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PROJECT FOG DROPS
INVESTIGATION OF WARM FOG PROPERTIES AND FOG MODIFICATION CONCEPTS

QUARTERLY PROGRESS REPORT

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TABLE OF CONTENTS

I. INTRODUCTION

The Office of Aeronautical Research of the National Aeronautics and Space Administration has authorized this Laboratory, under Contract No. NASr-156, to investigate warm fog properties and possible fog modification concepts. Analytical and experimental work during the first four years of research led to the development of a concept for fog dispersal by seeding with carefully sized hygroscopic nuclei. During the fifth contract year that concept was thoroughly tested in the laboratory and preparations were made for a series of field experiments. One of the objectives of this year's research has been to evaluate the effects of seeding dense natural fog. This quarterly report summarizes the results of the field experiments and of the subsequent data analysis.

II. TECHNICAL DISCUSSION

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 candidate 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.

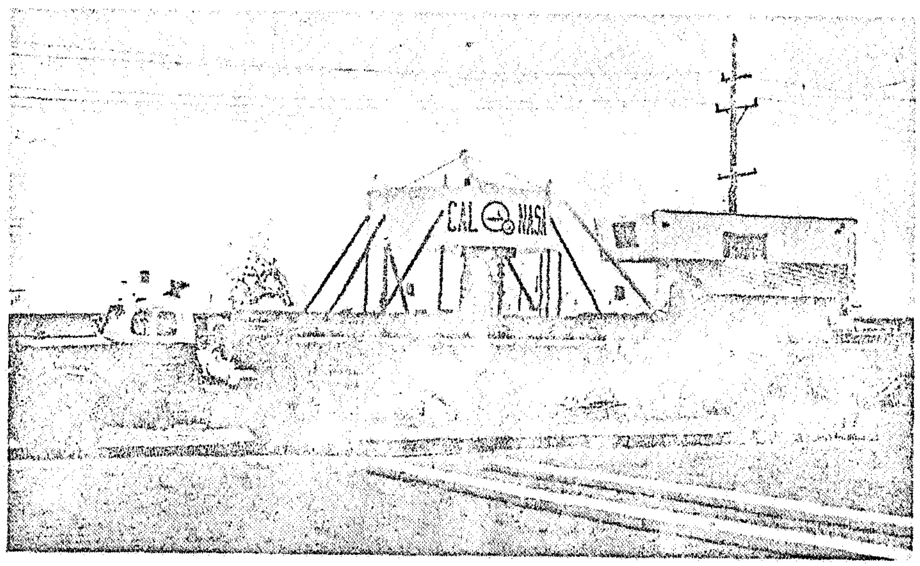

Figure 1 MOBILE SEEDING APPARATUS

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 Hasellblad 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 Paper 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.

*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	10 μ	20 μ	18 μ
TYPICAL DROP DIAMETER RANGE	4-36 μ	6-64 μ	4-50 μ
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.

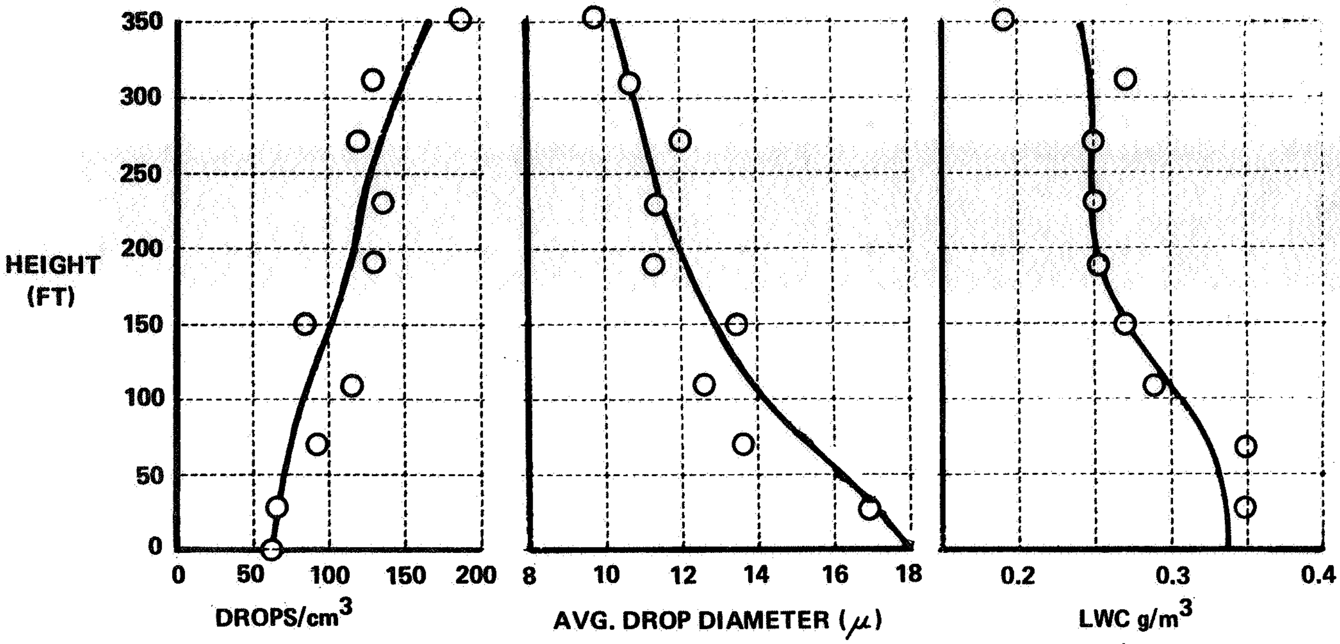

Figure 2 VERTICAL PROFILES OF VALLEY FOG PARAMETERS (AVERAGE DATA FROM FOUR FOGS)

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 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.

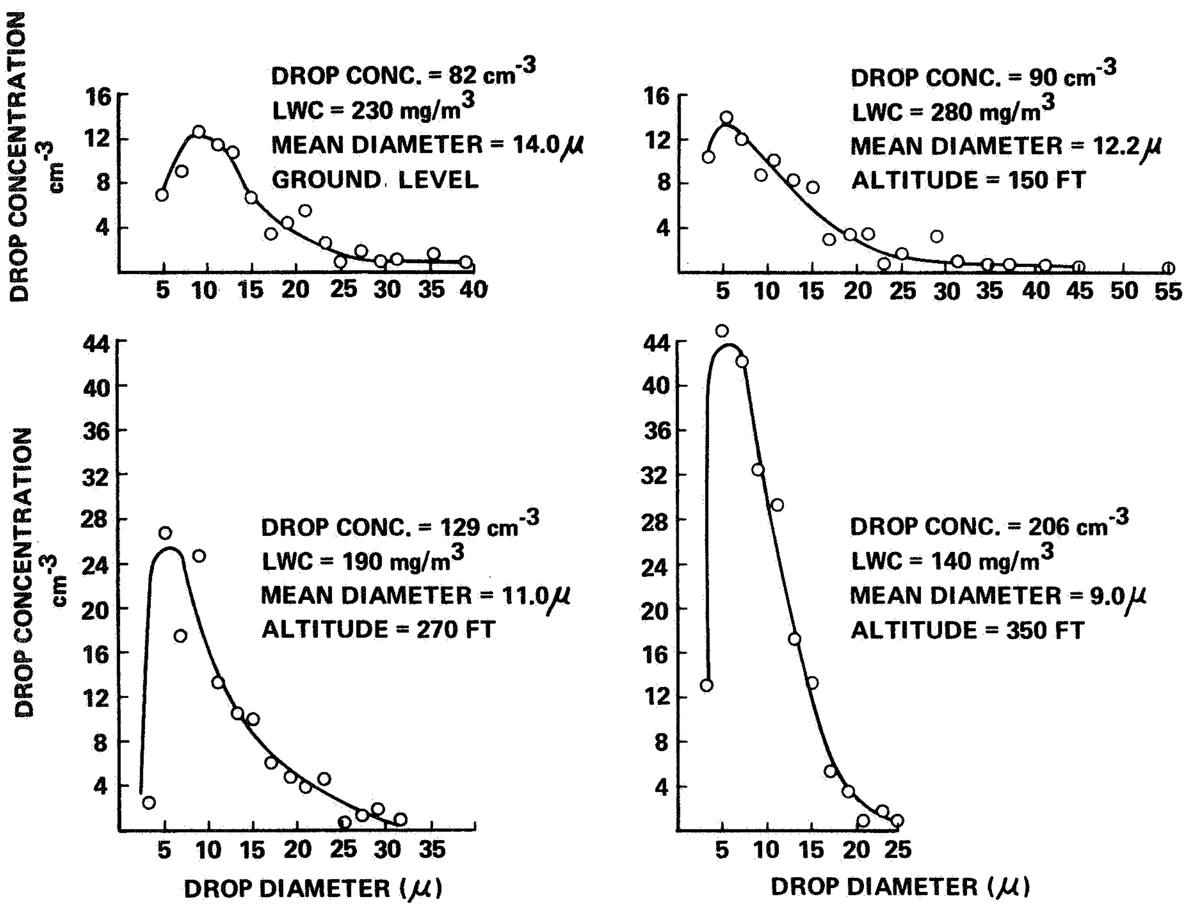

Figure 3 DROP SIZE DISTRIBUTIONS AT FOUR LEVELS IN A VALLEY FOG - ELMIRA, N.Y. 30 AUGUST 1968

In the phase diagram (Figure 4) typical conditions 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.

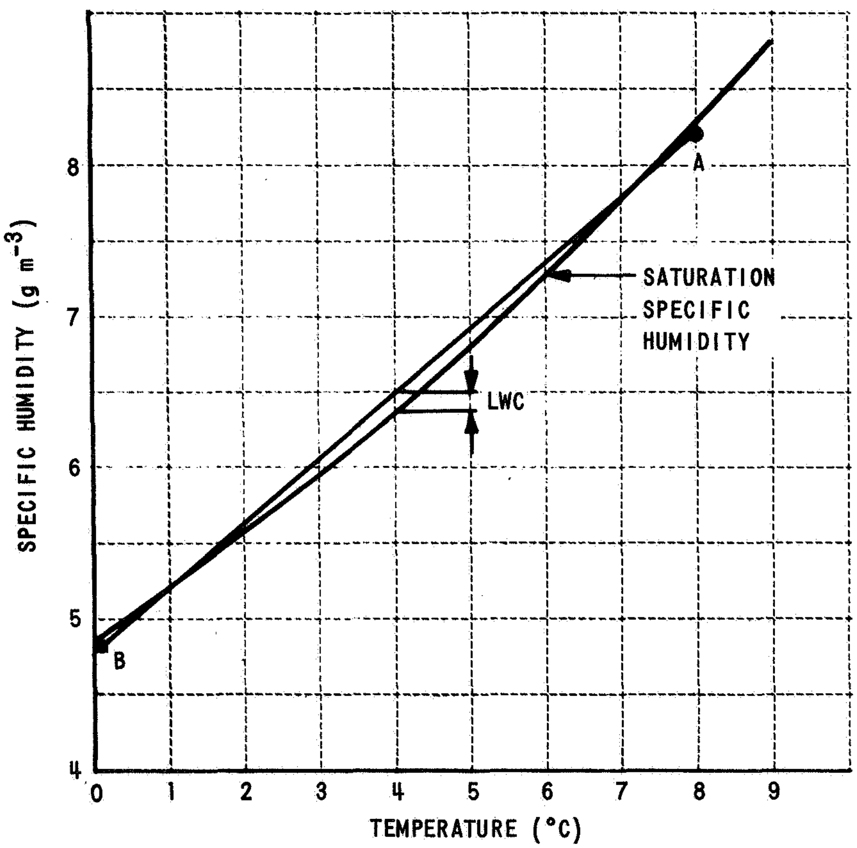

Figure 4: SATURATED SPECIFIC HUMIDITY AS A FUNCTION OF TEMPERATURE

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 account 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 260° at three knots.

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 miles.

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 transmissometers indicated any change in visibility during the same period of time. The improvement in visibility by a factor of 2.5 to 3 is typical

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

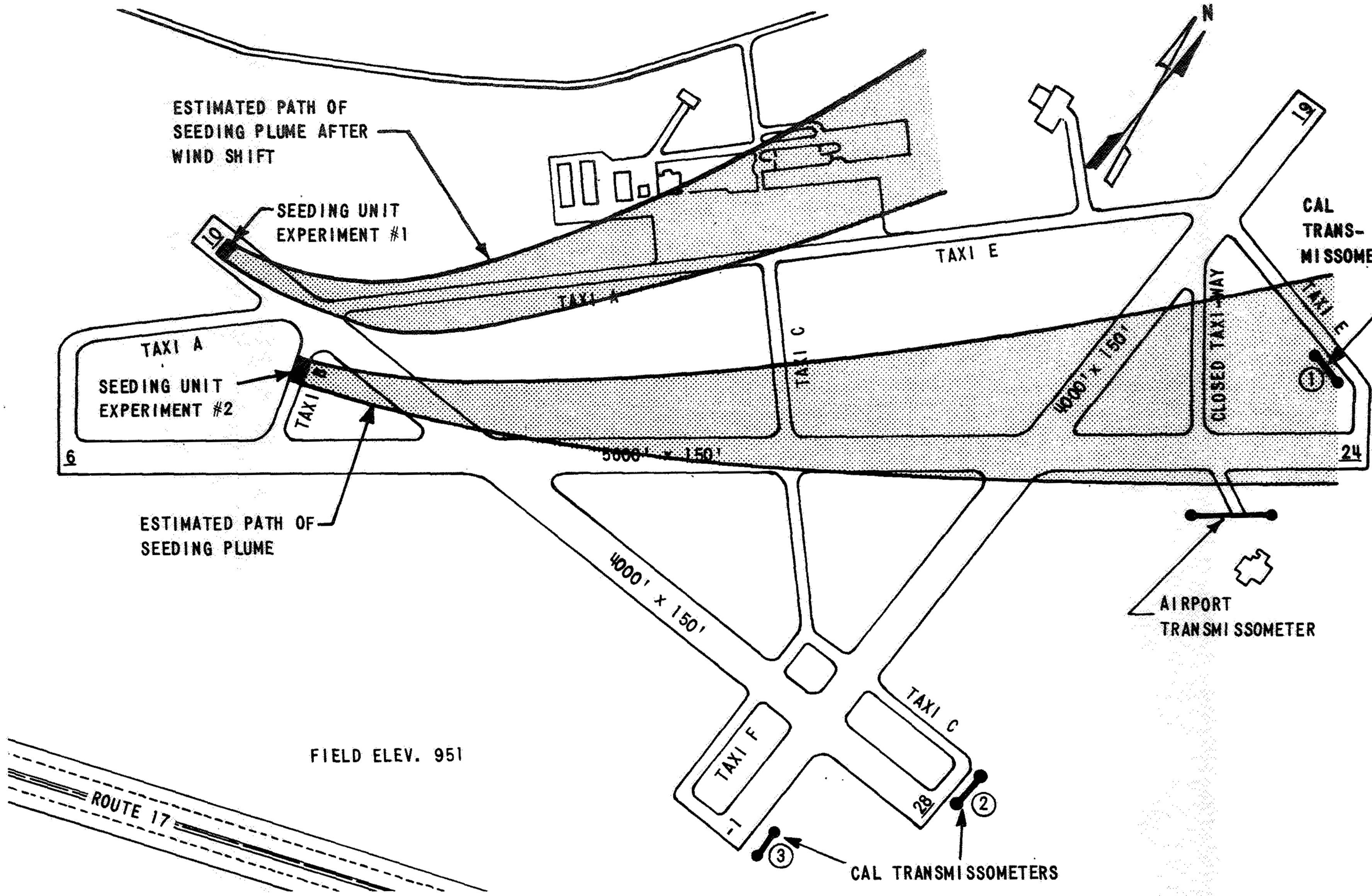

Figure 5 LOCATION OF SEEDING UNIT AND TRANSMISSOMETERS AT EXPERIMENTAL FIELD SITE - CHEMUNG COUNTY AIRPORT, ELMIRA, NEW YORK, SEPTEMBER 8, 1968

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.

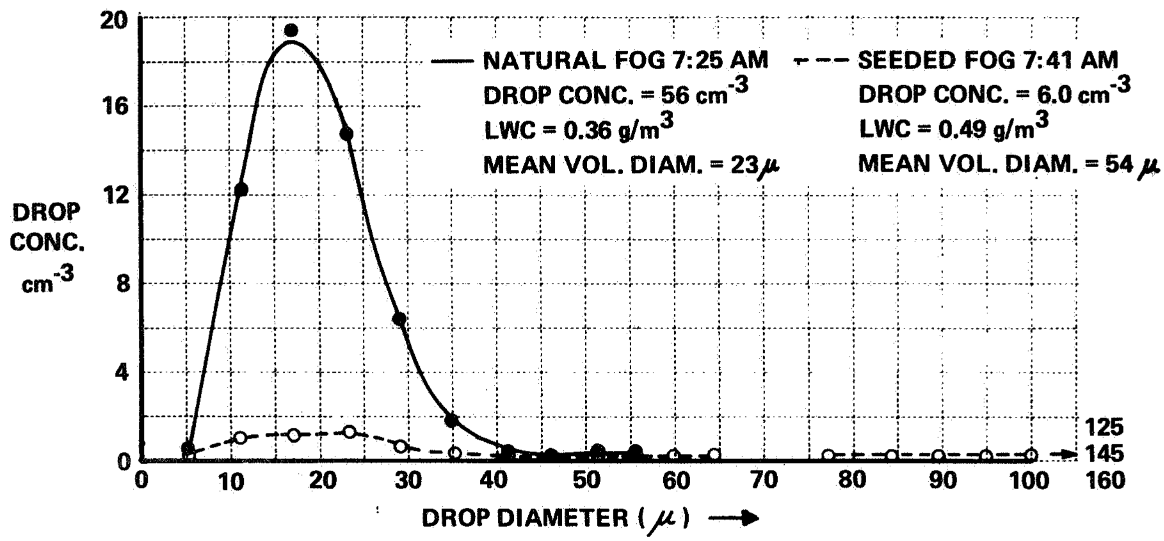

Figure 6 COMPARISON OF DROP SIZE DISTRIBUTIONS FOR NATURAL AND SEEDED FOG SEPT. 8, 68

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 seeding 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.

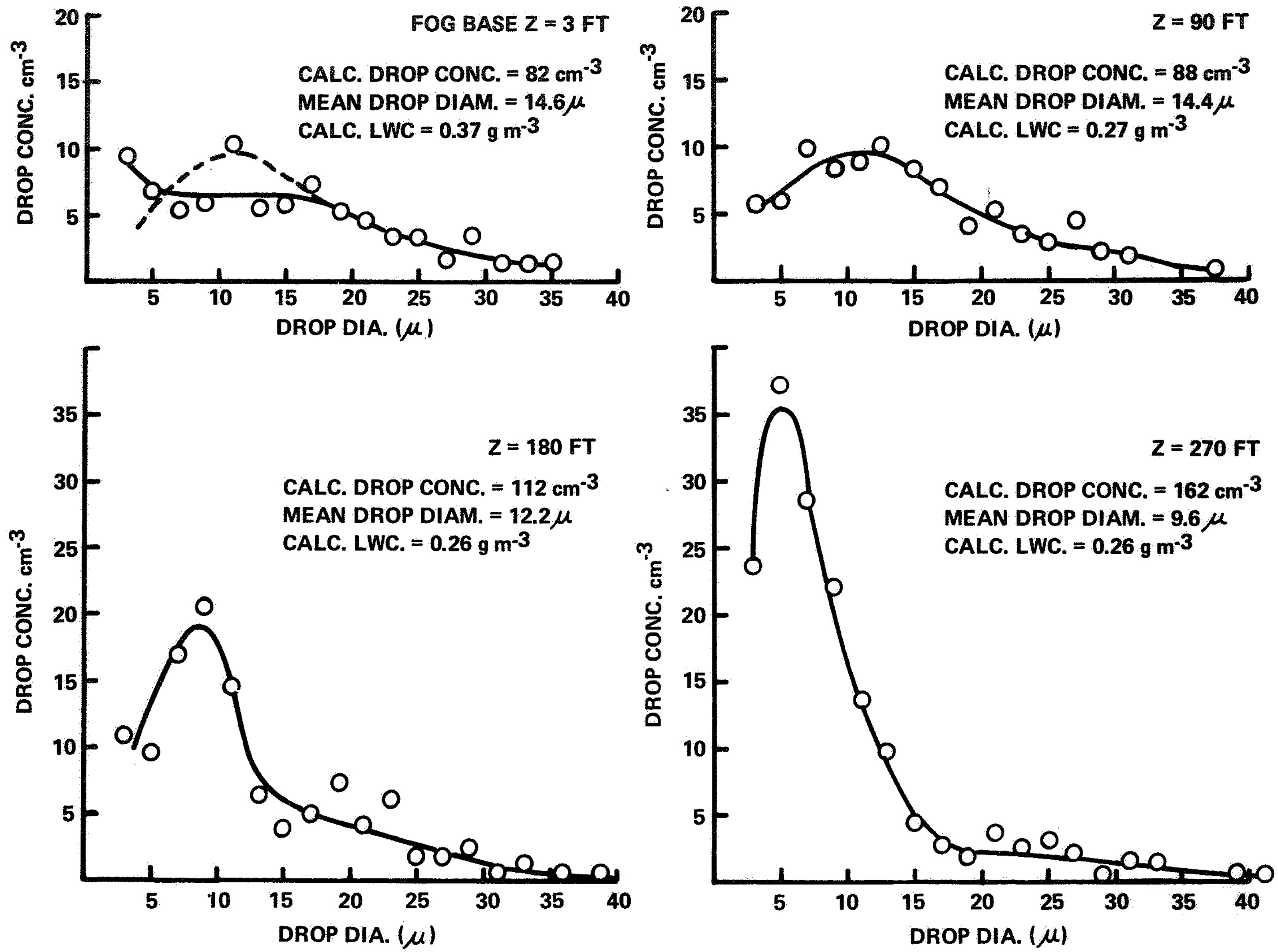
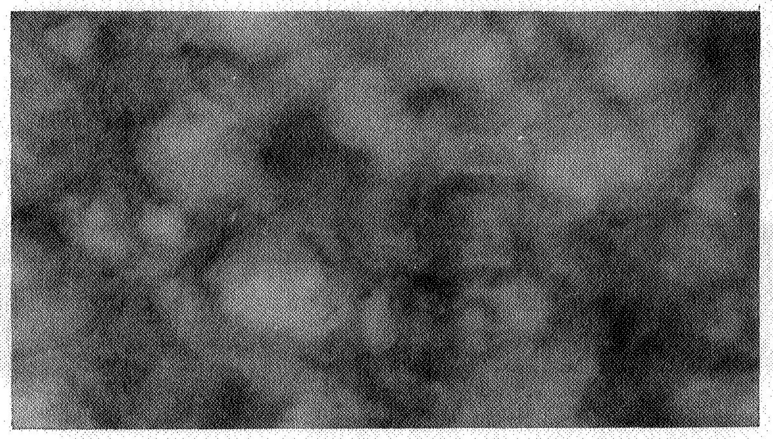
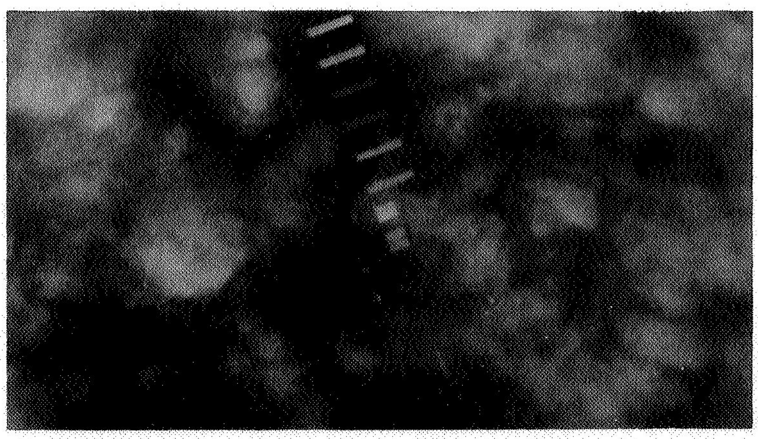


Figure 7 DROP SIZE DISTRIBUTIONS AT FOUR LEVELS IN A VALLEY FOG PRIOR TO SEEDING - ELMIRA, NEW YORK, 16 OCTOBER 1968



TARGET AREA ONE MINUTE PRIOR TO SEEDING.

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



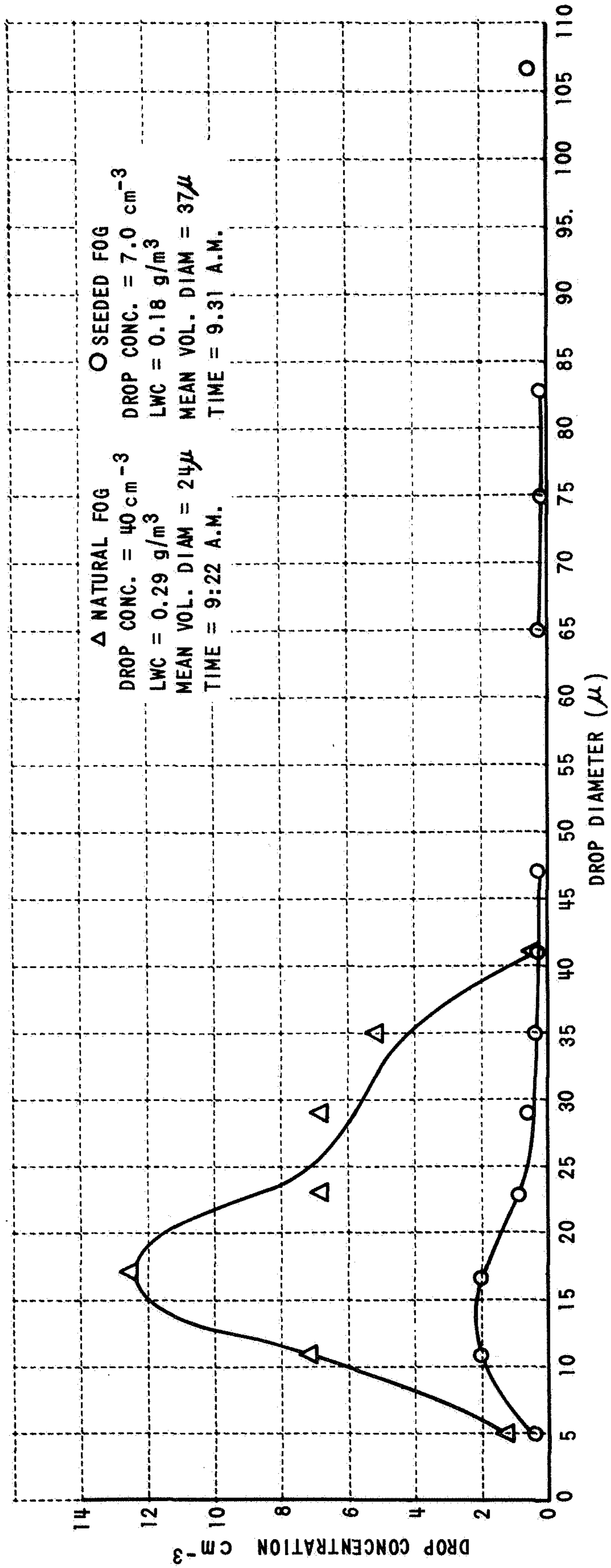
THE TARGET AREA 15 MINUTES AFTER START OF SEEDING

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.