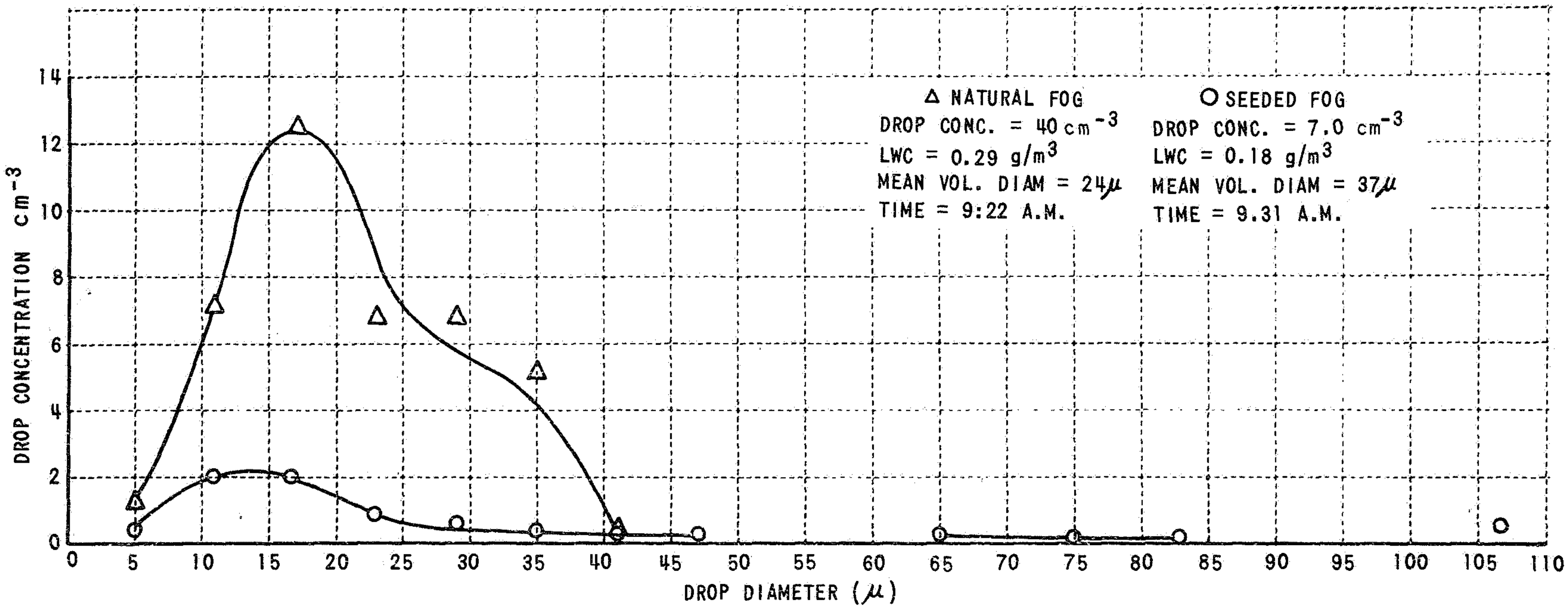
THE TARGET AREA 15 MINUTES AFTER START OF SEEDING

Figure 8 FOG TOP VIEWED FROM AN ALTITUDE OF 10,000 FEET. NOTE THE HANGARS (200 FEET LONG) AND AIRCRAFT ON THE GROUND AFTER SEEDING.

15 additional minutes before unmodified fog began to encroach into the seeded region and reduce visibility.

Figure 9 shows a comparison of drop size distributions for the seeded and natural fogs. The curves represent data taken approximately one minute before seeding began and again approximately nine minutes after seeding had started. Tabulated in the legend of the figure are several fog parameters as determined from the data. Note the rather dramatic shift in the drop size distribution after seeding. It is apparent from the data that the seeded fog was comprised of fewer droplets having somewhat large size. Accompanying the shift in drop sizes for the data shown was a decrease in liquid water content of the fog due to sedimentation of the largest saline drops. The combined effects of drop size differences and liquid water changes were responsible for the visibility improvements that occurred. Analysis of data has indicated that approximately 60% of the visibility improvement was accounted for by the decrease in fog liquid water caused by precipitation of the large saline droplets after seeding.

Figure 9 COMPARISON OF DROP SIZE DISTRIBUTION FOR SEEDED AND UNSEEDED NATURAL FOG
ELMIRA, N.Y. 10/16/68



III. CONCLUSIONS

These experiments have demonstrated the validity of a concept for improving visibility in dense natural fogs by seeding with sized hygroscopic particles. Data analysis has shown that the initial visibility improvement in seeded fog is the result of a favorable shift in the drop size distribution (even though liquid water content is temporarily increased). Subsequent improvement in visibility is due to a reduction in liquid water content associated with precipitation of large saline droplets formed on artificial nuclei.

Airborne seeding experiments were most effective in causing fog dissipation. In the ground seeding experiments, it is likely that mixing of unmodified fog into the narrow seeded region limited the visibility improvements that occurred. Multiple seeding passes with the aircraft enabled us to treat a much wider volume of fog and minimized the effects of mixing.

Several problems still exist. In most cases it was apparent in both airborne and ground based seeding experiments that a substantial amount of clumping of seeding material had occurred. Thus, the efficiency of the seeding material was substantially reduced. More effective methods for particle dissemination must be devised.

An equally important problem is that of selecting and testing non-corrosive, ecologically safe chemicals to replace NaCl as the seeding material. Laboratory experiments have shown that several hygroscopic materials are almost as effective as salt for fog dispersal. Additional work leading to the selection of more suitable seeding agents is now underway. Field evaluation of one or two of the most promising materials is one of the objectives of next year's research.

V. COMPUTER SIMULATION OF FOG SEEDING EXPERIMENTS

By
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Introduction

A computer model has been developed to simulate the response of natural and artificial fogs to seeding with hygroscopic nuclei. The same theoretical principles of warm fog modification with sized hygroscopic nuclei that were discussed by Dr. Jiusto form the basis of the computer model. The computer model, however, permits us to eliminate certain simplifying assumptions that were employed in earlier theoretical treatments. The model also allows us to study in detail the influences of such variables as the properties of the natural fog, the amount and size distribution of seeding materials, and the method of dispensing the seeding material into the fog. In addition, a computer model facilitates the investigation of such complicating factors as the coalescence between falling solution drops and the fog drops (important in the modification of stratus decks and deep fogs), and the action of atmospheric turbulence in dispersing the seeding material and mixing of unmodified with modified fog.

Before turning to a description of the computer model, it is important to emphasize the two-way exchange of information between the field-experimentation program and the computer modeling work on Project Fog Drops, an exchange that contributed to the improvement and success of both phases of the project. The field-experimentation program provided detailed data on the properties of valley fogs at the experimental site near Elmira, N. Y. (including drop size distribution, liquid water content, visibility, vertical structure and condensation nucleus measurements), which are necessary inputs if the computer model is to provide accurate simulations of seeding effects. The computer model, in turn, provided information on the seeding rates required to produce significant clearing under various conditions and the times required for this clearing to be effected. The latter quantity was important in the placement of measuring equipment in relation to the mobile seeding rig in the ground-based seeding experiments and to the seeded area in aerial seeding experiments.

Description of the Computer Model

In a mathematical sense, the computer model integrates numerically a system of ordinary, first order, differential equations which describe the growth and sedimentation of the solution drops that form on the particles of hygroscopic seeding material, the accompanying reduction in relative humidity, and the resulting evaporation of the natural fog drops. The results of seeding are assessed by periodically computing and printing out such measures of the effectiveness of seeding as the horizontal visibility and liquid water content of the fog, as well as the relative humidity and drop size distribution.

In order to model the effects of the sedimentation of solution drops and provide an accurate description of the vertical variation of visibility and other fog properties, the effects of seeding are computed at several equally spaced vertical levels in a model fog. The initial supersaturation, the size distributions of fog drops and of particles of seeding material, and the cooling rate (if any) at each vertical level are specified at the beginning of a simulation. The size distributions of fog drops and of seeding particles and, hence, of solution drops that form on the particles, are approximated in the model by discrete size classes.

The basic equations of the computer model are shown in Figure 1. For each size class, k, of fog or solution drops in the model, there is a drop-growth equation (Eq. (1)) of the type given by Fletcher (1962) in which the

Figure 1

BASIC EQUATIONS OF COMPUTER MODEL

DROPLET GROWTH EQUATION (FOG DROPLETS AND SALINE DROPLETS)

$$\frac{dr_k}{dt} = \frac{G}{r_k}\left(S - \frac{a}{r_k} + \frac{b_k}{r_k^3}\right), \tag{1}$$

WHERE $b_k = \dfrac{4.3\, i_k\ m_k}{M_k}$

EQUATION FOR TIME RATE CHANGE OF SUPERSATURATION

$$\frac{dS_j}{dt} = -C_1 \frac{dT_j}{dt} - C_2 \frac{dm_j}{dt} \tag{2}$$

EQUATION FOR SEDIMENTATION OF SALINE DROPLETS

$$\frac{dh_k}{dt} = -W(r_k) \tag{3}$$

EQUATION FOR VISIBILITY

$$V_j = \frac{3.912}{2\pi \sum_k N_k r_k^2} \tag{4}$$

time rate of change of the drop radius r_k depends upon the local supersaturation S and the magnitude of r_k. The constant b_k is a function of the van't Hoff dissociation factor i_k, molecular weight M_k, and mass m_k of the nucleus upon which the drop was formed. The thermodynamic constant G and the radius of curvature constant, a, are treated as functions of the ambient temperature only.

For each of the equally spaced vertical levels, j, in the model, the time rate of change of the supersaturation Sj at that level is computed (Eq. (2)) from the externally imposed cooling rate $\frac{dTj}{dt}$ (if any) and the net condensation rate $\frac{dmj}{dt}$ at that level. The constants C_1 and C_2 are treated as functions of the ambient temperature only. The release of latent heat of condensation and the extraction of water vapor from the atmosphere are both accounted for in the evaluation of the condensation constant C_2. It should be noted that the provision for externally imposed cooling in the model provides us with an additional capability of simulating processes of fog formation on a population of condensation nuclei.

The time rate of change of height h_k for each size class, k, of solution drops is computed (Eq. (3)) from the instantaneous terminal velocity of the drops W (r_k). The terminal velocities of the solution drops are computed from the Stokes relation for drops of less than 25 microns radius and from a more general empirical function (Best, 1950) for drops of radius greater than 25 microns. The instantaneous value of the local supersaturation S governing the growth of a given size class of solution drops falling between two of the vertical grid levels is determined by linear interpolation between the instantaneous supersaturations at the immediately adjacent upper and lower grid levels. Similarly, the rate of condensation on that size class of solution drops is linearly apportioned to the net condensation rates at the immediately adjacent upper and lower grid levels according to the relative position of the drops between the grid levels.

Sedimentation of the fog drops (which is relatively slow) is neglected in the present model. Consequently, the various size classes of fog drops evaporate under the influence of the supersaturation Sj at their original level, j, and, in turn, contribute to reduction of the net condensation rate $\frac{dmj}{dt}$ at that level.

In the computer model, this system of coupled differential equations is integrated numerically by means of a variable-time step, fourth-order predictor-corrector routine to establish the temporal evolution of supersaturation, size distributions of fog and solution drops, and related fog properties such as the visibility and liquid water content. In order to eliminate the necessity of prohibitively small time steps when the fog drops have evaporated to small sizes, the radius of a size class is equated to the equilibrium radius at the prevailing supersaturation whenever the radius falls below one micron.

Horizontal visibility Vj at each vertical level, j, in the model fog is computed (Eq. (4)) by summing the contributions to the extinction coefficient of all the size classes of fog droplets at that level and the linearly apportioned contributions of all size classes of solution drops lying between that level and the immediately adjacent vertical levels. The liquid water content at each vertical level is computed through a similar procedure.

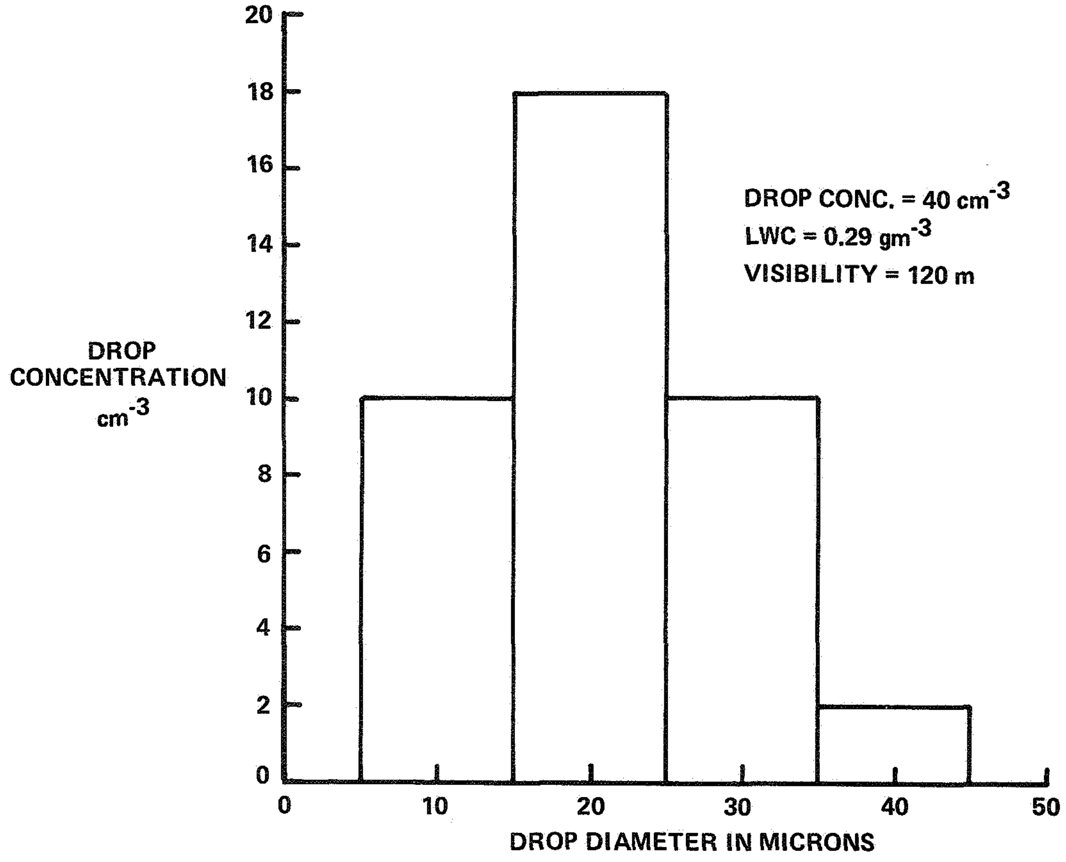
Simulation of an Aerial Seeding Experiment

In order to provide a concrete example of the use of this computer model, a simulation of an actual aerial seeding experiment will be discussed in some detail. In this experiment, described earlier by Mr. Kocmond, 700 lbs of NaCl having a size range of 10-30μ diameter were dispensed over a 1/2 mile by 1/4 mile area at the top of a 100 meter deep fog. Substantial clearing was produced in the seeded region with the horizontal visibility increasing from approximately 100 m just before seeding to 800 m (~ 1/2 mile) 15 minutes after the start of seeding.

In the computer simulation of this experiment, the size distribution of the fog drops obtained just prior to seeding was approximated by the discrete size distribution shown in Figure 2. The fog properties computed from this discrete size distribution are almost identical to those measured in the actual fog. For simplicity, it was assumed that this initial fog drop distribution applied throughout the 100 m depth of the fog, thereby neglecting any variation in the properties of the natural fog with height. The properties of the condensation nuclei upon which the various size classes of fog drops were assumed to be formed were deduced from condensation nuclei measurements at the experimental site.

Figure 2

FOG DROP SIZE DISTRIBUTION USED IN COMPUTER SIMULATION OF FOG SEEDING BY AIRCRAFT



The 10-30μ diameter size distribution of the NaCl seeding material was approximated by the discrete size distribution shown in Figure 3. In the computer simulation, the effects of dispensing various amounts of this size distribution of NaCl particles on the top of the 100 m model fog were investigated. The results are shown in Figure 4, where computed curves of horizontal visibility vs. height in fog are plotted as a function seeding rate and time after deposition of the NaCl at the top of the fog. The 120 m visibility in the model fog before seeding is indicated by the vertical line for time equal zero.

Examining the general height dependence of the computed visibility, we see a decrease in the effectiveness of seeding with distance from the top of the fog. Because of this decrease, it may be necessary to rely on coalescence between the solution drops and the fog drops as the main mechanism for effecting a modification of the lower layers of stratus decks and deep fogs when seeding from above by aircraft. Coalescence is neglected in the present simulation because of the relatively shallow depth of fog.

The 1.0 g m^{-2} concentration of NaCl on the top of the fog corresponds to the average concentration of seeding material dispensed in the experiment, but, since the distribution of seeding material on the top of the fog was not entirely uniform, curves for one half and twice the average concentration are also shown.

After 20 minutes, in the case of 0.5 g m^{-2} concentration of NaCl, all of the solution drops which formed on the NaCl particles had fallen out of the fog and the maximum visibility improvement was achieved (there being no mechanism for the degradation of visibility improvement in the present simulation) It is seen that the maximum visibility improvement is relatively modest, with visibility ranging from about 200 m at the ground to 400 m at the top of the fog.

With the 1.0 g m^{-2} concentration of NaCl, the visibility at the top of the fog improved to three kilometers in 10 minutes, but visibility at the ground reached only 170 m. After 26 minutes, when all of the solution drops had fallen out of the fog, the visibility at the ground improved to a maximum of 360 m.

Figure 3

SIZE DISTRIBUTION OF NaCl SEEDING MATERIAL USED IN COMPUTER SIMULATION OF FOG SEEDING BY AIRCRAFT

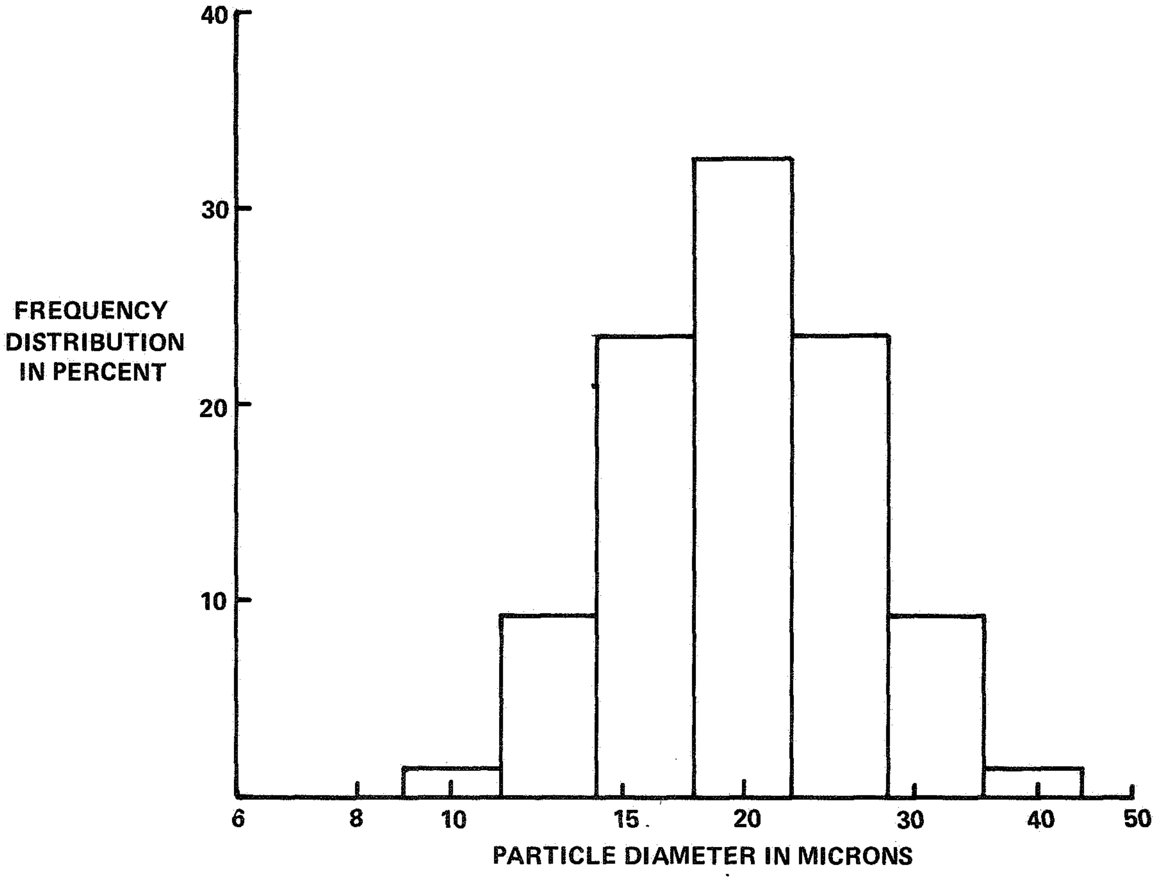
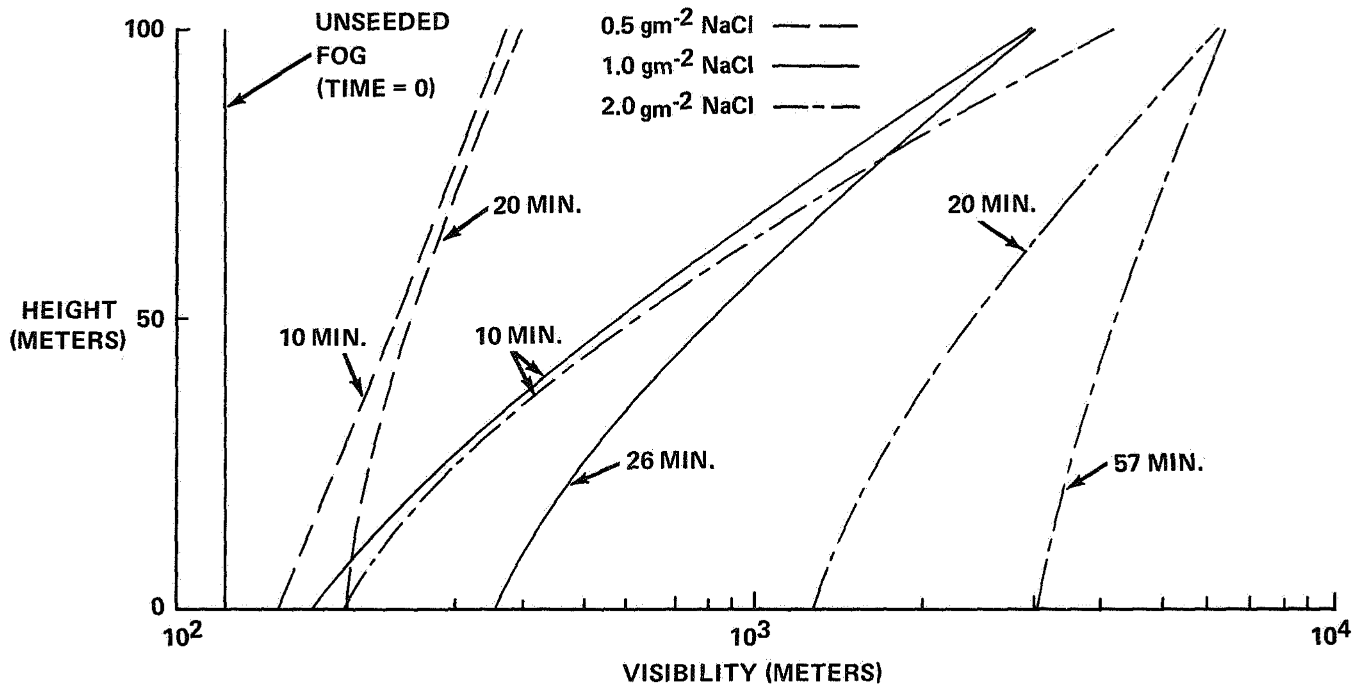


Figure 4

COMPUTED CURVES OF VISIBILITY VS. HEIGHT AS A FUNCTION OF SEEDING RATE AND TIME AFTER DEPOSITION OF NaCl SEEDING MATERIAL AT TOP OF FOG



With the 2.0 g m^{-2} concentration of NaCl, which was certainly achieved over limited areas of seeded region in the actual experiment, the visibility improvement after 10 minutes was not materially better than that produced by the 1.0 g m^{-2} concentration. After 20 minutes, however, a visibility of over one kilometer was produced throughout the depth of fog. After 57 minutes, when all of the solution droplets had fallen out of the fog, the visibility reached three kilometers at the ground and 6 1/2 kilometers at the top of fog.

It is important to note the increases in time required for the complete fallout of the solution drops formed on the NaCl particles with increases in the seeding rate. This is caused by greater reductions in the relative humidity, which result in the decreased growth and retarded sedimentation of the solution drops. For example, the relative humidity reductions produced by the 0.5 g m^{-2} concentration of NaCl were only a few hundreths of a percent throughout the depth of the fog. On the other hand, the 2.0 g m^{-2} concentration of NaCl reduced the relative humidity to 98% at the ground, 97% at the 50 m level, and 94% at the top of fog.

Because of this effect, it would seem desirable in this type of seeding situation to employ somewhat larger particle sizes (at the expense of requiring greater seeding rates) to obtain reasonably rapid sedimentation in the presence of sizable relative humidity reductions and thereby minimizing targeting problems. In the actual seeding experiment, it appears that this effect was unintentionally achieved through partial clumping of the seeding material in dissemination.

Concluding Remarks

We have briefly discussed a computer model for the simulation of the modification of warm fogs with sized hygroscopic nuclei and the use of the model in conjunction with the field experiments on Project Fog Drops. For the future, if the modification concept is to become a widespread operational reality, it should be evident that computer modeling has an important role to play in the optimization of seeding techniques for a wide variety of warm fog situations.

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VI. LABORATORY EXPERIMENTS WITH SEEDING AGENTS OTHER THAN NaCl

By

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Buffalo, New York

Introduction

As previously stated one of the objectives of Project Fog Drops has been to investigate the use of various seeding agents other than NaCl for use in fog dissipation studies. From the onset of our research we have recognized that high strength aluminum alloys, as well as other metals, are susceptible to stress-corrosion cracking when repeatedly exposed to saline solutions.

In spite of this drawback, NaCl was initially chosen for laboratory and field evaluation because of its high efficiency in promoting droplet growth and its ease of handling. As a natural sequence to our field experiments we have turned our attention to studies of non-corrosive chemicals that could be used in place of salt. Some of our recent laboratory evaluations of chemicals look promising. Other tests, including evaluations of a wide variety of polyelectrolytes, have shown that certain chemicals have very little effect on fog.

Although the task of isolating candidate materials for field evaluation has really just begun, the results to date are significant and are reported here because they have a bearing on the discussions of this symposium.

Test Procedure

Fogs were produced in the 600 m^3 cloud chamber described by Mr. Pilié and Dr. Jiusto in earlier papers. In a typical experiment, the procedure used to evaluate the seeding agent was to produce one fog for use as a control and observe its characteristics as a function of time. A second fog was then produced in an identical manner and seeded with a predetermined amount of material. In both the control and seeded fogs a slow secondary expansion was initiated to cause the fogs to persist.

Seeding nuclei were dispersed into the fog from the chamber top and allowed to settle through the fog volume. When solutions were tested, droplets were injected into the fog by a droplet disseminator located approximately 25 feet above the chamber floor.

Summary of Results

The primary objectives of our laboratory tests are twofold: (1) we want to determine the maximum visibility improvement that can be achieved by seeding with various non-corrosive chemicals and (2) we wish to compare these results with data obtained from seeding experiments using NaCl particles of carefully controlled size.

Table I summarizes the maximum visibility improvements obtained in several recent experiments. Results from previous tests in which sized dry NaCl particles were used are also tabulated for comparison.

The data suggest that NaCl, urea, and certain phosphates are effective in promoting laboratory fog dissipation. As shown, the polyelectrolytes did not significantly improve visibility in laboratory fog. As always, care was taken to properly size the particles to insure substantial residence times of the nuclei in the fog. Not apparent from the data, but nonetheless an important factor when considering the use of polyelectrolytes for field experiments, is the fact that each of the polyelectrolytes tested produced an extremely slippery surface on the chamber floor after seeding; a condition which probably could not be tolerated for airport application.

An analysis of the data was performed for some experiments to determine the factors responsible for visibility improvements and, at the same time, to establish reasons for the lack of significant improvement in certain other cases.

Table 1

VISIBILITY IMPROVEMENT FACTORS* FOR SEEDING EXPERIMENTS IN 600 m^3 CLOUD CHAMBER

SEEDING MASS	SEEDING AGENT	PARTICLE DISTRIBUTION		MAXIMUM VISIBILITY IMPROVEMENT FACTOR
		MODE (μ)	SIZE RANGE (μ)	
5 gm	NaCl	4	2-10	7.5
5 gm	NaCl	8	4-20	6.2
10 gm	NaCl	8	4-20	13.2
125 gm	NaCl		44-125	6.1
5 gm	urea		4-20	6.6
6 gm	NH_4NO_3.urea.WATER	4	2-20	1.5
15 gm	NH_4NO_3.urea.WATER	4	2-20	4.7
30 gm	NH_4NO_3.urea.WATER	4	2-20	6.1
5 gm	MONOSODIUM PHOSPHATE		68% 4-20	4.8
5 gm	DISODIUM PHOSPHATE		95% 4-20	7.1
5 gm	HEXAPHOSPHATE		58% 4-20	2.7
5 gm	POLYELECTROLYTE 'B'		20-44	1.3
15 gm	POLYELECTROLYTE 'B'		20-44	1.3
5 gm	POLYELECTROLYTE - 193A		10-20	1.8
5 gm	POLYELECTROLYTE - 193B		20-44	1.5

*VISIBILITY IMPROVEMENT FACTOR IS DEFINED AS THE RATIO OF THE VISIBILITY OF THE SEEDED FOG TO THE VISIBILITY OF THE CONTROL FOG AT THE SAME TIME AFTER INITIATION OF THE EXPANSION

In Figure 1, representative visibility curves are shown for a laboratory fog seeded with a sized polyelectrolyte, in this case a type of polyacrylamide. As shown, there is very little difference between the control and seeded fogs. Many other polyelectrolytes were tested. All gave essentially the same result.

Drop size distributions were also examined to see if there were any noticeable differences between the seeded and unseeded fogs. A comparison of characteristic distributions from a polyelectrolyte seeding experiment at the time of maximum visibility improvement (factor of 1.3) is shown in Figure 2.

The similarities between the seeded and control-fog drop-size distributions are readily apparent. Note also that in both cases the LWC, drop concentration and mean volume diameter are nearly alike. Other comparisons were much the same. In all our tests no significant improvement in visibility could be attributed to seeding with polyelectrolytes.

On the other hand, laboratory seeding tests indicate that certain phosphates are effective as fog modifying agents. In Figure 3 the effects of seeding fog with 5 gm of disodium phosphate (Na_2HPO_4) are shown.

Drop size distributions about 15 minutes after seeding are compared in Figure 4 with data taken in the control fog at the same time after the start of the fog forming expansion. Note the rather substantial shift in drop sizes and change in drop concentration in the seeded fog. At the time these samples were taken, the liquid water content in the seeded fog was somewhat less, a result of sedimentation and fall-out of the largest drops formed on the seeding nuclei.

Another chemical, monosodium phosphate (NaH_2PO_4), appears to be nearly as effective as NaCl in dissipating laboratory fog. The visibility traces for a set of experiments in which the fog was seeded with 5 gm of NaH_2PO_4 are shown in Figure 5.

Drop size distributions 20 minutes after seeding are shown in Figure 6. Again the reasons for the improvements in visibility after seeding are vividly demonstrated by the differences in the drop size distributions and drop concentrations for the two fogs.

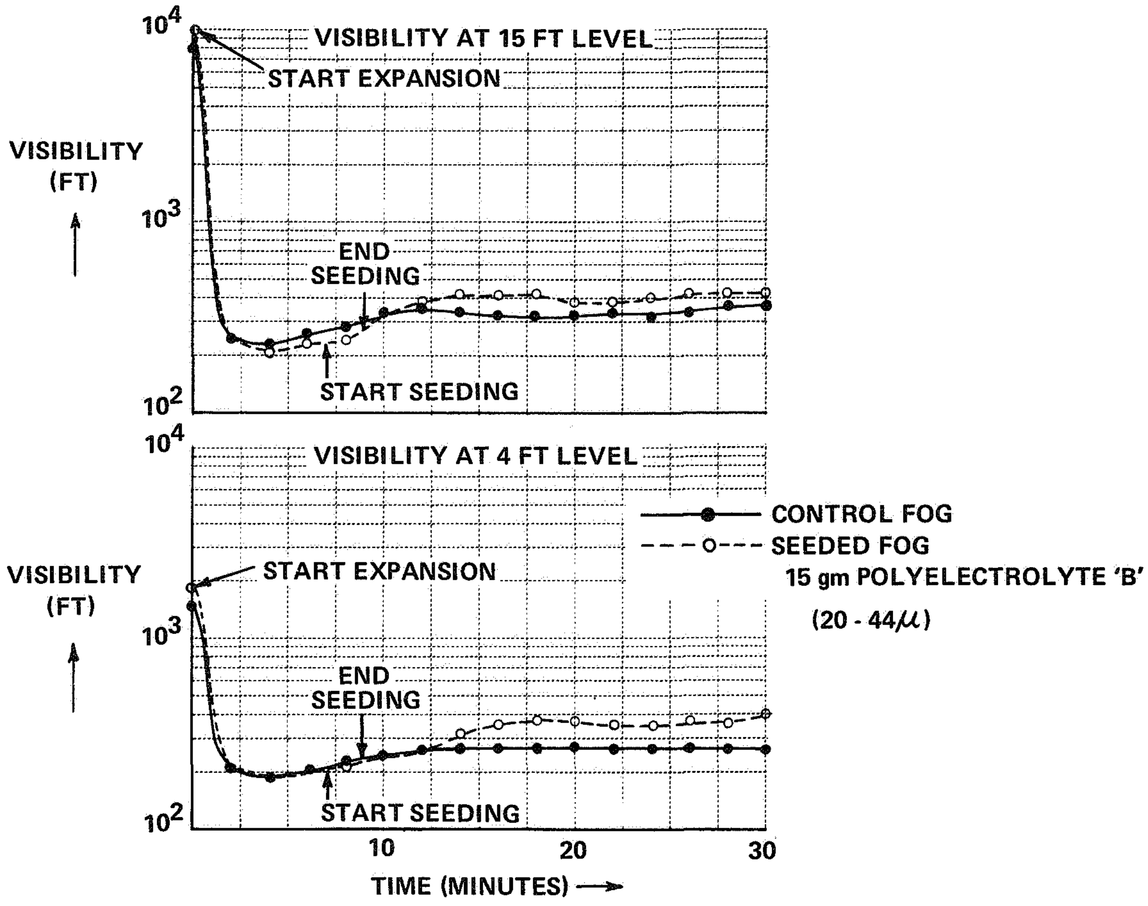


Figure 1

Visibility as a function of time in a seeded and control fog

Figure 2

DROP SIZE DISTRIBUTION FOR A CONTROL FOG AND A SEEDED FOG AT T = 25 MIN. POLYELECTROLYTE 'B'

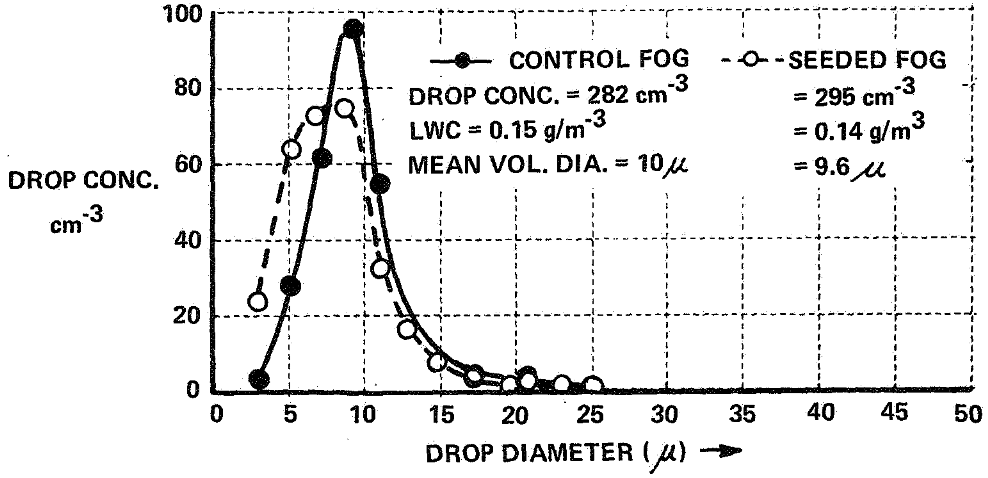
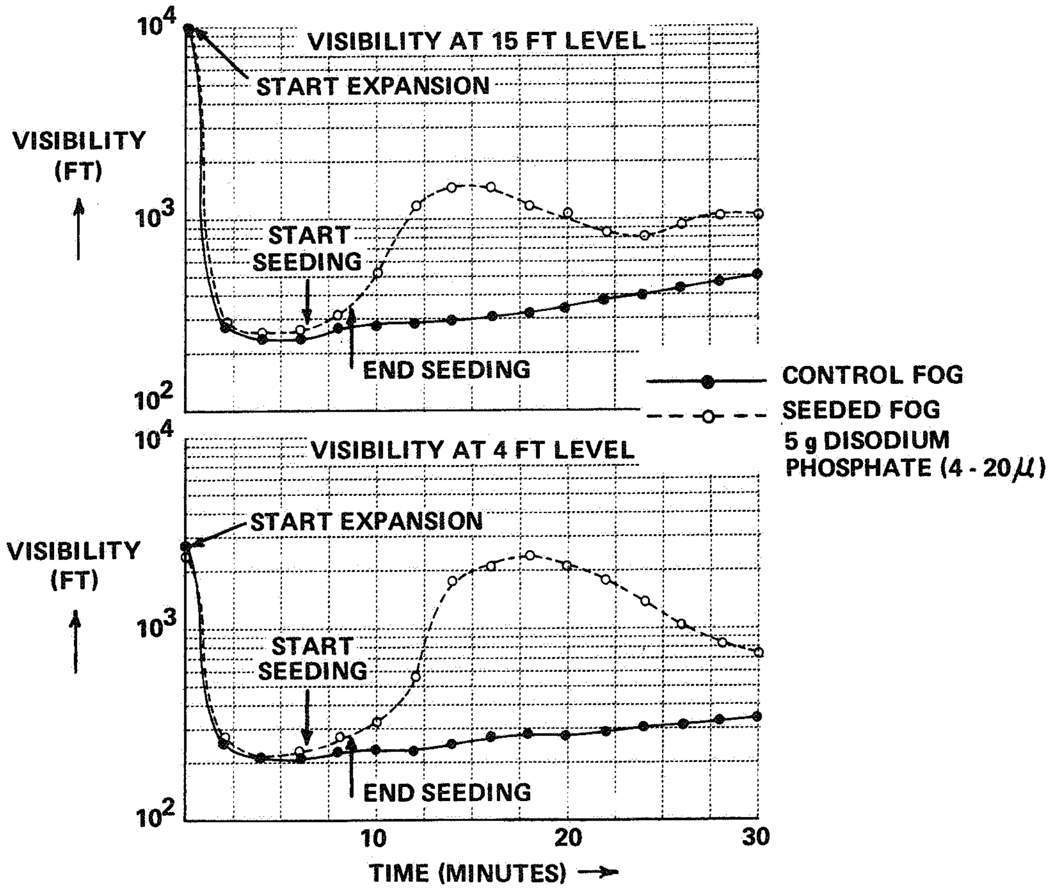


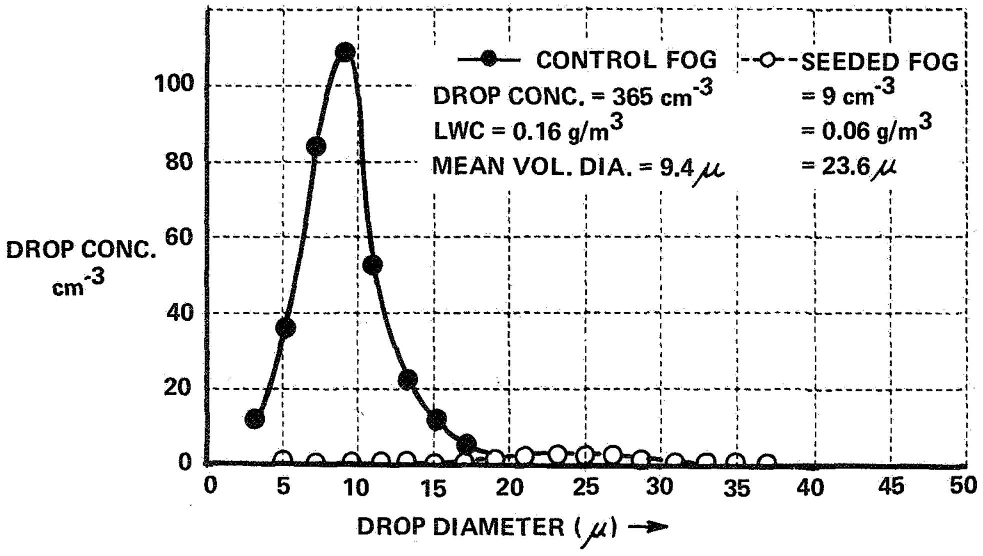
Figure 3



Visibility as a function of time for a seeded and control fog

Figure 4

DROP SIZE DISTRIBUTION FOR A CONTROL FOG
AND A SEEDED FOG AT T = 20 MIN.
Na_2HPO_4



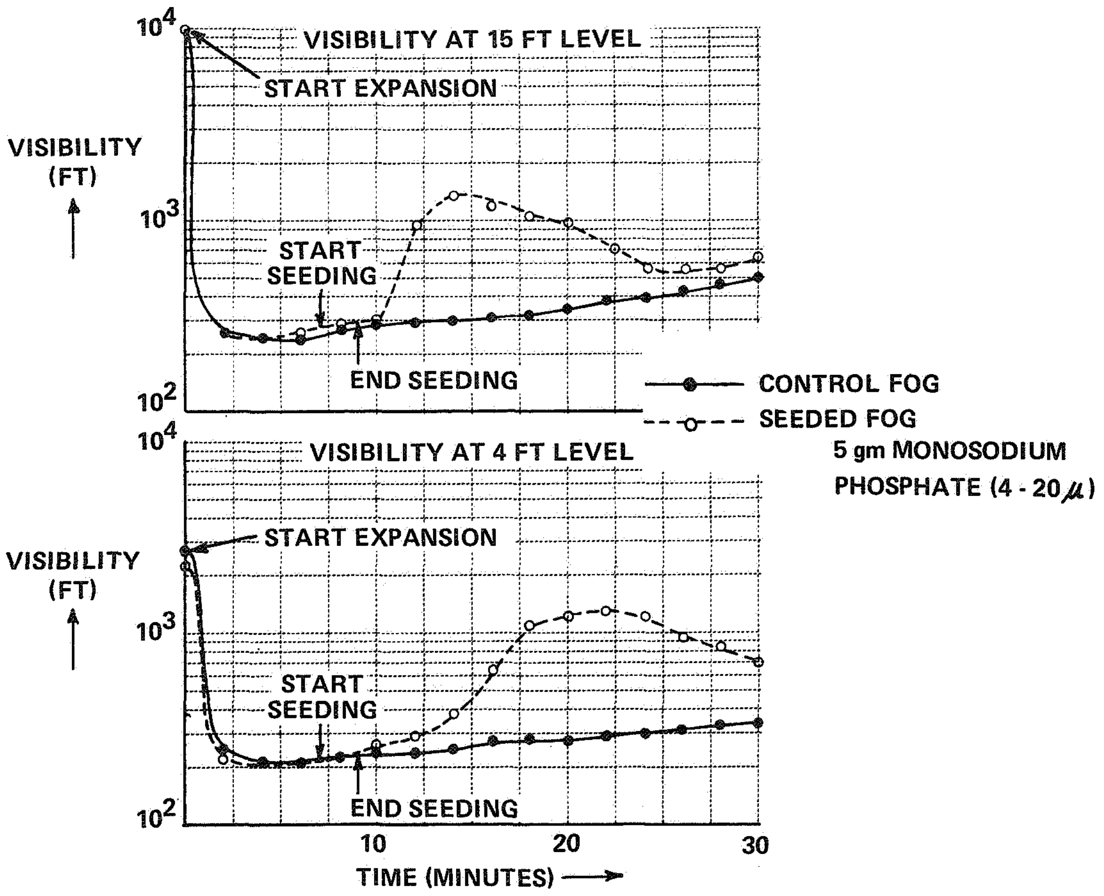


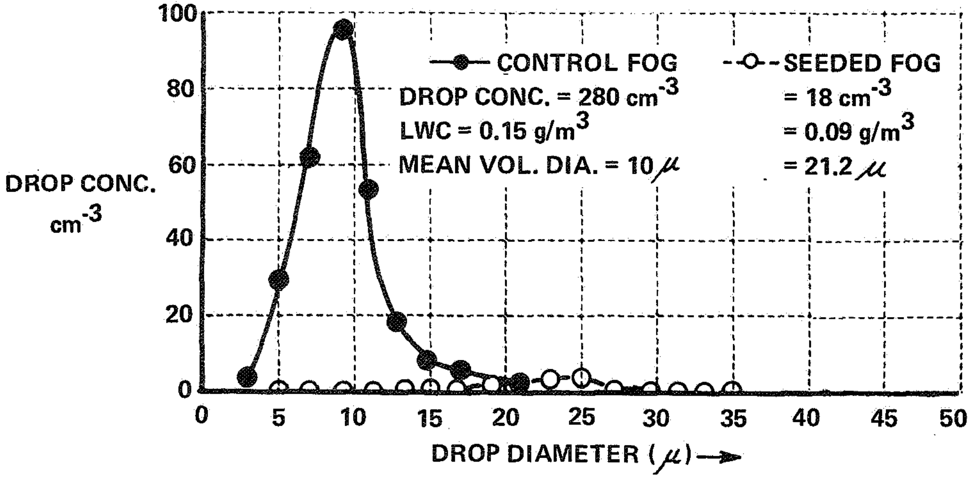
Figure 5

Visibility as a function of time for a seeded and control fog

Figure 6

DROP SIZE DISTRIBUTION FOR A CONTROL FOG AND A SEEDED FOG AT T = 25 MIN.

NaH_2PO_4



Conclusions

These initial experiments in which various types of sized phosphate chemicals were used to improve visibility in dense laboratory fog have been encouraging. Refinements in sizing of materials and tests with other seeding agents are planned. The results of our laboratory tests with sized polyelectrolytes suggest that these materials are ineffective as seeding agents. Stress-corrosion cracking experiments will be conducted to determine the corrosive effects of various seeding agents on several types of metals. Once we have isolated one or two of the most promising non-corrosive chemicals in the laboratory, we plan to evaluate the seeding agents in a series of field experiments. It is our intention to conduct field evaluations of these chemicals during the later summer and early fall of 1969.

VII. GENERAL DISCUSSION

Participants:

Mr. William A. McGowan,
NASA Headquarters, Moderator

Dr. Robert D. Fletcher,
Air Force Air Weather Service

Mr. George Ettenheim,
Meteorology Research, Inc.

Mr. Howard Eakins,
Federal Aviation Administration

Mr. Roger G. Flynn,
Air Transportation Association

Mr. W. B. Beckwith,
United Air Lines

Dr. Robert M. Cunningham,
Air Force Cambridge Research Laboratories

Dr. Larry G. Davis,
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Mr. Clement J. Todd,
Navy Weather Research Facility

Mr. James Y. Deen,
Braniff International Airways

Mr. Edmund Bromley, Jr.,
Federal Aviation Administration

Robert D. Fletcher - The Air Weather Service that I represent is, as many of you know, an operational organization. We do not conduct research. We rely instead upon our friends and compatriots in the Air Force Cambridge Research Laboratories and elsewhere to do the research; we pick up the results of successful such research as quickly as we can and try to put them to use. We have done this in the area of weather modification (primarily with modification of supercooled fog) at places such as Elmendorf Air Force Base in Alaska, and at several bases in Germany. Our efforts, however, in the area of warm fog, which seems to be the principal topic today, are small. I can name two.

A year ago, we lined up four large C-141 jet aircraft, one behind another at 750-foot intervals on the runway at Travis Air Force Base, California, and ran the engines as fast as they could go without having the aircraft jump the chocks. The visibility, near zero at the start, went up to three-quarters of a mile less than five minutes after engine run-up. However, very shortly after the engines were turned off, the fog closed in from the sides. During the course of the tests-- we ran three of them-- the heat was enough that the clearing went all the way up through the fog, which was about 300-feet thick. Turbulence, as you may suspect, was very high, especially on the last aircraft, but all of them stayed in place. We ran this test mainly to find out if there was a possibility of using an aircraft as an emergency measure-- at some remote airfield, for example. We found that the approach was feasible, and I think that there are possibilities for extension of the idea. Incidentally, the French are trying a system of this sort at Orly Airport, near Paris, with underground jet engines.

At Travis Air Force Base this past winter, we unfortunately encountered few cases of warm fog. We were able to make a couple of tests on the same day in December 1968 using milled sodium nitrate, which was blown up by a stationary ground-based fan placed near the approach end of the runway. This did produce some results; there was indeed an increase in visibility. The sodium nitrate was secured from MRI in two size ranges--15 to 40 microns and 40 to 80 microns in diameter. The size of the clearing that was created was perhaps two-hundred yards across.

All of our other efforts have been in the area of supercooled fog dispersion. For those of you who may be interested, we are now completely operational using airborne seeding. We also have achieved some operational successes with ground-based propane-dispensing units, e.g., at Fairchild Air Force Base near Spokane.

The big problem, as mentioned this morning, with any of the ground-based techniques we have used is wind drift or, put in another way, proper positioning of the propane-dispensing equipment. We have mounted the dispensers on movable trailers. The equipment includes a movable fan, which assists in distributing the resulting ice crystals, mounted in a trailer behind a jeep. Propane works very well at subfreezing temperatures. A large area can be cleared, but the area may not drift to where it is wanted. We have been successful on several occasions --perhaps lucky, I should put it--in having the clearing move over the runway to the extent that we could get B-52s and KC-135s, all large aircraft, in and out of Fairchild Air Force Base.

The truly successful exercise, however, has been airborne. A year ago (1967-68) at Elmendorf Air Force Base, near Anchorage, Alaska, we ran on a test basis. This past winter, we went operational. We used one WC-130 aircraft, a good-sized airplane, with a dry-ice crusher aboard and a dispensing unit that shoves the dry ice out the bottom. Through the courtesy of the Naval Weapons Center at China Lake, we also have been testing silver-iodide fuses on the same aircraft. Both techniques have worked although, as one might expect, small bugs showed up in each. The silver iodide requires somewhat colder temperatures to be effective. Sometimes the silver-iodide fuses failed to fire. The expense is a bit more also than that of the dry-ice dispensing. A year ago, even though the project was run on a test basis, we were able to get nearly 200 large aircraft in and out of Elmendorf that otherwise would have been diverted or delayed. The success of the test prompted us to go operational this winter, and we have made possible over 300 flights of the big airplanes to this point.

We are conducting this winter a test in Germany where the supercooled fogs exist at much warmer temperatures--that is, closer to the freezing point. Cases have been tried in which the temperatures at the cloud tops, measured by wiresonde by the way, were perhaps $1^{\circ}C$ below freezing. Sometimes we had success, sometimes we didn't. Under such conditions, it was hard to predict the likelihood of success. But if the temperatures were even 3 or 4° below freezing, we found that the system works very well, and that there was no difficulty in making a clearing. Again, the wind is a problem, particularly in places where there are nearby mountains. One can form one, two, three or four seeded lanes upwind of the runway. The seeded area may drift and go back, drift sideways, or perform other difficult-to-predict maneuvers. One simply has to learn from experience how to do the seeding. I am sure the same kind of problem will come up with respect to the airborne seeding of warm fog.

I might recount one case in Germany this past winter in which the average low-level wind was around 15 knots. We seeded upwind about ten miles and were fortunate enough to find that the pattern did move over the airport in such a fashion that the aircraft could operate. We were just lucky that the wind remained steady. Several times with much lighter winds, we missed the runway.

That is the story of our operation. We look forward to additional discussions of this sort and hope to hear more about results of operations carried on elsewhere. As I said earlier, we are in the business of picking up information on procedures that appear to us to be near implementation, and then implementing them if they test out successfully.

Thank you very much for giving me the opportunity to talk.

George Ettenheim - First of all, I would like to take this opportunity to compliment Cornell on the work that they have done over the past year. We have done some similar work, but unfortunately on a much, much smaller scale. I think that the efforts that have been shown here today have obviously been very well done. I would like to just take a minute and go on from where Mr. Kocmond left off this morning, after he showed the results of the tests at Elmira, to give you an idea of the visual results of a couple of typical tests.

I might just mention in passing that we have conducted on the order of 50 to 60 field tests, but the emphasis of our efforts has been to come up with a means of opening up a small hole in stratus or radiation fog so that an aircraft can land VFR. This is strictly a small-scale, VFR problem. The two tests that I am going to show you are using two different materials, both of them carefully sized but two rather different size distributions. You have heard a lot of conversation today about the tradeoffs between large particles which do the job quickly, or small particles that take quite awhile.

We have set up the criteria that a pilot who wants to land VFR, doesn't want to sit around for a half-hour before he can put the airplane on the ground. Five to ten minutes is a sort of reasonable length of time from seeding to a hole opening. The first test that we will look at has full captions on it. These will fill you in on the details.

I will fill in the details for the second test. I am including these two cases, not as sensational results, but because what I want to show you is that there are a variety of types of fog far beyond what we have seen today, and that when you get out in the real world, as people have indicated, the problems sometimes become very complex. For those of you who have not seen movies of fog tests, I would like to bring you along part of the way by mentioning that if you can run a test very early in the morning, before sunrise, the photography is fairly easy because everything is fairly uniformly lighted. On the other hand, as soon as the sun breaks the horizon, you have an extremely low sun angle so that any undulations in the top of the surface create an odd condition where the tops of each cell are very well lighted and any depression is in a shadow area.

Initially I am sure the impression that you will get, especially on the first test, is that it is very hard to tell whether there are actually undulations in the surface. I hope that by the time you have seen the entire film, this will become more apparent. I wish to point out that on each of the tests we have made observations of the thickness of the fog, we have measured the turbulence and the liquid water content as minimal parameters in each test.

I think with those introductory remarks, we will now have the film if we might.

(Film Narration: This fog is 700 to 800 feet thick, and there is quite a bit of turbulence. This is really stratus, one of the most difficult situations to try to modify.

Here we are dispensing material that has a rather broad distribution of sizes but the small particles, below 15μ, have been removed. You can see the aircraft dispensing. He puts out 500 pounds of material in essentially two passes, each 1500 feet in length. At this point in time, the area that has been seeded is hardly distinguishable from the remainder of the area. But fifteen minutes later, this area--I don't know if you can see the airplane on the right side of the hole--we actually have VFR contact with the ground through that hole and a landing would have been possible although these are far from ideal results. That was at 6:00 in the morning.

Here, at 7:40 in the morning, it is still quite early. In this case, we use a balloon which you will see periodically as an identification point. The balloon is put up from the ground. This is of great value in locating the exact spot where you want to create the clearing and see the effect. Approximately five minutes after seeding, the aircraft makes a descent into the area. You can see a rather sharp cutoff of one end of the hole on your right. The area continues to open.

This is obviously a much less dense fog than the one we had previously looked at. This is at about eight minutes. You can see the aircraft coming up at the bottom of the picture. This is a good example of wake versus material. You see he has gone through there several times but his wake hasn't effected the end of the hole which was the cutoff of the material dissemination. The aircraft is making another simulated landing. Now we can see the highway, streams, etc. down through the area, this is about twelve minutes after dispensing. End Narration)

I would like to extrapolate some of the data that was presented earlier on the quantities of material that may be required. The first test was 500 pounds of material on 700 to 800 feet of stratus. The second, 200 pounds of material in 500 feet of fog but not the very, very strong stratus that we had seen earlier. Figures were presented earlier of using material, in a model, at rates of from a half to two grams per square meter of the top surface of the fog. In these tests, we have gone as high as ten grams per square meter, and in some cases had very, very successful results. In other cases, two minutes after dispensing you can't even tell where the airplane had flown. The reason for this is an area which has not been explored very far today, but I wish to mention. Natural turbulent diffusion mixing of the atmosphere can gobble up huge quantities of this material, and spread it over an area perhaps ten times the area which you desire to affect. In that case, you must initially put out ten times the quantity of material to get similar results; and it is just not a factor of ten. We have measured turbulence in fog that would require on the order of a hundred times the amount of material as would be required in other "very simple cases." I am not trying to scare anybody off. I am trying to point out that there is good hope if we limit ourselves to some reasonable practicalities when we think about what we simply call "fog". But really what we are talking about is everything from a shallow radiation fog with very little mixing and the rare idealized point where all of us have tried to start tackling the problem, to something which becomes complex, almost beyond your wildest dream.

I think in closing I would like to say that we have a good handle, we have a good start, I think a good direction to pursue, but there certainly is a long way to go before we are going to have push-button operation, and maybe five years is a good number; maybe it is three. Thank you very much.

Howard W. Eakins - Mr. Ettenheim, what was the ceiling height of the clouds when you started number 1 and 2 tests?

George Ettenheim - I can't tell you exactly, except the observer on the ground was limited to about 20 miles an hour driving on the road because the visibility was so low. We sat above, anxiously waiting for him to get there.

Roger G. Flynn - A Comment. We agree with what you say about the turbulence situation. We have encountered that too.

W. B. Beckwith - First, as an individual, I have been more or less pre-occupied with fog dispersal for about 17 years. It is heart-warming to see a large group like this all interested in the same goal, fog dispersal, be it aviation or other applications.

If I may now put on my Air Transport Association cap, I would like to say in terms of our discussions which we have heard today, the airlines' stake in fog dispersal represents about $75 million annually. This cost figure is running up at a rapid rate every year.

The disruptive effect upon passengers is, of course, a number that you cannot put a dollar sign on, and it is a very serious one.

May I also say that the airlines have been interested in fog dispersal for many years. The FIDO system was tried in the late 1940's. Initial chemical tests, using a brine system which is a modification of the salt system, was tried operationally some 17 years ago.

The cold fog dispersal program which the airlines have been operating for six years has been very effective. However, this program is rather limited because of the rather limited locale of supercooled fog which is of concern to aviation.

The ATA tests which were run about a year ago and for which the airlines paid $100,000, did produce some operational results which were very encouraging. The pay-off from that has taken the form of an operational program of fog seeding with polyelectrolytes at Portland, Oregon this winter. The Cornell system of salt seeding which we have heard so well described had some operational pay-offs at two other airports this winter; namely, Sacramento and Los Angeles.

It might be of interest to those of you here that the total outlay in fog dispersal contracts this year for the airlines is in excess of a quarter-million dollars. But let me hasten to say, we would not necessarily pay that price repeatedly on a national basis or even on a regional basis at this point. We have not worked up any precise cost-benefit figures on the operation, and more development work is required.

Operations at the three airports where warm fog dispersal has been conducted this winter produced successful results. There has been only one test at Los Angeles because there has been little fog. (Apparently when one organizes an airport for fog dispersal, lo-and-behold, no fog forms).

We in ATA and the airlines very much appreciate the work at Cornell which has been funded by NASA. I have a great deal of admiration for the fine planning and designing of the experiments that Cornell conceived. We have followed this very closely, and our ATA MET Committee has visited Cornell to look over their test facilities. We have studied their reports with a great deal of interest.

The airlines, of course, are interested in the most effective, practical and economical warm fog dispersal techniques. At the present time, it looks like the chemical approach is the most feasible. However, we should not overlook other possible approaches which are being developed.

None of them have been really operationally tested in recent years except perhaps the old FIDO system. That method, in its original form, was not an economically feasible proposition. However, the economic pressure on aviation is increasing every year and some of the older methods that have not been economically feasible in years past, may eventually have to be reconsidered.

We welcome the renewed interest in warm fog dispersal which was stirred up by our 1967-68 test program. We certainly do encourage as much as we can and give moral support to all future work like the NASA-Cornell Program. Since there are some other applications of fog dispersal outside of aviation, I would like to express a thought that has been on the minds of many of us in the airlines for a number of years, and that is the very great need for some Government agency to evaluate techniques being used or being tested, or that have promise of real operational application.

The Boeing 747 airplane is around a very short corner. You can imagine the chaos that will be produced when an airport like Chicago, Los Angeles or JFK becomes fog bound and we dump three or four of the 747's into airports that aren't scheduled to receive them. The hotel problem in itself is a major problem even with our present type equipment.

There are many outfits that have some good concepts. They need research money which should be provided by Government. The airlines cannot see fit to provide this kind of support at the present time. We are interested in techniques that are developed to the point where they are ready for operational testing.

The SST poses another problem and obviously we must get the show on the road and move this program with all possible haste. In the long-range picture, we do hope that some device will be developed to provide a push-button type fog control. This obviously means a ground dispensing system. We have done a little bit of funding for some test work along these lines; namely, the Fog Sweep, which was developed by FMC. Successful tests were run on radiation fog in Sacramento and less successfully in winds of up to 27 knots at Nantucket. So we know what the problem is on wind effects. Additional work must be done on ground dispensing equipment. Thank you very much.

Robert M. Cunningham - The problem of warm fog dissipation has been under active study by AFCRL for a number of years. In 1954, we observed and measured the large wake effect from a B-17. This effect was large enough to mask any potential clearing due to CaO or $CaCl_2$ seeding. These agents were being used to test their effectiveness for warm fog dissipation.

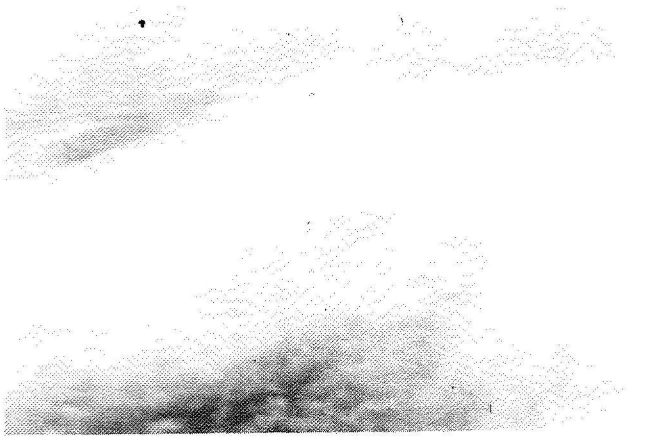
Magono et.al. (1963) dropped water from a helicopter in order to dissipate stratus. Plank (1964), however, attributed the cloud dissipation to the helicopter wake rather than the water drop. The idea of using the helicopter for mixing of dry air downward into the fog and thereby evaporating the fog, has recently been more thoroughly tested. Jim Hicks, U.S. Army Terrestrial Sciences Center, used small Army helicopters in Greenland with some success but concluded that with the helicopters then available, the operation was too marginal in its effects and also too dangerous. Lately, using large helicopters, we have tested this technique on shallow ground fog near Smith Mountain, Virginia with spectacular success (See Figure 1).

The problem remaining is to determine under what conditions the downwash hole will reach the surface, precisely how large it will be and how long will it last. The more important variables being considered are helicopter size, wind shear, thermal stability and water content. Various flight patterns for the helicopter are being tested. This method takes advantage of the large volume of air that the helicopter pushes downward in order to support itself. Hovering or near-hovering flight is used, at speeds of 15-30 knots. Large volumes of air are mixed laterally into the helicopter wake. We are investigating the optimum height to fly above the fog to maximize both the volume of air forced downward and the depth of penetration.

In many fog situations, the thermal stability is great. The downwash penetration is adversely affected by this stability, and probably more importantly affected by wind shears that can be large with strong thermal stability. We have already had difficulty with a situation of fog with calm air at the surface but with a 20 knot wind at fog top of only 200 feet.

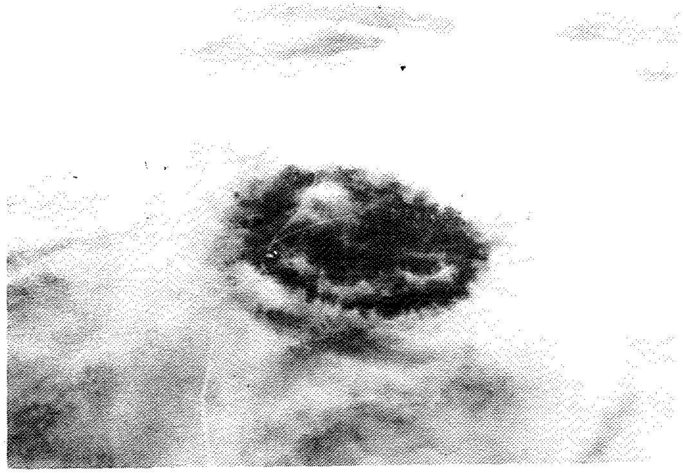
CLEARING GROUND FOG ~4 MI. SSW MONETA, VA.

17 NOV. 1968



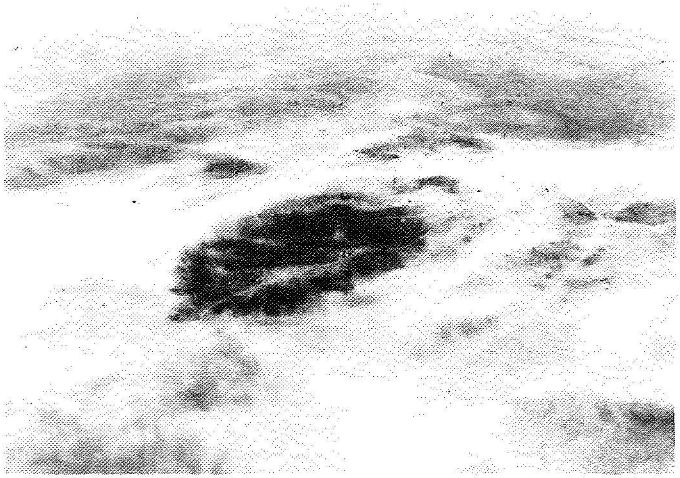
0733:00 LOOKING NE

INITIAL CIRCULAR SWATH
~ 700' DIA.



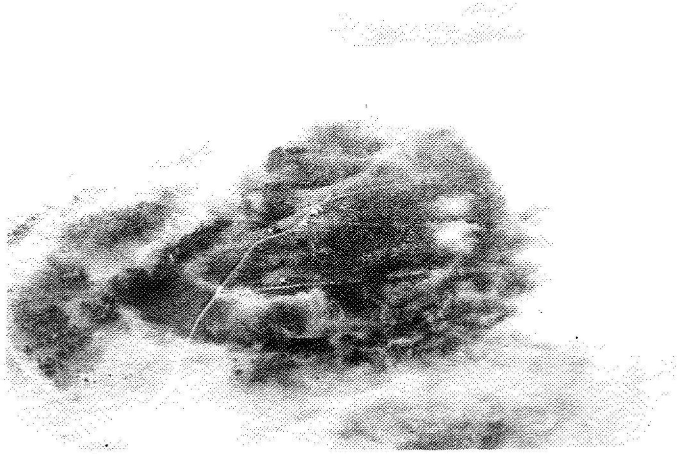
0736:00 LOOKING SW

CLEARED HOLE ~1600' DIA.



0738:00 LOOKING NE

CLEARED HOLE ~2100' DIA.



0739:00 LOOKING SW

CLEARED HOLE ~2500' DIA.

One operational problem of general interest concerns navigation at fog top over a runway. We have found that normal GCA procedures are inadequate particularly when in slow moving flight. The helicopter pilots in order to fly the properly spaced concentric circles, find it necessary to fly with some visual reference. We have proposed the use of balloons on a tether held just above fog top for this purpose. The work on fog dispersal with the use of helicopter wakes is being directed by Mr. Vernon G. Plank. Mr. Bernard Silverman also in our Cloud Physics group has been directing a fog measurement and dispersal program since 1959. Measurements of fog and initial attempts at salt and carbon black seeding were made in Arcata in 1960-1961. A series of fog measurements to determine fog drop size, water content and visibility variability were made at Otis AFB in 1953 and 1954 on a program called "Cat Feet". A number of instruments for fog measurement were developed and tested for this program.

Recently we have turned our attention to the development and evaluation of the hygroscopic particle seeding method. We have placed considerable priority on the development of sophisticated computer models which attempt to simulate the modification effects caused by seeding with various types, sizes, and quantities of hygroscopic particles. In contrast to the results given here by Eadie of Cornell, Silverman has suggested that larger salt particles are needed to clear the fog from the top all the way to the ground. Larger particles are required to resist the counteracting influences of turbulent diffusion and maximize the clearing effects due to coalescence. It will not, in fact, be possible to clear relatively deep fogs without capitalizing on the coalescence process. The effect of environmental turbulence on the size of the clearing and on its persistance is being considered both in the field, as just previously described by George Ettenheim, and as one of the parameters considered in a new fog model.

A word regarding applications - Airport clearing should not be considered as the only application for work being done on warm fog dissipation. After our original helicopter tests in Eglin AFB, word of this initial success reached a rescue squadron in Southeast Asia. They tried this technique several times on stratus clouds topping small mountains. The holes produced were sufficiently large and deep to permit successful rescue operations.

Recently we have had conversations with Massachusetts State Highway personnel who are concerned with pockets of fog on super highways. The use of the helicopter to clear a path in these pockets is being seriously considered.

It appears that some practical warm fog dissipation techniques are at hand; however, they are of limited use. Applications should be carefully chosen to fit our present abilities.

Larry G. Davis - Our group became interested in the warm cloud modification problem through our activities in St. Croix, Virgin Islands and in Puerto Rico. We have been using hygroscopic seeding techniques to increase precipitation from small tropical cumulus clouds in areas where extra water is needed.

After participating with the Cornell group in the Elmira tests, we felt there was a practical solution to the warm fog problem, so we began to develop the techniques and equipment, and to use the data from Cornell to work out nomograms which could be used in salt seeding attempts at airports.

We are presently operating programs at the Los Angeles International Airport and the Sacramento Metropolitan Airport. We have been working in both areas about a month and a half. The Los Angeles results were very straightforward. There was only one attempt on January 7, and since that time, they have had rain and hail. This one attempt was very successful.

The Los Angeles experiment is a four-month experiment, and is basically designed to try to increase the visibility to 1600 feet RVR for aircraft takeoff. This program has much more limited objectives than the one described by Dr. Cunningham where they are trying to cut a hole in stratus. Therefore, our approach is a lot different.

Our aircraft make an approach on the ILS system which they use to navigate within the confines of the airport. They release the materials at low altitudes, 150 to 200 feet. As clearing begins, the releases are made at successively increasing heights (300 to 400 feet).

We feel that the results obtained by the Cornell group, along with our own experience, demonstrates that we have a workable chemical in sodium chloride. However, other chemicals also appear promising and present less of a corrosion problem. We feel that wind variability and diffusion presents the most significant operational problem and is the area that needs attention. An additional problem concerns the interfacing with normal flight patterns in the vicinity of the airports. Proper release patterns have to be worked out on a local basis and coordinated with the ATC.

We have conducted over 20 seeding runs in Sacramento, with wind speeds less than 5 to 6 knots and almost all the runs have been operationally successful, meaning that aircraft have either taken off or landed after the increased visibility due to seeding.

Essentially, our failures have occurred during periods with variable winds. We have obtained increases of visibility but it is of such a short duration that aircraft cannot be brought into position for landing or take-off.

Our attempt to solve the wind variability problem has concentrated on the use of multiple aircraft and which are positioned such as to account for wind drift. The positions are obtained based on the calculations from the Cornell studies.

For example, the first aircraft will be positioned based on a 300 foot release and the second aircraft will be positioned based on a 600 foot release. They fly a tight racetrack pattern such that they will intersect the middle again. An alternative pattern is to position themselves relative to the end of the runway with the help of RAPCON (from McClellan AFB in Sacramento) and they will do a 40-degree bank turn, holding this turn at the 300 foot level and at the 600 foot level.

The materials we are using are not precisely sized. We have found there was a compromise between the cost of materials and what is optimum in terms of size range.

We are using Morton's 200 fine salt. The particle diameters are roughly 2 microns to 60 microns with a peak at 15 to 20 microns in diameter. We mix this with Cab-O-Sil, a commercial polysilicate to fluidized material to keep it from clumping in the hoppers. We dispense at rates between 40 to 150 pounds per minute.

We are still conducting experimental work on dispensers. There are a lot of practical problems to be solved. I am sure George Ettenheim can amplify on this.

Our present feeling is that the biggest problem facing operational fog programs at airports is the manner in which the materials are dispensed. The problem of targeting the cleared area over the approach and role-out zone appears to be the most significant problem to be solved.

Clement J. Todd - A number of things that I was prepared to say have already been said, but there are still a few points that I would like to make.

First, let me say that the group I work with has been studying the clearing of warm fog with computer models for the past three years. Soon after our model was developed, it became apparent that both the effectiveness and economy of hygroscopic treatments critically depends on size and number-density of the particles.

Meanwhile, we followed the reports from Cornell Aeronautical Laboratory with great interest. When they obtained their experimentally derived results that showed the same critical dependency on size number-density that we had found, my confidence in our modelling increased greatly. We were grateful that we were able to keep in close touch with CAL throughout this period.

A point I would like to make is that the formulas we used in our models are between 60 and 100 years old, and they have not been improved very much. This is significant with respect to progress in fog clearing during this period. These formulas were old at the time Houghton and Radford reported on "The Local Dissipation of Natural Fog" in October 1938. Why has it taken us so long to get to the point where we are actually using hygroscopic treatment to clear warm fog?

If you ask Professor Houghton, now Chairman of the Meteorology Department of MIT, he will tell you we did it 30 years ago; it is merely a matter of engineering to make it practical. So the question is, what is the nature of the engineering that now makes this look practical?

I think that being able to explore the solution to these 60 and 100-year old equations by computer has made it possible for many people to understand fairly thoroughly the relationship of size and number-density of treatment particles to the improvement in visibility, and the time this improvement takes. Before the advent of the computer, there were very few who had the analytical perception or patience needed to understand the implications of such formulas. Houghton was one of these few.

Another factor is being able to produce and handle large quantities of properly sized particles. Houghton produced his sized hygroscopic material by spraying, and he had to improve spray technology to get small enough sizes to make the system work. Presently, thanks to the chemical processing industry, we can do very much better in obtaining proper spray and dust sizes.

Houghton says that he was lucky in getting the good dispersion of his treatment material in the fog that gave him success 8 out of 9 times. I believe that he applied keen insight, not just good luck, in developing his equipment and experiment design. It seems apparent to me, that one of the major problems in field experiments being run now is achieving a proper dispersion of the treatment throughout the fog to be cleared. It is now possible to design a treatment system to give proper dispersion. Basic work has been done in this field for chemical warfare, prediction of fallout for atomic blasts, and air pollution. From design studies, it can be shown that the instantaneous plumes from a point ground source will be typically about 7° wide and will meander over about 15°. So one point source can hardly give even a satisfactory demonstration. If the treatment is to take place from the ground, a carefully designed line of point sources is needed.

I know it seems paradoxical, but I find from design studies that there is an advantage in using smaller treatment particles which stay suspended longer. They diffuse more thoroughly and precipitate larger amounts of water for the mass of material used. Certainly, the longer the time that it takes the fine particles to precipitate out would increase the uncertainty of hitting the target area; but my studies show that there will usually be a greater compensatory increase in the size of the area of effective clearing gained from using finer particle sizes.

The relationship between particle size, amount of material and time of clearing to targeting difficulty needs careful study.

Another factor that makes fog clearing more attractive now than it was 30 years ago is the changing economics. The cost to aviation of delays and cancellations is increasing. We must be a lot closer to the all-electronic landing system now than scientists were 30 years ago, when they decided not to pursue hygroscopic fog clearing because it would soon not be needed. Even so, it looks as though there will be a requirement for good visibility during touchdown and runout for some years to come.

Few people were interested in the detailed nature of fog before there was promise of economically significant modification. In their work to date, the Cornell Aeronautical Laboratory group has made many basic measurements; but there is still much to learn. Now that we would like to get ready to do commercial warm fog modification, we find that there are many basic questions about fog formation, regeneration, turbulent mixing, and microphysical make up that we need to answer if we are to approach this problem with confidence of success.

James Y. Deen - I would like to know how many ground generators would you expect or forecast to be required to clear the fog or allow operational landings at a given airport?

Clement J. Todd - Well, possible one, although the cleared area will meander back and forth with the wind. You just can't plainly expect any straight shots. They will be extremely rare.

I think that probably about three generators would be required to do an experiment in which you have some chance of the cleared area being over your instruments for measuring visibility. I think that you really ought to get up to five sources. And I visualize quite a lot larger number than that for practical applications at airfields. The sources would need to be located some distance upwind of the airport, equivalent to 30 minutes drift time.

James Y. Deen - You are saying that you would have generators upstream from the airport, say five miles or so?

Clement J. Todd - Yes, that is right. This is just a guess. We use quantitative imagination at the moment.

Roger G. Flynn - I have heard a number of comments today that sort of puzzled me as to whether we all understand what the game is. The way that we look at it we feel that we have got to clear an area from the middle marker at the decision height whatever that is, 200 feet, category 1; 100 feet, category 2, so that the pilot can pick up the approach light system, and then have the full length of the runway cleared. And then you have to keep in mind that the transmissometer is offset some 400 feet from the center line. So we need to kick that open, too, so that the control tower knows that it is in fact operational. But the name of the game is not to cheat the transmissometer. That is the easiest thing that we can do. So keep that in mind. We have got kind of a large job. When you get down to counting how many ground dispensers you need, we have to figure on a number of different kinds. It may be more than five, just a horseback guess. okay.

Clement J. Todd - Five is sort of the minimum to get a channel opened over a small area.

Edmund Bromley - These last few comments were just enough to make me want to tell you a little bit about what our program is. We have been watching very actively the work that the research people have been doing, and we have been very appreciative of the chance to come and listen to the results of the NASA program.

I could not let Mr. Flynn's remarks and Mr. Beckwith's remarks and some of the others go without making a brief mention of the FAA research and development program in fog dispersal. What I want to indicate to everyone here, is that there is an FAA research and development program and it has been one of actively monitoring the work of the research groups in the methods of dispensing fog. We do have an in-house study program on the costs and benefits of fog dispersal to aviation including some of the cost factors that were mentioned here today. We are most interested in the program from an overall system point of view. I think the activities that were mentioned with regard to the interface with the air traffic control system have to be looked at before any system becomes operational. I don't want to do any more than mention these interfaces that have to be looked upon. The problem of two aircraft flying in echelon in IFR weather may be a good experimental technique. I don't know that such a posture would be the one that you would want to follow on an operational basis. I am merely suggesting to the group that if you have some ideas and thoughts with regard to evaluating any of these systems, we would welcome them. We are just up the street in FOB 10A. We would like very much to hear your ideas in making something like this properly interfaced with the national airspace system that exists now.

Roger G. Flynn - That is an excellent point, because in the Sacramento work we had to dovetail very tightly with the air traffic control system. And some of our early failures were directly related to lack of comprehension on the part of controllers about what the pilot was trying to do. Once these things are ironed out, other things move rather smoothly. I am sure that Larry Davis' group has run into this problem too. And we think the FAA is in the fog dispersal business because they have been a tremendous help to us, and we would never have been able to get anything going if it hadn't been for the cooperation that we received.

I would like to just sum up how we feel about the whole effort that has been discussed today. We don't care who comes up with the best scheme. We are for the best scheme, and we want everybody to keep going and keep plugging, whether it be radiant heat or the salt method, or whatever. We think that the effort being expended now is a good one and that the money is going in the right direction. We may fail a little bit here and there, but we think that it should lead to a winning system, and I don't think that five years is out of line at all.

Larry G. Davis - I would just like to amplify on the fact that we have found the controllers to be very cooperative in establishing workable, safe patterns that would fit within the normal operating procedures. I think that his comment is well taken, that if you are going to have any system, ground based, airborne system or a combination of these two, you have to work very carefully with the facilities available, and the constraints that you find at the specific airport.

VIII. LIST OF ATTENDEES

William S. Aiken, Jr.	NASA Headquarters
Richard Allen	Avco Everett Research Laboratory
Walter Baginsky	Air Force Cambridge Research Labs.
Robert Baier	Cornell Aeronautical Laboratory
Don Barney	McGraw-Hill
Steven A. Barsony	Department of Transportation
W. B. Beckwith	United Air Lines
Jack Bergwerk	Steinhall Company, Inc.
A. S. Bomberger	NASA Headquarters
J. R. Boyer	United Air Lines
David R. Boldt	The Washington Post
F. E. Borton	Olin Mathieson Chemical Corporation
Edmund Bromley, Jr.	Federal Aviation Administration
Joseph A. Browne	Trans World Airlines, Inc.
Robert Burger	National Academy of Engineering
J. T. Burke	NALCO Chemical Company
Robert O. Carothers	Calgon Corporation
Thomas W. Cates	Federal Aviation Administration
C. F. Chow	Navy Weather Research Facility
Richard S. Clark	Naval Weapons Center
G. W. Cleven	Federal Highway Administration
Augustus V. Connery	Federal Aviation Administration
H. A. Corzine	U.S. Naval Air Systems Command
N. V. Cottrell	U.S. Naval Air Systems Command
J. E. Creed	Federal Aviation Administration
Herman Croom	Bolling Air Force Base
Robert M. Cunningham	Air Force Cambridge Research Labs.

John Damon	NASA Headquarters
Larry G. Davis	EG&G, Inc.
P. G. DeBaryshe	Avco Everett Research Lab.
J. Y. Deen	Braniff International Airways
Vito DePalma	Cornell Aeronautical Laboratory
A. R. Deptula	Office of Aerospace Research
H. Searl Dunn	NASA Headquarters
Walter R. Dunn	FMC Corporation
J. E. Dinger	Naval Research Laboratory
Donn Doak	NBC - WRC
Hans Dolezalek	Office of Naval Research
William J. Eadie	Cornell Aeronautical Laboratory
Howard W. Eakins	Federal Aviation Administration
David Eddlemen	Office of Federal Coordinator for Meteorology
George Ettenheim	Meteorology Research, Inc.
Albert J. Evans	NASA Headquarters
Donald L. Feller	NASA Wallops Station
Eric Fisher	FMC Corporation
Robert D. Fletcher	Air Force Air Weather Service
Howard L. Flohra	Federal Aviation Administration
Roger G. Flynn	Air Transport Association
James W. Ford	Cornell Aeronautical Laboratory
E. M. Frisby	Fort Monmouth
Donald M. Gales	Weather Bureau
William Garrett	Naval Research Laboratory
William A. Garrett	Gannett Newspaper
W. Ferguson Hall	Environmental Science Services Admin.
Arthur L. Handman	The MITRE Corporation
Charles W. Harper	NASA Headquarters
Wayne Heel	Federal Highway Administration

James R. Hicks	U.S. Army Material Command
Arthur Hilsenrod	Federal Aviation Administration
Edward E. Hindman, II	Navy Weather Research Facility
Don O. Horning	University of California
John T. Howe	NASA Headquarters
R. E. Jarmon	Arlington, Virginia
James E. Jiusto	State University of New York
F. Robert Johnson	Dynatech Corporation
John P. Keany	NASA Headquarters
James L. Kerr	Bureau of Reclamation
Warren C. Kocmond	Cornell Aeronautical Laboratory
Peter E. Kraught	American Airlines, Inc.
H. Kurzweg	NASA Headquarters
Stanley J. Lacy	Weather Bureau
James D. Lacy	Federal Highway Administration
George A. Lan	The Dow Chemical Company
Isaac L. Ledbetter	Federal Aviation Administration
Jerome Lederer	NASA Headquarters
Newton A. Lieurance	Environmental Science Services Admin.
Eugene J. Mack	Cornell Aeronautical Laboratory
Ronald J. Maselke	Buffalo Evening News
James D. Matthews	Mohawk Airlines
Hubert McCaleb	National Transportation Safety Board
James A. McColman	North Carolina Department of Water and Air Resources
Robert P. McGowan	U.S. Army Limited War Laboratory
William A. McGowan	NASA Headquarters
J. R. Melcher	Massachusetts Institute of Technology
Frank V. Melewicz	Federal Aviation Administration
Allan Merkin	NASA Headquarters
C. R. Mertz	International Salt Company

Ron Mogford	H.I.R.E.R. Corporation
Paul Moore	Federal Aviation Administration
George Moritz	International Salt Company
James W. Murphy, S.J.	Saint Mary's University
Roger Navarro	NASA Wallops Station
Fred L. Niemann	NASA Electronics Research Center
Daniel J. Norton	Detroit Metropolitan Wayne County Airport
Seth Payne	McGraw-Hill
T. Post	Serendipity Associates
Tom Phipps	World Weather, Inc.
Roland J. Pilié	Cornell Aeronautical Laboratory
Antonio Pinna	EPOCA and Panorama Magazines
Leon S. Pocinki	GEOMET, Inc.
William Poellmitz	Meteorology Research, Inc.
Edward R. Redding	NASA Headquarters
Gayle S. Rinehart	Atmospheric Sciences Laboratory
R. S. Robertson	NALCO Chemical Company
J. J. Roemer	Olin Mathieson Chemical Corporation
Lothar Ruhnke	Environmental Science Services Admin.
R. E. Ruskin	Naval Research Laboratory
Murray H. Schefer	Naval Air Systems Command
Raymond B. Schnell	U.S. Army Advanced Material Concepts Agency
Ira R. Schwartz	NASA Headquarters
Michael Septoff	GEOMET, Inc.
Earl K. Seybert	W. R. Grace and Company
Joseph F. Sowar	Federal Aviation Administration
J. S. Stickle	NASA Langley Research Center
J. Robert Stinson	Bureau of Reclamation
Dee G. Sullins, Jr.	Office of Aerospace Research

Dee F. Taylor	Department of Agriculture
Scott Thayer	GEOMET, Inc.
James Thompson	Federal Aviation Administration
Clement J. Todd	Navy Weather Research Facility
H. B. Tolefson	NASA Langley Research Center
Karl Treml	Embassy of Germany
Mary Jane Ullrich	The Port of New York Authority
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Harvey R. Wendorf	Federal Aviation Administration
Frances L. Whedon	Department of the Navy
Fred D. White	National Science Foundation
William C. White	Naval Weapons Center
Glenn Wilson	Staff Senate Committee, Aeronautical and Space Sciences
Peter H. Wyckoff	National Science Foundation
George Yount	Weather Bureau
George Zigrossi	Cornell Aeronautical Laboratory
Harry J. Zink	Department of Transportation

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