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

QUARTERLY PROGRESS REPORT
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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. The program to date has emphasized analytical and experimental work on:

1. Models of the micro- and macroscopic properties of warm fogs.

2. The characteristics of aerosol droplets and means of favorably altering these properties.

3. The construction of apparatus for simulating certain fog conditions.

4. The design and construction of apparatus for measuring certain fog parameters.

5. Observations in natural fog to gather more detailed information about the properties of natural fog.

6. Experimental alteration of the growth and evaporation rate of otherwise stable aerosol droplets.

7. Formulation of fog modification concepts based on the above findings, as well as a review of other possible techniques.

8. Assessment of the supercooled fog problem in the United States and specification of the geographic areas where an operational seeding program might be practical.

This report briefly describes accomplishments of the second quarter of the third contract year. Plans for the next quarter are outlined.

II. DISCUSSION

A. Measurements in Natural Fog

During the latter part of October and early November of this year we conducted a field program in Central Pennsylvania in order to obtain additional data about certain characteristics of natural fog. In particular, we were seeking information about the drop size distribution, nuclei concentration, liquid water content and vertical temperature variation in fog.

On two dates, during periods of pre-frontal fog, we were able to take measurements of all the desired fog parameters except vertical temperature variation, which, in both cases, was impractical because of fairly high winds (10 knots). We were also able to make daily measurements of the nuclei concentration with the thermal diffusion chamber and also with the G-E small particle detector. It was unfortunate that the number of radiation fog cases this fall were minimal owing to a dry spell throughout most of the period.

In the last progress report (RM-1788-P-10) we presented a description of the instrumentation used in the field program and, at that time, had started the analysis of data. Results of the analysis are now complete and are presented below.

1. Drop-size distribution: Measurements of drop-size distribution in fog were made on several dates in locations other than our field site. On certain clear, calm nights when there was sufficient moisture in the air, radiational cooling was effective in producing patches of ground fog and occasionally valley fog in the area. Generally, however, the dryness of both the ground and the attending air mass prevented widespread fog from forming. Because of the portability of our drop-size measuring apparatus we were able to seek out the fog on these occasions and obtain additional data. Measurements of the other fog parameters, however, could only be made when fog actually occurred at our field site.

In Figures 1 and 2 sample photographs are presented which show the impressions fog and cloud droplets make on gelatin coated slides. From a previous calibration and from past work done by Jiusto (1965), we found the actual drop diameters to be about one-half the crater-like impressions left in the gelatin. In the photographs one division of the grid represents 95μ.

The droplet impressions in Figure 1 were taken during a pre-frontal fog that occurred at the field site on November 8, 1965. Visibility was about 1/8 mile with some light drizzle in the area. The drop size range is typical for frontal fog and was found to be 2 to 50μ diameter, although in the photograph the largest impression shown was produced by a drop of only about 34μ. In contrast, the drop sizes in Figure 2 are much smaller, generally averaging about 6 to 8μ in diameter and having a size range of 1 to 20μ. These droplets were sampled from a low lying stratus cloud that had obscured the nearby ridges surrounding the field site. Visibility within the cloud was < 1/8 mile and some light drizzle was falling.

From the results of numerous other slides taken in fogs and clouds, the following average values were found.

Table 1

Average drop size ranges, mean drop diameters and volume mean diameters of fog and cloud droplets

Fog or Cloud Type	Average Drop-dia. Range	Mean Drop-dia.	Vol. Mean Dia.
3 frontal fogs	2 - 50μ	7.8	14.2
2 radiation fogs (1 valley & 1 ground fog)	1.5 - 39μ	3.5	7.5
3 stratus cloud cases	1.5 - 43μ	4.9	9.6

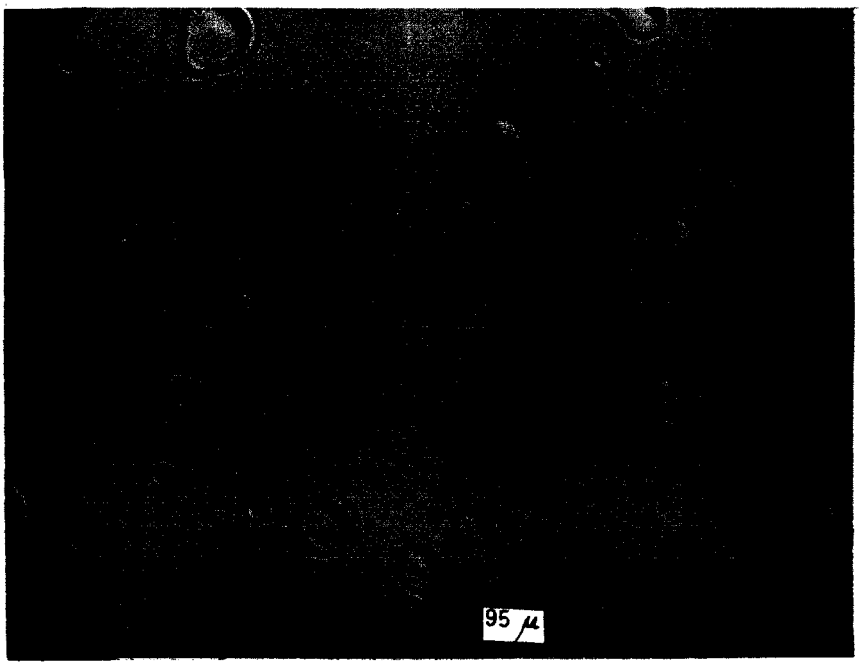


Figure 1 FRONTAL FOG DROPLET IMPRESSIONS

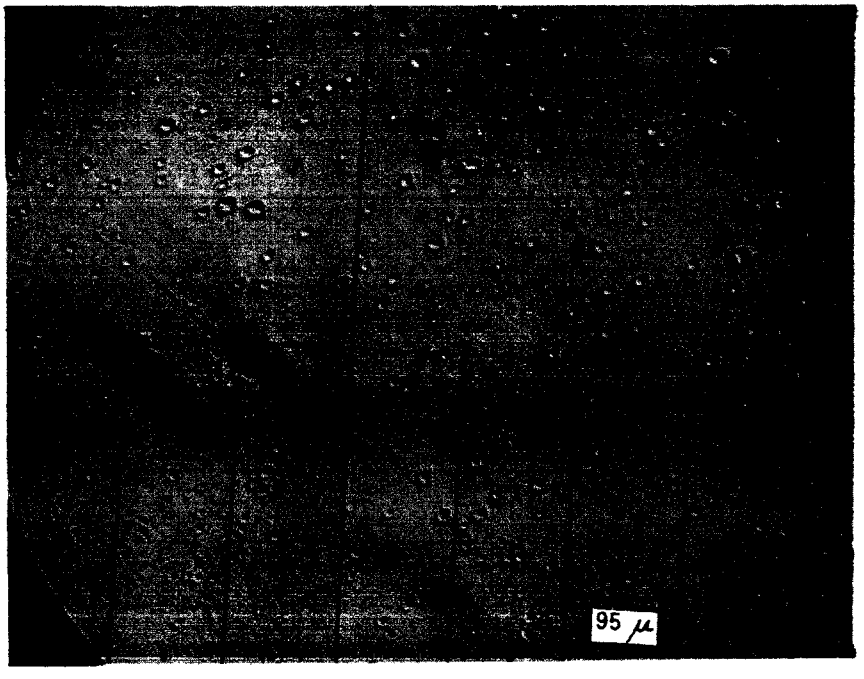


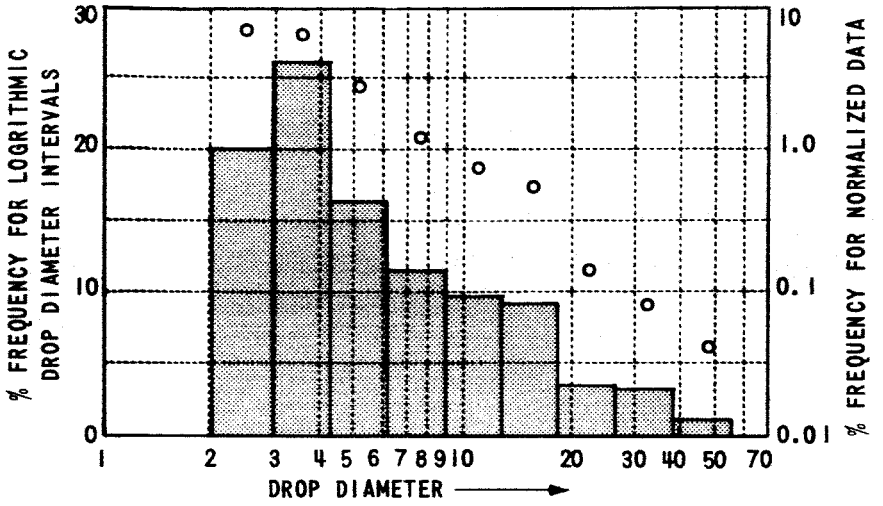
Figure 2 STRATUS CLOUD DROPLET IMPRESSIONS

In the analysis, several photomicrographs were first taken of each slide sample. The drop sizes were then read directly from the photographs with a calibrated eyepiece and classified according to true drop diameter. Since the collection efficiency of the slide was not the same for all drop sizes (very small drops in the airstream tend to flow around the slide) it was necessary to apply a collection efficiency correction to each class of drop sizes. The correction factors were taken from the experimental results of Langmuir and Blodgett (1946) and take into account the slide width, airflow rate and ambient conditions. The resulting drop size distributions are shown in Figures 3, 4, and 5 in which the corrected average drop-size distributions are given for frontal fog, radiation fog and stratus clouds, respectively.

As expected, the use of narrow slides not only improved our measuring capability but also revealed lower average drop sizes than indicated by most previous measurements. The results of our measurements are in good agreement with the data given by Pedersen and Todsen (1960) for stratus clouds and fog. The fact remains, however, that in order to obtain samples of the smallest droplets (i.e. $< 1.5\mu$) it will be necessary to either substantially increase the airflow rate or use slides of even narrower width. Since it is difficult to duct air past the slides at speeds in excess of 100 mph the desired sensitivity to these small drops can be achieved by using a droplet collector of only 1 or 2 mm width. Continued measurements in the Buffalo area are planned using these design improvements.

2. Nuclei Measurements: Cloud and fog nuclei, the centers upon which all fog droplets must grow, were measured on a daily basis at our field site using the thermal diffusion chamber. The total concentration of nuclei was also measured with a conventional expansion chamber. From our measurements, we planned to gather additional information about a) the concentration of fog nuclei in areas relatively free of pollution but known to have frequent occurrences of natural fog, b) the correlation between the total nucleus content and the concentration of fog nuclei and c) the variation of nucleus concentration prior to or during episodes of natural fog.

Figure 3
AVERAGE DROP SIZE DISTRIBUTION FOR THREE FRONTAL FOGS



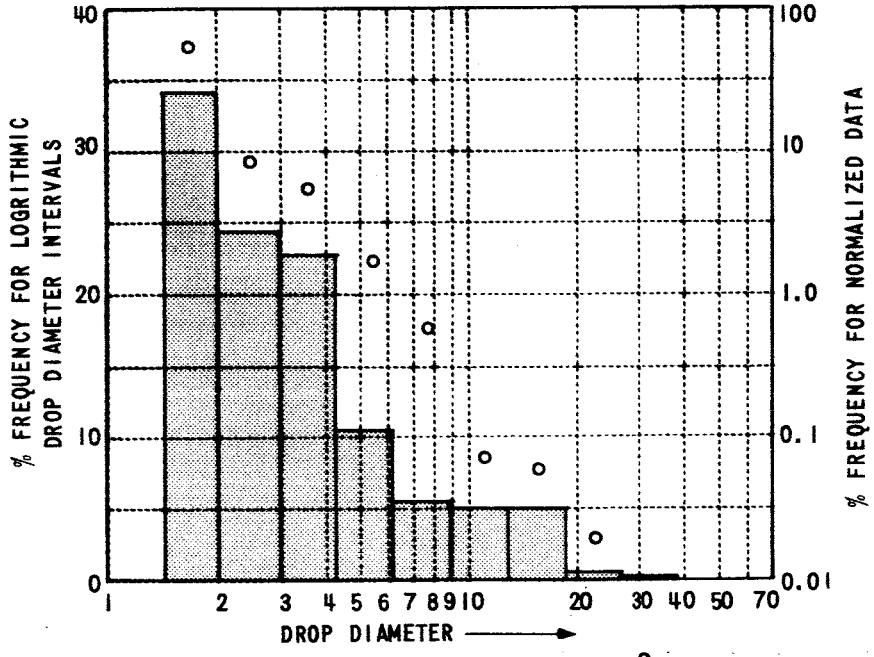
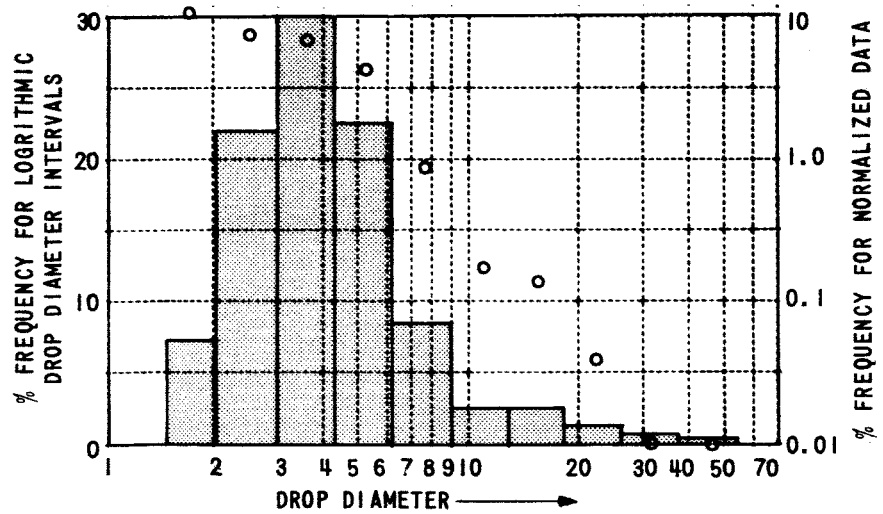


Figure 4
AVERAGE DROP SIZE DISTRIBUTION FOR TWO RADIATION FOGS (1 GROUND AND 1 VALLEY FOG)

NOTE:
Left scale is to be used for Histograms. Right scale is to be used for o in which data are normalized to drop diameter increments of 1 μ.

Figure 5
AVERAGE DROP SIZE DISTRIBUTION FOR THREE STRATUS CLOUD CASES



In Table II the results of observations taken in Central Pennsylvania are compared with past measurements taken at Buffalo and Springville, N.Y.

Table II

Average nuclei concentrations at three locations

Supersaturation	Avg. no. of nuclei/cc^3 (Buffalo, N.Y.)	Avg. no. of nuclei/cc^3 (Springville, N.Y.)	Avg. no. of nuclei/cc^3 (Central Pa.)
3.0%	5300	3075	2600
0.9%	3450	1725	1720
0.1%	495	415	410
0.02%	425	335	380

At high supersaturations the observations in Central Pennsylvania follow the same type of trend that was found in Springville. For instance, at 3.0% supersaturation the average concentration of nuclei at our field site was nearly 54% less than in Buffalo and almost 15% less than in Springville, N. Y. This trend toward lower numbers in regions of low atmospheric pollution was discussed in the Second Annual Summary Report and in the discussion of Hawaii data presented in the last quarterly report. Briefly, we have shown that the effects of atmospheric pollution become increasingly obvious at higher supersaturations since most contaminants in the Aitken size range (10^{-5} to 10^{-6} cm) are not large enough to grow to fog droplet sizes at very low supersaturation. Many of these nuclei, however, are very hygroscopic and do contribute to industrial haze. Of particular interest here is the fact that at 0.02% supersaturation the average concentration of fog nuclei at our field site was only 10% less than in the highly contaminated atmosphere of Buffalo. We discovered that our results were strongly influenced, at this low supersaturation, by the measurements made on four separate days in which the nucleus concentration averaged between 750 and 900 nuclei/cc^3. On three of these days the wind was S to SW and was accompanied by a peculiar odor generally associated with pulp mills. One such mill is

located in Tyrone, Penn., a town about 22 miles S-SW of our field location. Evidentally, a prolific source of fog nuclei is provided by the chemicals used in these mills. This source of fog nuclei appears to play an important role in the formation of some fogs in the area. On all occasions in which we noticed the odor, there was a substantial amount of haze in the area, even though on each occasion conditions were not good for the formation of natural fog. We are attempting to obtain some of these chemicals for examination in the laboratory.

In our studies of nuclei we have found that, in general, very little correlation exists between the concentration of fog nuclei and the total nuclei content. For example, it is not uncommon to find 150 nuclei/cc^3 active at 0.1% supersaturation even though the total nuclei content (as measured by the expansion chamber) may be as high as 95,000/cc^3 or as low as 2500/cc^3. We have also found from our hourly measurements that on certain occasions the fog nuclei count may steadily increase even though the total nuclei count is falling. One such occasion was noted during the early morning hours of November 3, 1965. The wind was from the south at 2-5 knots and the temperature was about 40°F. At 0200 EST, the concentration of fog nuclei measured at 0.1% supersaturation numbered 225/cc^3 while the total nuclei count stood at 6000/cc^3. By 0600 EST the measured fog nuclei concentration had nearly tripled to 650 nuclei/cc^3 while the total nuclei count fell to 4500/cc^3. On this particular night the relative humidity never rose above 70% so that there was little chance of natural fog forming.

This example clearly illustrates why measurements made at high supersaturations (i.e. > 10%) cannot be expected to reveal the subtle changes that sometime occur in the concentration of fog nuclei. Since only a fraction of the total number of nuclei that are present at any given time are potential nucleating sites for fog droplets, the presence of these fog nuclei cannot be detected except through the use of instruments like the thermal diffusion chamber (i.e. instruments capable of reproducing the very low supersaturations found in fog and clouds).

Because of the infrequent occurrence of fog experienced during the field trip we were unable to correlate variations in fog nuclei concentration with fog formation. We plan to continue our measurements in the Buffalo area and perhaps conduct a supplementary study near Springville, N. Y. during April or May of this year when periods of radiation fog are fairly frequent. Perhaps at that time we will be able to more carefully study the variation in fog nuclei that may occur prior to natural fog formation.

3. Liquid Water Content: Perhaps one of the more important parameters that requires additional knowledge before certain fog modification concepts can be considered is the liquid water content in natural fog. Because these observations are extremely scarce we have, in the past, relied on developing analytic expressions to describe the distribution of liquid water in fog (see Second Annual Summary Report RM-1788-P-9). These expressions have been valuable in formulating our mathematical fog models and in assessing the general fog problem, but the requirement for additional experimental measurements still exists. To help satisfy this requirement we obtained a few additional liquid water measurements while at Philipsburg, Penn. The instrument used for these measurements was discussed in the previous quarterly report.

During the four weeks of operation in Central Pennsylvania we were able to make measurements of fog liquid water on the two occasions in which widespread fog occurred. Measurements were taken approximately 5 meters above the ground, atop our laboratory van. Table III shows average measured values of liquid water content in the two frontal fogs as a function of visibility. Estimates of visibility were made from the airport transmissometer located alongside our apparatus.

Table III

Average values of LWC for 2 frontal fogs as a function of visibility

Visibility	Average LWC
100 meters	0.22 g/cc^3
200 meters	0.12
300 meters	0.05

Although these averages represent mean values for just two fog cases they are in quite good agreement with the values given by our physical fog models (i.e., average LWC for advection fog was given as approximately .17 g/m^3).

4. Vertical Temperature Variation: In the past we have stressed the importance of obtaining measurements of the vertical temperature variations in dense radiational fog. Because the flux of heat from the earth's surface is greatest on clear, calm nights we were particularly interested in measuring the vertical extent of the resultant temperature inversion layer prior to and during periods of radiation fog. Since all of the fog cases occurring at the field site were of the frontal type and were generally accompanied by winds of 5 to 10 knots and overcast skies, no measurements of this fog parameter could be made. The fairly strong winds not only produced substantial vertical mixing in the lowest layers of the atmosphere but also made use of the tethered radiosonde impractical.

Acknowledgments

We wish to express our gratitude to the personnel of Penn State University who assisted in our experiments and to the Department of Meteorology for their cooperation in this program. Without their assistance we could not have conducted this field program. We also owe thanks to the personnel of the FAA, Philipsburg, Penn. airport, who secured weather records and transmissometer data for us.

B. Investigation of a Possible Method for Preventing Dense Radiation Fog

We have suggested in the past that dense radiation fog might be prevented if extremely hygroscopic, large nuclei are introduced into the atmosphere before the fog begins to form. To briefly review our thinking along these lines and to review some of our more current findings the following discussion is presented.

In the process of natural fog formation, droplets grow first on those nuclei that are both large and very hygroscopic. As the humidity increases, other nuclei of less hygroscopic substance may start to hydrolize, but generally, these nuclei do not become fog droplets since they require a greater supersaturation for growth than normally found in fog. The number of nuclei that do participate in the ensuing fog is determined by 1) the distribution of size and hygroscopicity of the nuclei and 2) the rate at which excess water vapor is made available for droplet growth.

From numerous nuclei measurements made with the thermal diffusion chamber, we have found that the number of nuclei that are active, even at 0.1% supersaturation, is generally two or more times as great as the number of drops found in natural fog. From this we can conclude that the maximum supersaturation found in most natural fogs rarely exceeds 0.1% and in most cases is much less.

In relatively dry air prior to fog formation, the maximum cooling rate likely to be encountered is of the order of $3^{\circ}C/hr$. At this rate water would be made available at a rate of 8×10^{-10} gm cm^{-3} sec^{-1} and heat would be lost by the atmosphere at a rate of 2.4×10^{-7} cal cm^{-3} sec^{-1}. If we assume that this heat transfer rate is the maximum encountered during the fog formation process and if we account for the latent heat of vaporization released by condensation, the maximum rate of temperature change after condensation is initiated can be computed to be $0.93^{\circ}C/hr$. This rate of cooling makes water available for condensation at a rate of 2.58×10^{-10} gm cm^{-3} sec^{-1}.

Immediately after the fog has formed the heat loss through radiation is reduced so that the rate of temperature change is of the order of $0.1^{\circ}C$/hr in the fog. At this rate, excess water vapor is made available at approximately 2.6×10^{-11} gm cm^{-3} sec^{-1}. It is instructive to compare these rates at which water is made available for condensation, with rates at which large hygroscopic nuclei can extract water from the atmosphere. To make this comparison, we have computed the amount of water that would be condensed out of a saturated atmosphere onto a four micron diameter dry salt nucleus, as a function of time. The expressions developed by Keith and Arons (1954) were used for these calculations. Results are presented in Table IV. Also shown in the table are the relative humidities at which the droplets of the given sizes are in equilibrium.

TABLE IV

Growth time and mass of water required to produce a solution drop of diameter (d) from a 4μ diameter NaCl nucleus (Mass = 7.2×10^{-11} gm)

(d) solution drop (μ)	mass H_2O (gm)	time required to grow to (d) at 100% RH (sec)	equilibrium relative humidity
7.6	2.01×10^{-10}	0.07	76.0%
8.6	3.12×10^{-10}	0.17	85.2
10.7	6.23×10^{-10}	0.63	92.7
16.1	21.26×10^{-10}	5.92	98.3
18.1	31.16×10^{-10}	11.03	98.7
28.8	124.6×10^{-10}	105.0	99.7

Let us suppose that fifteen nuclei of this type are introduced into each cubic centimeter of air at a time when the humidity has reached a value between 85 and 90 percent. Because these nuclei are hygroscopic, condensation begins on them immediately and droplet diameters soon reach equilibrium values between 8 and 10 microns. Now that condensation has begun, the cooling rate is automatically limited to a maximum of approximately 1° C/hr so that

water is made available for condensation at a rate of only 2.5×10^{-10} gm cm^{-3} sec^{-1}. In this initial growth period, when the heat loss rate by radiation is still high, the equilibrium relative humidity must remain substantially below 100%. If it did not, the amount of water extracted by the 15 growing droplets per cm^3 would exceed 37×10^{-10} gm cm^{-3} sec^{-1}, a value 15 times greater than water is being made available. This number corresponds to the growth rate of 10μ dia. drops in a saturated atmosphere. It seems probable therefore, that the drops will grow at such a rate that they remain in approximate equilibrium with the ambient relative humidity at any time.

Even though the rate of heat transfer by radiation decreases rapidly as water condenses, we can assume for calculation purposes that the maximum rate of temperature change (after condensation begins) continues until the liquid water content is 0.05 gm/m^3. At 2.5×10^{-10} gm cm^{-3} sec^{-1} of water being made available (which corresponds to 1°C/hr temperature change) this liquid water content would be achieved in 180 seconds. During this period the fifteen drops per cubic centimeter would grow to 18.5μ diameter.

At this point in the fog formation we must consider the reduced cooling rate, which is not expected to exceed approximately 0.1°C/hr. At this cooling rate, water is made available at a rate of 0.93 gm m^{-3} hr^{-1} or 2.6×10^{-11} gm cm^{-3} sec^{-1}. During the next hour therefore, the total liquid water content will rise to approximately 0.14 gm/m^3. If all water is condensed on the 15 nuclei per cc added earlier, these droplets would achieve a diameter of 26.8μ by the end of the hour.

Two important features of the fog must be recognized now for comparison with the fog that would have formed had it not been seeded.

1. According to our model, a fog of liquid water content equal to 0.14 gm/m^3 would consist of 200 droplets having a volume mean diameter of 11.2μ. The extinction coefficient for such a fog would be 3.9×10^{-4}. The extinction coefficient for the seeded fog would be 1.7×10^{-4}. Since the extinction coefficient is inversely proportional to visibility we may conclude that visibility in the seeded fog would be 2.3 times greater than what would have occurred without seeding.

2. The fall velocity of an 11.2μ diameter particle is approximately 0.35 cm/sec, which is negligible. The 27μ diameter particle on the other hand has a terminal velocity of 2 cm/sec. At this velocity a drop at the top of a 100 meter fog would fall to the surface in 41 minutes.

With the above considerations in mind we have constructed a (1 x 1 x 8) ft chamber in which artificial fog can be produced. On the inside walls of the chamber, moist blotter paper is used as a moisture source to provide a saturated environment in which nuclei can grow. We have installed three photo-resistors in the chamber to sense changes in light transmission (i.e. fog density).

In our experiments, we plan to first examine the density and duration of fog produced on nuclei that occur naturally in the atmosphere. We will then flush the chamber with laboratory air, introduce a new air sample containing both natural and artificially produced nuclei, and again examine the behavior of the ensuing fog. It is expected that a less dense fog will form on the relatively few artificial nuclei that have been provided, since these nuclei are the most favorable sites for condensation. The artificial nuclei used in our experiments must be large enough to produce droplets that settle out of the chamber but not so large that the nuclei fall out before achieving substantial growth. On the other hand, smaller nuclei ($< 1\mu$ dia.) must be kept from participating in the experiment since these nuclei grow to drop sizes just a few microns in diameter, and hence, produce an unfavorable drop-size distribution from the standpoint of fog dissipation.

Most of the preparatory detail for the experiments has been worked out, however, we still must determine the most efficient and reliable way of producing nuclei of the proper sizes. We are planning a number of experiments. In one investigation we plan to produce these nuclei by spraying salt solutions of various molality into a test chamber in which the humidity is kept low by either heating or desiccation. The solution droplets, upon entering the dry atmosphere, will quickly evaporate and produce a single nucleus/drop. The size of the nuclei will be dependent on the size and concentration of the original solution droplets. By varying the concentration of the solution, nuclei of differing sizes can be produced.

An equally acceptable method of producing nucleating sites for fog dispersal experiments may be to pressurize saturated solutions of the salt and dispense the aerosol into the fog chamber in droplet form. Since the equilibrium relative humidity of a saturated sodium chloride solution is approximately 76%, the solution droplets will quickly condense some of the available water and grow to larger drop sizes. The final drop size achieved in the saturated environment will again be dependent on the initial size and molality of the solution drops.

These experiments are currently under way. Once we have tested these and other methods for providing the best size distribution of nuclei for our experiments we will begin seeding laboratory produced fogs in our fog chamber.

C. Investigation of Electrical Means of Fog Dispersal

In the last quarterly report we described an apparatus constructed for measuring the mobility of charged droplets. A corona discharge is used to produce ions that attach to the droplets in a manner similar to that suggested for fog suppression. This apparatus is illustrated again in Figure 6 for the convenience of the reader. Our objective in these experiments was to use measured mobility spectra and drop size distributions to estimate the average amount of charge attached to the drops. The data obtained from these measurements could then be used to evaluate the suggested method for suppressing fog in which we have proposed charging alternate adjacent regions of the fog in opposite polarities. Tests with this apparatus with N_2^+ and O_2^+ ions demonstrated that it operated properly. The current produced by the collection of charged droplets was not detectable however. A more sensitive apparatus was therefore required.

To fulfill this need we have recently constructed a modified Faraday cage depicted schematically in Figure 7. It consists of a large (3 ft x 3 ft x 3 ft) metal box, in which a corona can be produced by a high voltage pulse applied to a wire suspended from the top of the box. The fog is created by the condensation of steam produced by boiling water under a screened opening in the bottom of the box. The inside metal surfaces of the box are covered with blotting paper and kept moist to help stabilize the fog. Suitably placed windows in the sides of the box permit visual observation of the fog. After a fog of sufficient density has been produced the source of steam is removed and the fog allowed to stabilize. Under these conditions a mixture of air molecules and fog drops are present in the box. A high voltage is then applied to the corona wire for a time long enough to produce a quantity of charged air molecules. These molecules are swept out toward the walls of the chamber and in so doing, many collide and attach to some of the fog drops. The length of time for the application of high voltage is determined by the time required for the ion to travel from the wire to the walls. Throughout this time, the box is kept grounded to insure neutrality of the whole system. A short time after the high voltage is turned off, the connection between the box and ground is broken. The only charge remaining in the box

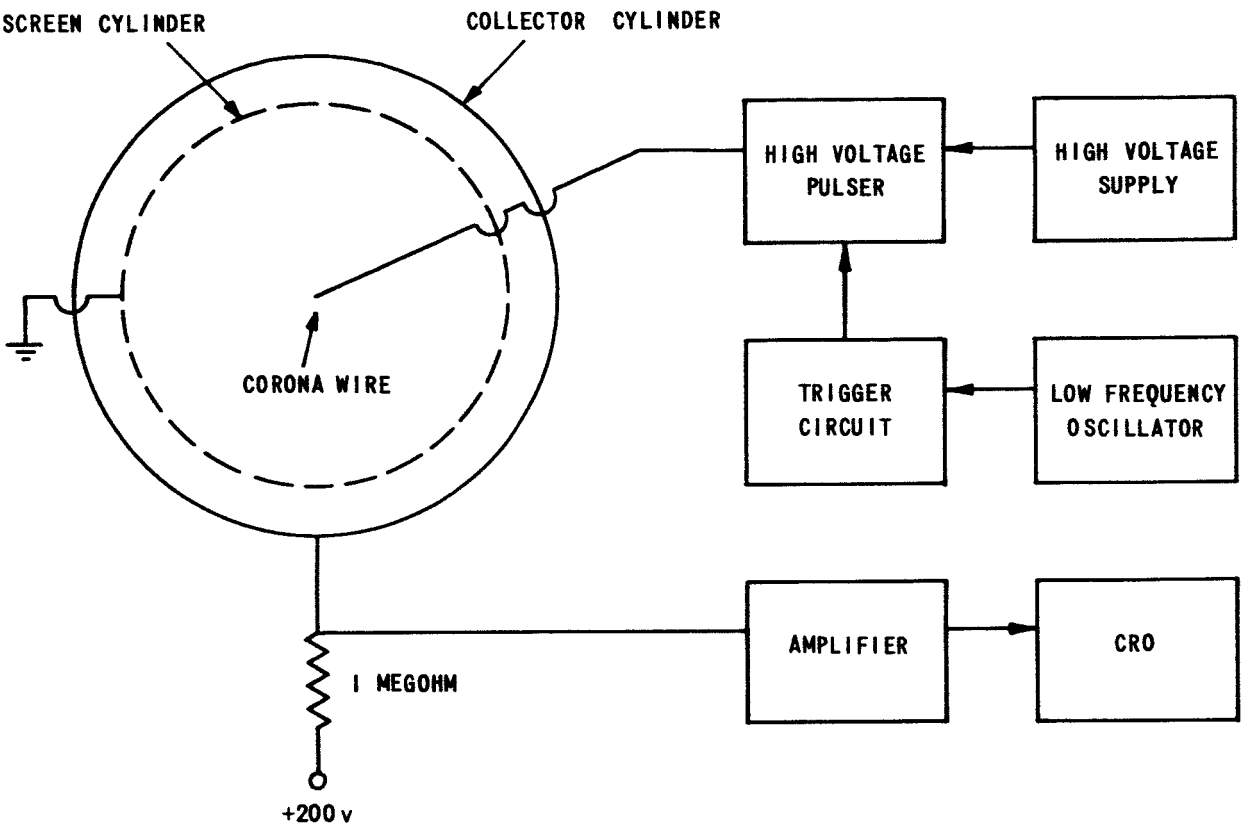


Figure 6 MODIFIED ION MOBILITY APPARATUS

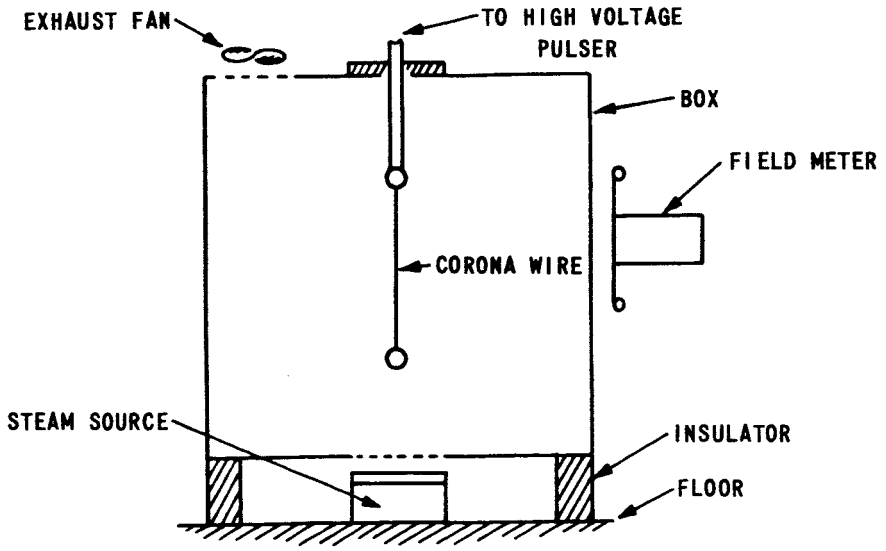


Figure 7 APPARATUS FOR DETERMINING CHARGE ACQUIRED BY FOG DROPLETS

is that on the large drops. The charge on the cage itself is equal and opposite to that on the drops, so that the entire system is neutral. At this point an insulated exhaust fan is turned on, and the fog (and air) in the box is blown out and replaced by laboratory air. In so doing, the charged droplets are removed, leaving the system charged to a potential determined by the amount of charge on the drops. The polarity is of course opposite to that of the charge on the drops. An electrostatic field meter mounted in the center of a flat plate at a known distance from the box is used to measure the resultant potential of the box. From the measured potential and capacitance of the box to ground, the charge left on the box (and thus the charge on the droplets) may be calculated. By measurement of the volume density and size of the drops as they are exhausted from the box, the average charge acquired per drop can be calculated.

Initial tests of this apparatus are now being conducted.

III. FUTURE PLANS

1. Continue laboratory investigations of fog dispersal by electrification principals.
2. Investigate the proposed ideas for producing condensation nuclei and conduct laboratory experiments to evaluate the concept for preventing dense radiation fog.
3. Continue nuclei measurements on a daily basis and begin to correlate current data with the results of measurements taken last year.

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