AD690787

ECOM - 5247
April 1969
AD

FOG DROP SIZE DISTRIBUTIONS - MEASUREMENT METHODS AND EVALUATION

By

Gayle S. Rinehart

ATMOSPHERIC SCIENCES LABORATORY
WHITE SANDS MISSILE RANGE, NEW MEXICO

Distribution of this report is unlimited

ECOM

UNITED STATES ARMY ELECTRONICS COMMAND

FOG DROP SIZE DISTRIBUTIONS - MEASUREMENT METHODS AND EVALUATION

By

Gayle S. Rinehart

ECOM-5247

April 1969

DA TASK 1T061102B53A-20

ATMOSPHERIC SCIENCES LABORATORY
WHITE SANDS MISSILE RANGE, NEW MEXICO

Distribution of this report is unlimited.

ABSTRACT

In connection with evaluating fog modification efforts, several published methods of measuring the size distribution of fog droplets were reviewed. An evaluation cast doubt on the validity of the gelatin, Formvar, and polyvinyl alcohol, and oil collection media for recording droplets less than 4μ diameter. Efficiency of several collection methods appeared to be poor for less than 4μ diameter droplets when lack of drop size distribution correlation with visibility measurement was considered.

During a fog dispersal test, pyrotechnically produced hygroscopic reagents were observed to cause an increase in the number of concentrations of the small sized droplets of a natural fog.

During nonfog conditions, several types of pyrotechnic flares containing different hygroscopic reagents were tested for usefulness as fog modification agents. Measurement of drop and particle size distributions downwind from the ignition point of these pyrotechnics revealed that the effect of small droplet sizes in decreasing visibility in air of high humidity would negate the improvement made by removal of large size drops.

CONTENTS

CONTENTS (Cont)

INTRODUCTION

To evaluate methods of increasing visibility in or dispersing warm (above 0°C) fog, knowledge of the change in physical properties of the fog is imperative. One of the most meaningful physical properties is the drop size distribution, because the greatest visibility impairment in fog results from light scattering by water droplets. Since scattering cross-section coefficients are drop-size dependent, the change in drop size distribution after a modification experiment is of paramount interest.

To evaluate the possible methods of determining drop size distribution for purposes of evaluating fog modification techniques, published methods were surveyed. This survey revealed that drop size determinations were somewhat method-dependent. To estimate the validity of various published distributions and their dependence on measurement methods, a laboratory study of four types of collecting media and three collection methods was undertaken.

In light of knowledge gained from these experimental results, published values of the number and sizes of natural fog droplets were reevaluated. Basis for acceptance and rejection of the number of droplets in the various size increments, as valid measurements, is discussed.

Knowing the limitations of techniques for capturing and measuring fog drops, one impactor method employing oil as a recording medium and the natural settling method employing gelatin and Formvar as media were selected as the best combination of the capture methods and recording media examined. The suitability of the above capture method and media combinations was tested in May and June of 1968 on a radiation fog at Ft. Rucker, Alabama, and an advection fog at Arcata, California, in conjunction with fog modification experiments.

To investigate the growth and fall-out of the drops resulting from the condensation of water on nuclei created by pyrotechnic flares, a follow-up experiment was carried out. Four types of pyrotechnic flares were burned in nonfog conditions and size distributions measured downwind at three distances from the source of the nuclei. From this study the effectiveness of these pyrotechnics in dispersing fog was extrapolated. This report summarizes the results of these studies in three parts.

In Part I, results of laboratory studies on published droplet capture methods and recording media for determining fog drop size distributions are presented and discussed. The information obtained from these studies was incorporated in the evaluation process for establishing the validity of published fog drop size distributions as outlined and discussed in Part II.

In Part III, results of fog drop size distribution and visibility measurements of a radiation fog are discussed. Measurements made before and during a weather modification experiment employing pyrotechnically produced hygroscopic nuclei are presented and evaluated. During nonfog conditions, four types of pyrotechnics which produced hygroscopic reagents were compared for suitability for weather modification applications.

PART I

DROPLET CAPTURE METHODS AND RECORDING MEDIA

Although an annotated bibliography of methods of collecting and determining fog and rain drop distributions exists (1), few of these methods are applicable to capturing or sizing fog droplets below 20μ diameter. A survey of these and more recent approaches to determining fog drop size distributions was carried out in this laboratory as an insight to judging the value of various approaches.

A. Review and Discussion

Four general types of media for directly capturing or replicating fog droplets smaller than 20μ diameter are as follows:

(1) Capturing and measuring replicas by means of plastic (Formvar).
(2) Capturing and measuring impressions made in a layer of small particles (magnesium oxide, soot) or an amorphous solid (i.e., gelatin, polyvinyl alcohol, dye stain).
(3) Capturing in fluid (oil, silicon fluid, petroleum jelly).
(4) Capturing on spider webs or wire.

Replication in Formvar

A 5% solution of Formvar in ethylene dichloride or chloroform for use as a fog droplet capture medium is employed as follows. A layer of Formvar/solvent solution is spread on a flat collecting surface. The layer is usually allowed to dry and is then remoistened with solvent just before use. As droplets hit and penetrate the layer, the solvent evaporates causing the Formvar plastic to harden around the captured droplets. Eventually the water from the droplets evaporates through the Formvar leaving behind a permanent replica of the droplets.

The size of the droplets has been estimated by multiplying the replica by a factor of 0.5 for large drops (2). Small drops of diameter thinner than the Formvar layer do not spread but evaporate eluding a standard correction factor (3). The number of droplets captured has been related to the number existing in an aspirated volume of air by applying a factor to allow for the collection efficiency of various

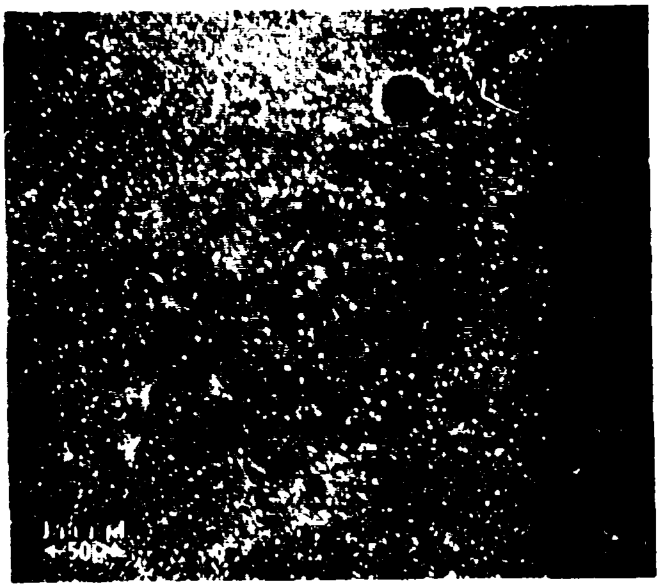


FIGURE 1. FCRMVAR REPLICAS OF NATURAL FOG FRCM ARCATA, CALIFORNIA, SHOWING BACKGROUND BLUSHING.

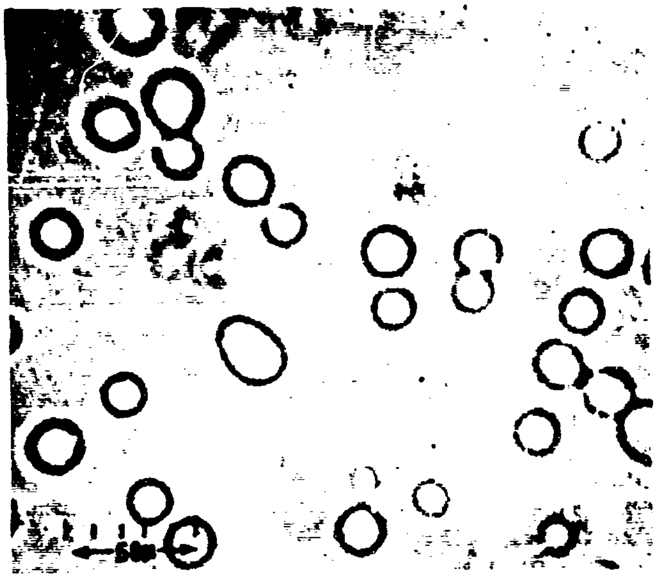


FIGURE 2. IMPACTED SYNTHETIC FOG DROPS ON FRESH KNOX GELATIN.

sized droplets (4); however, later investigations have shown the capture efficiency for small droplets to be much higher (3). Although air is usually aspirated over the collection surface or the collector is moved by aircraft through air, gravity settling has also been employed (5). The volume of air through which collected droplets have fallen during the slide exposure time can be calculated by considering the terminal velocity of the collected droplets and the sampling area.

Because of blushing, the practical lower limit of distinguishing fog droplets by employing the Formvar method in most cases is near 2μ diameter (6). Blushing is caused by the presence of tiny droplets of about 1 or 2μ diameter, which result from local cooling due to the evaporation of the solvent. The cooling hardens the Formvar, possibly trapping bubbles of solvent vapor as they rise through the medium. Examples of fog droplets (dark rings) and blushing (light dots) are shown in Figure 1.

Impressions in Layer of Small Particles or Amorphous Film

The first use of the small particle film method is attributed to May (7) who coated microscope slides with a magnesium oxide film by waving the slide over burning magnesium ribbon. Fog droplets cause craters in the film upon impaction; these can be related to droplet size by multiplying by a spread factor. It was found that droplets were reliably detectable only down to 10μ according to May (8) and 25μ diameter according to Rief and Mitchell in a more recent study (9) because of the apparent hardening of the magnesium oxide layer.

An amorphous film of methylene blue on microscope slides (9) and a water blue film on nitrocellulose (10) have been employed. Correction factors for sizes of drops falling under gravity on slide and film were 0.42 (9) and from 0.5 to 0.33 times the observed size depending on the drop size (10).

Gelatin layers have been employed to size droplets in a number of cases (11, 12, 13, 14). The 5% gelatin solution is warmed, spread on slides, and allowed to dry. Impinging droplets hit the gelatin surface and cause craters which can be viewed clearly under phase contrast microscopy (Figure 2). Natural settling of droplets on gelatin coated slides has been employed by Hosler (14) who approximated the spread factor correction under natural fall as 0.5 to 1.0 times observed. Mechanical impactors with gelatin slides have been used by Liddell and Wooten (11), May (12), and Meszaros (13). Velocities in the Meszaros impactor require a size correction of 0.7 times observed; while the Casella impactor (designed by May) requires 0.55 to 0.65 (7).

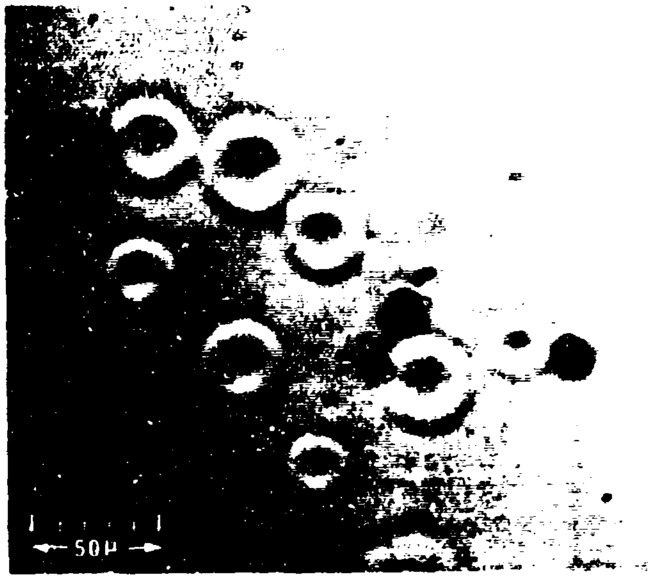


FIGURE 3. WATER DROP REPLICAS (WHITE CRATERS) AND CHLCRIDE DROP REPLICAS (DARK CIRCLES) ON SENSITIZED POLYVINYL ALCOHOL.

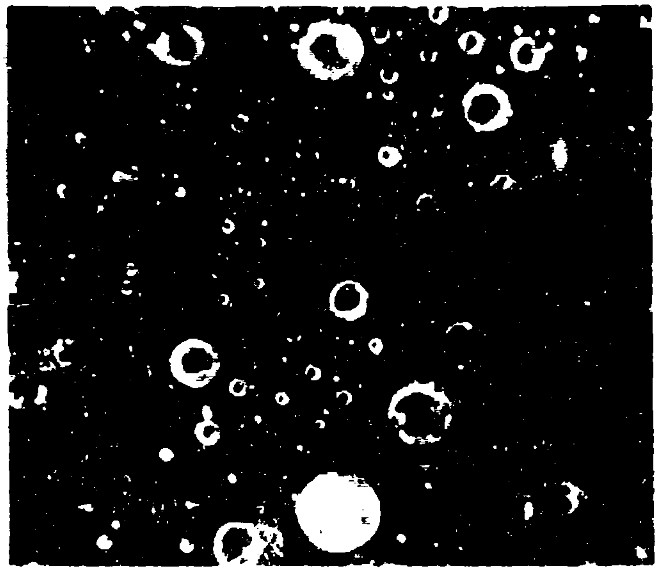


FIGURE 4. SYNTHFTIC FOG DRCPLETS CAPTURED IN SILICON OIL.

Polyvinyl alcohol (PVA) is used in a manner similar to gelatin. The PVA is dissolved in a water solution of silver nitrate and hydrogen peroxide (15). The solution is applied to clear Kronar film (Eastman Kodak Co.) by dipping and drying. The film thus prepared is sensitive to approximately 0.02% chloride droplets (dark craters in Figure 3) with droplet detection down to 1μ diameter. The PVA film is superior to gelatin in crater formation and humidity resistance and has a spread factor of 0.56 (16). An explanation of the mechanism of PVA-film darkening of chloride drops is given by Koenig (17).

Collargol has been employed in a single stage impactor by Dessens (18) and by Godard (19). The collargol films must be prepared 5 to 10 minutes before use, and impressions of good quality can be obtained without the use of phase contrast microscopy when freshly prepared collargol slides are used. The impression diameter when multiplied by 0.34 yields the actual drop diameter and the detection limit is 0.5μ diameter.

Capturing in Fluid

Fluid has been used as a collector medium by Diem (20), May (7), Okita (21, 22), Keily (23), and Kumai and Francis (24). Diem used mineral oil, Okita employed cedar oil, and Kumai and Francis used silicon fluid. Others used oil of an unspecified type. The capturing efficiency of a variety of oils is not good when employing gravity settling (9) because of low droplet penetration and lengthy sampling periods. The droplets evaporate into the oil medium necessitating quick sample study. The size detection limit in oil is specified by Keily (23) as 2μ diameter; however, the author believes that the limit is equal to the limits of the optical microscope (somewhere between 0.5μ and 1.0μ diameter).

An advantage of the use of fluid lacking in replication methods is the clarity of the spheres (Figure 4) and the distinguishability between small droplets and particles which is not found in gelatin. No size correction factor is required in fluid since there is no droplet distortion. The disadvantages in using fluid capture are the lack of a permanent sample, poor droplet penetration into fluid, and the possible coalescence of the droplets.

Collection on Spider Webs

Dessens (25) and Arnulf, et al. (26) employed spider webs to capture small droplets in fogs, photographing them shortly after collection. Arnulf estimated that numerous particles smaller than 4μ diameter must have escaped capture by the web filaments, and this conclusion was borne out by data of Eldridge (27).

Knowledge of wind speed past the web is essential for calculating the volume of air sampled. The webs may be mounted and rotated at a known speed, thus eliminating the uncertainty associated with natural wind variability. Droplets collected on the webs must be photographed soon after collecting, preferably in an environment in which relative humidity is near that of the air sampled.

Collection Efficiency of Natural Settling, Impactor, and Web Methods

The collecting efficiency for the Casella cascade impactor has been documented (7), and correlations between number and size of drops and visibility have been good (28). The vacuum impactor efficiency (24) as determined by experiment indicated higher values than theoretically calculated for nearly all sizes. Small collector areas coated with oil have been found to have higher collecting efficiencies when samples are impacted than those theoretically calculated (23, 24, 29). The collection efficiency for various sized droplets when aspirated over and caught on film using Formvar replication has not been published in the open literature except when used in the MacCready device. MacCready's values (2) are in good agreement with those of Dessens (2) using the spider web technique down to 8μ diameter.

The distance between the web filaments does not permit capture of all droplets below 15μ diameter (19) and for this reason numbers of drops in sizes below this become increasingly more unreliable when employing the web technique.

Gravity collection is not efficient for small droplets because they do not fall under the force of gravity alone. Slight turbulence or wind overcomes their downward velocity component and prevents their settling. They do not penetrate oil well and evaporate from the surface, and they do not leave impressions in gelatin or PVA.

B. Experimental Procedure

Four collection media (PVA, Formvar, gelatin, and oil) were investigated employing three collecting methods (gravity settling, Casella 4-stage impactor (7), and two-stage vacuum impactor (30)). Other media were discarded because of difficult or lengthy preparation procedures, lack of sensitivity to droplets smaller than 2μ in radius, poor quality of replication, and nonpermanence of sample.

Two types of fog generating equipment were employed: an aspiration type medicinal nebulizer and an ultrasonic droplet generator (Ultramist III, Macrosonics Corp., Rahway, N. J.).

Formvar

A standard microscope slide was coated with 5% Formvar/ethylene dichloride solution by placing a drop of the solution on the slide and spreading this coating by means of another slide. The slide was found to dry within 10 to 90 seconds, depending on the thickness of the solution. A thinly coated slide was exposed to a stream of drops of 7 to 10μ diameter (average) generated by the ultrasonic generator for one minute while being observed under the microscope. Photographs of this slide during and after the collection period are shown in Figures 5 and 6. Figure 5A shows the slide after 10 seconds exposure and Figure 5B after 20 seconds exposure. Figures 6A and 6B show the droplets evaporating and in the final state.

The capturing of fog droplets by gravity settling onto a 5% Formvar solution did not appear to be reliable. Small drops falling on the slide early evaporated, while some larger ones (over 10μ diameter) spread and then decreased in size. This may explain the absence of large droplets when Formvar was used in the data of Admirat and Soulage (6). Small drops (less than 5μ radius) appeared to be unchanged upon impaction, while larger drops (over 20μ) spread. Since the hardening Formvar is of variable thickness, it would be expected that spread factors would also vary. After further study this was found to be true (3) even in softened Formvar. Because of the rapid drying time and the evaporation of droplets, Formvar was deemed unsuitable as a collection medium for the cascade or vacuum impactor.

Gelatin, Polyvinyl Alcohol (PVA)

Studies on aged gelatin in field conditions showed its inability to retain impressions made by droplets (Figure 7A and 7B). Rejuvenation of old gelatin is possible by rinsing with distilled water (12). Certain gelatins seem to lose their impressionable nature faster than others, and the author has found filtered Knox unflavored gelatin (Figure 2) to be quite suitable for retaining images.

One packet of Knox unflavored gelatin is added slowly to 500 ml distilled water. The solution is warmed in a water bath at approximately 85°C with occasional stirring until all the gelatin is dissolved. The warm solution is filtered through an 0.8μ pore size membrane filter under suction and can be reheated when required. An eyedropper is used to withdraw the gelatin solution to avoid picking up bubbles on the gelatin surface.

Natural settling of fog droplets on gelatin films did not make permanent impressions in all cases (Figure 8). This did not appear to be as

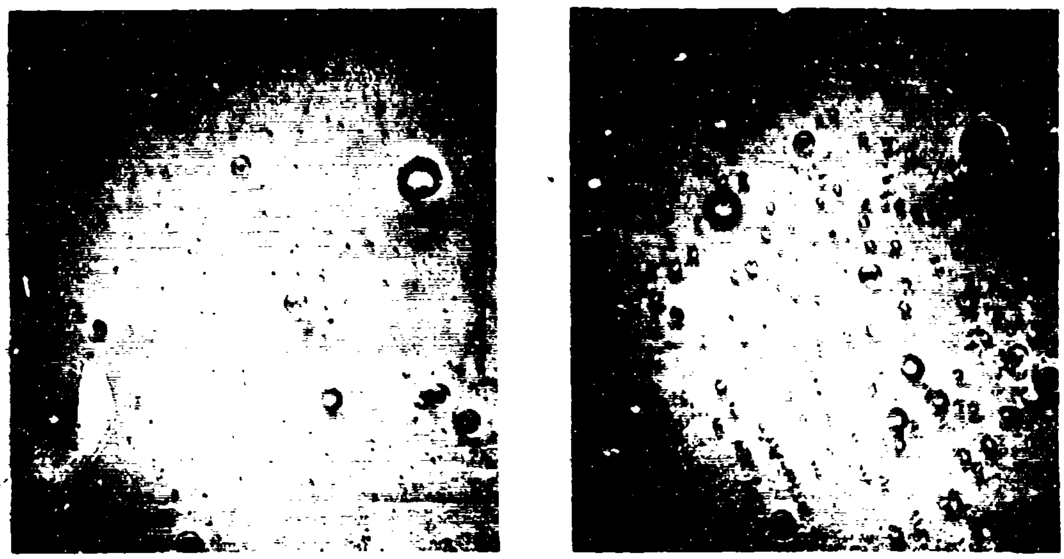


FIGURE 5. SYNTHETIC FOG DROPLETS FALLING ON THIN FORMVAR SOLUTION.

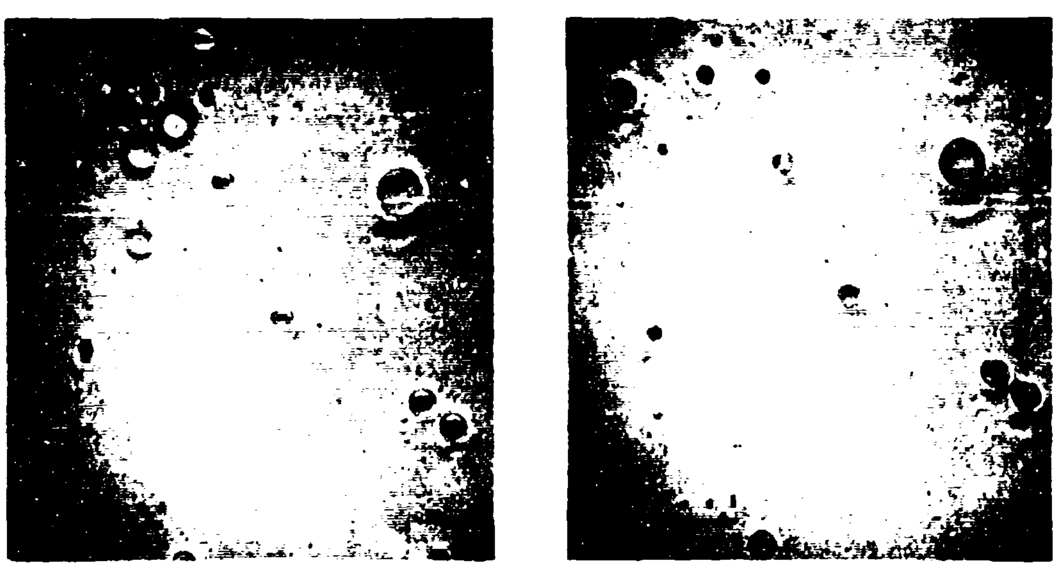
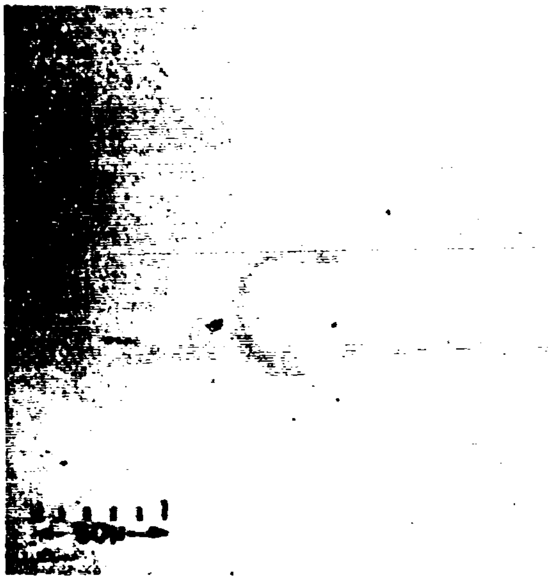


FIGURE 6. SYNTHETIC FOG DROPLET REPLICAS AFTER FORMVAR SOLUTION HAS DRIED.



A. AT FT. RUCKER

B. AT ARCATA

FIGURE 7. POOR REPLICATION OF FOG DROPLETS ON GELATIN.

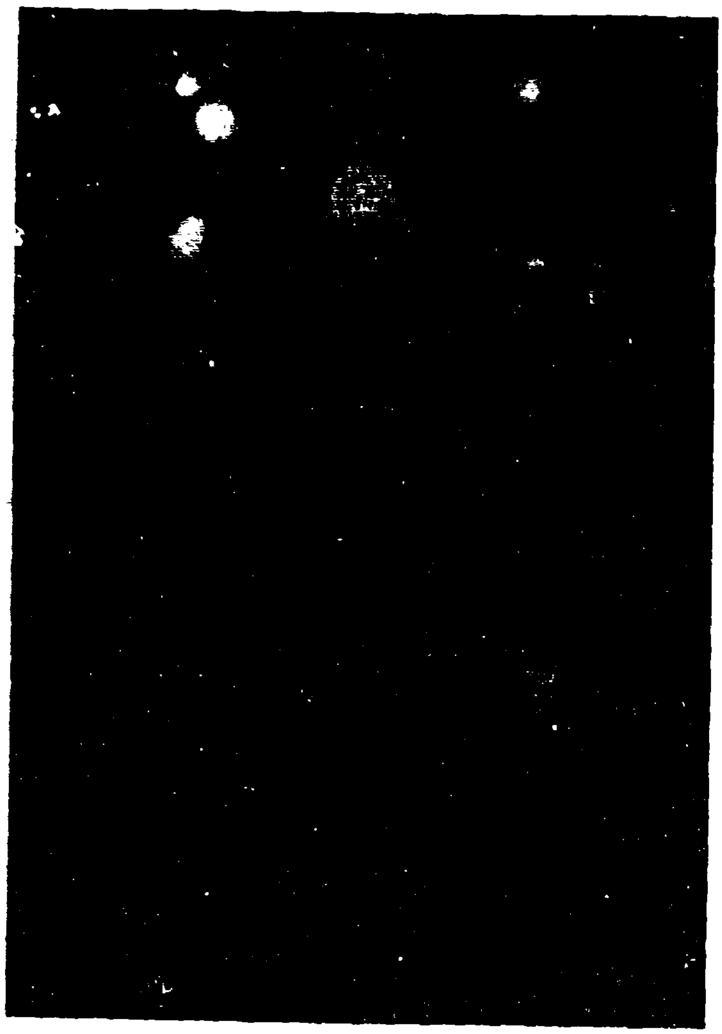


FIGURE 8. FAINT FOG DROPLET IMPRESSIONS ON GELATIN AFTER NATURAL SETTLING.

critical for larger drops or impacted samples on gelatin-coated slides; however, several faint craters are visible on an impacted sample (Figure 2), and it can be assumed that some drops were not recorded as in the case of natural settling.

PVA was found to be superior to gelatin in recording impressions of droplets under natural settling; however, not all droplets were permanently recorded (Figure 9). Some remaining yet faint impressions are shown in this figure. PVA employed in vacuum and cascade impactors appeared to record impressions better than when gravity settling was used, although faint impressions indicate that some were not recorded.

Silicon and Petroleum Oil

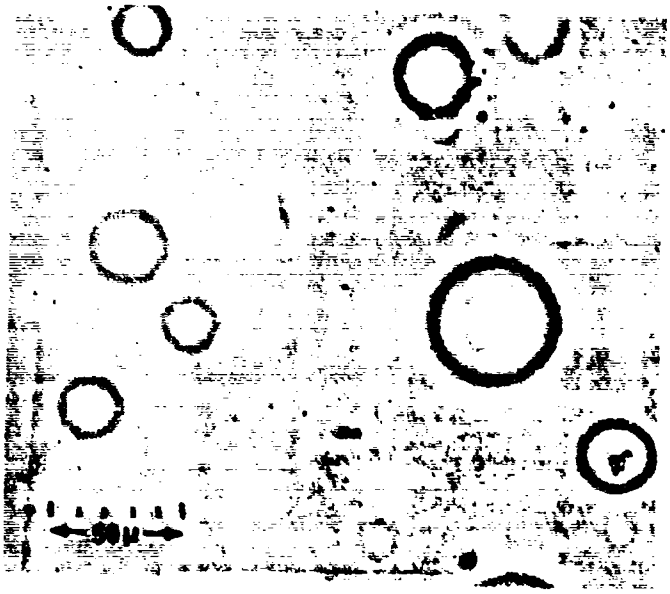
Use of petroleum oil and silicon oil for gravity settling yielded poor results owing to the evaporation of droplets on top of the oil. Even droplets suspended in oil evaporated quickly into the medium. Water-saturated petroleum oil gave better results; however, droplets still evaporated more slowly in the silicon fluid than in the saturated oil. Therefore, silicon fluid was employed in the three collection methods.

Thick silicon oil (1000 centipoise) is easier to work with because it is more viscous and can be held vertically when on a slide without running off. The sample once captured remains in a smaller area for easier microscope counting. Small droplets, however, do not penetrate thick silicon oil easily. If the velocity of the droplets to be collected is increased to allow small drops easier penetration, larger droplets in the same volume of air go completely through the oil layer and flatten against the slide.

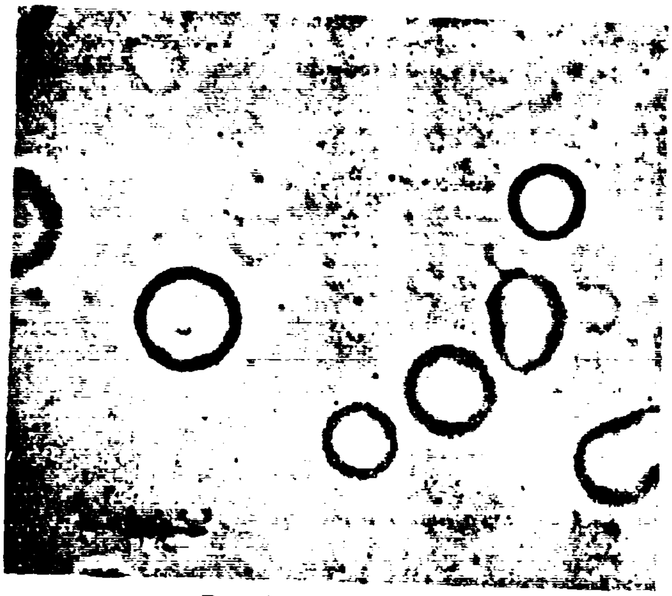
One method of relieving this problem is to place a thin layer of thick oil next to the slide and cover it with a lighter oil. This practice allows large droplets to penetrate the second layer partially and small droplets to penetrate the first layer more easily.

Since viscosity varies with temperature and the number and size of droplets in a given volume of air also vary, no standard viscosity fluids are recommended. In general, at 25°C Dow Corning No. 200 silicon fluid (1000 centipoise) at average air speeds of six m/second gives fair collection for all sizes (Figure 3). When the Casella and vacuum impactors were used with silicon fluid some losses occurred due to evaporation before slides could be removed from the instrument. An oiled cover glass was placed on the sample preventing the evaporation and flattening of droplets on the top of the oil film of the collector. Most droplets on slides preserved in this manner lasted for hours; however, small drops (1 to 2μ diameter) evaporated after about 15 minutes.

NOT REPRODUCIBLE



A. NATURAL SETTLING



B. IMPACTION

FIGURE 9. FAINT FOG DROPLET IMPRESSIONS ON PVA AFTER NATURAL SETTLING AND IMPACTION.

A short sampling time was essential when sampling with an oil medium in the Casella impactor because the droplets coalesced with others lying on the top of the oil layer, and evaporation losses were large.

The vacuum impactor had the same drawback as the Casella impactor mentioned above, but sampling was very fast and only one slide had to be removed from it, thus reducing evaporation before protecting with an ``led cover glass.

C. Conclusions

Formvar, PVA, gelatin, collargol, fluid, and dye spread on various flat surfaces can be employed to document fog droplets. A factor must be applied for collection efficiency and spreading, except when employing oil or fluid with which no spread factor is required. Except for Formvar when blushing is present, the impression media allow measurement of droplets down to approximately 0.5μ diameter. For oil, the somewhat higher limit of measurement of 2μ diameter (23) is possible.

Short sampling periods for gelatin, PVA, and Formvar are necessary because long exposure to high relative humidity causes poor definition of craters or blushing. Short sampling periods per surface exposure are required for oil to reduce coalescence, and photographs of oil-captured drops must be made soon to record small droplets. Formvar cannot be used reliably due to evaporation of captured fog droplets and variability of spread factors during drying.

PART II

A COMPARISON OF PUBLISHED VALUES OF FOG DROP PARAMETERS

In light of knowledge gained in Part I of this report, a reevaluation of published values of fog droplet parameters was deemed necessary. The verification of the drop size distribution dependence on collection methods as determined in Part I is borne out by results of the Puy d'Dome Comparison Conference, 1965 (6); yet few attempts (28 and 31) have been made to elucidate the reason for noncorrelated results.

Part II of this report presents a review of published fog drop size distributions and discusses the attributes and disadvantages of each method used for the purpose of correlating fog drop parameters.

A. Comparison of Data

Table I gives some published fog droplet parameters. Only those data obtained with methods and media allowing droplet size collection and measurement to below 5μ radius are included in the table. Entries in the table are grouped according to the type of collecting method or media employed. The paragraphs that follow discuss the relative merits of these groups and the individual entries therein.

<u>Oil</u>

Kumai (24) found the fog drop distribution mode to approach 2μ radius, after good efficiency of a syringe-operated vacuum impactor had been shown. Diem's (20) mode for stratocumulus was 2μ radius when employing an aircraft carried droplet pistol. Other clouds had modes of 5μ and 10μ. Minervin (29) found the mode to be near 3.5μ radius when sampling from an aircraft on an oil-coated slide, estimating that smaller sizes must have been missed. Keily (23) showed an increasing number of droplets toward lower limits of detection (2μ diameter) when oil was employed utilizing a method having good collection efficiency. Kojima (33) noted that 3 out of 4 types of fog examined had modes below 10μ when captured in cedar oil and corrected for impaction efficiencies. In the remaining case, fog blown in from over the sea had a mode of 5 to 10μ radius.

Houghton (35) employed natural settling to capture drops listing the mode of distributions between 3 and 8μ. This author believes he probably missed many small droplets because of the inefficient gravity settling.

TABLE I. COMPARISON OF DROPLET PARAMETERS AND COLLECTION METHODS

TYPE MEDIUM	DETECTION LIMIT RADIUS(μ)	MODE RADIUS(μ)	NO./CM^3	VISIBILITY (m)	REF	COLLECTOR - REMARKS
		MEDIUM: OIL (CEDAR, SILICON, PETROLEUM)				
P	0.5	3	ng	ng	20	Aircraft droplet pistol
S	1	5-6	2.5	ng	24	Syringe impactor
S	1	2	2.5	ng	24	Syringe impactor (Sum of dist.)
ng	1	3.5	ng	ng	29	Aircraft impacted
-	1	1.5,14	ng	ng	23	Aircraft impacted
C	1	0-5 5-10	10- 175	ng	32 32,33	Syringe impactor
C	1	0-10 5-10 10-70	0.7- 22	ng	34	Syringe impactor
P	1	3-8	7-24	45.6- 744	35	Natural settling
		MEDIA: GELATIN, STAIN, FORMVAR, PVA				
G	0.5	1	ng	50	11	Casella impactor
G	0.5	3-10	1-50	70- 150	13	Own impactor
G	0.5	Median <1-2.4	1-1300	75- 400	28	Casella impactor
S	0.5	8-13.5	1-8	ng	36	Natural settling
F	2	10	ng	ng	2	Own impactor
P	1	5-40	1-70	.70- 270	37	Electrostatic impactor
		MEDIUM OR PRINCIPLE: WEB, TRANSMISSION				
W	2	10	ng	ng	2	Web. No values below 4μ radius
W	2	<2	250*	71	26	Web. No values below 2μ radius
T	-	0.35	800- 10500	ng	31	Calc. from transmission of Arnulf
T	-	0.5- 2.5	38000 64000	ng	27	Calc. from IR transmission
W	2	<2	100	-	25	Web. Correlated with transmission measurements

* According to estimated data (31).
ng = not given

Except for sea fog, when impaction techniques of known efficiencies were used, the fog or cloud drop distribution mode approached 2μ or less. Kojima (34) found that advected sea fogs had higher modal values.

Gelatin, Stain, Formvar, Polyvinyl Alcohol (PVA)

Most of the users of gelatin and Formvar employed impaction methods. May (28) and Liddell and Wooten (11) found the median or mode to be from 2.4μ to less than 1μ radius. Homma (36), MacCready (2), Meszaros (13), and Evans (37) could distinguish 1μ droplets yet found modes of near 10μ radius in a number of distributions. The absence of the mode at small radii in Homma's study could be because he did not impact samples and, therefore, missed small droplets. MacCready employed Formvar but because of blushing could not see below 2μ radius; still, however, the number in the less than 5μ radius region increased toward lower limits. Meszaros (13) impacted samples on gelatin but was unable to show good correlation between visibility and observed drop size distributions, which had modes from 3 to 10μ radius. Calculated and actual visibilities differed by a factor of 10 to 20 in most cases. Conversely, May (28) found the median radius below 2μ in most cases and was usually able to correlate drop size distributions and visibility to within a factor of 2.

Meszaros (13) suggested that the lack of observation of small droplets and the presence of low droplet concentrations (1 to 10 drops cm^{-3}) could be due to local conditions. She used the Casella (May) impactor on several occasions as a comparison instrument and was still unable to find the large drop concentrations observed by others.

There is some evidence that the gelatin used by the Meszaros was not recording small droplet impressions. Studies described in Part I showed that even impacted droplets are not always recorded and that drops less than 5μ diameter are least likely to be recorded in an adverse condition. This may explain why few droplets smaller than 5μ were noted by Meszaros.

Meszaros showed the results of sedimentation and impaction methods as being well correlated down to about 8.0μ radius. Her impactor data showed a decrease in number of sizes smaller than 8μ, with a cutoff value at about 6μ. This cutoff has not been noticed by others who employed gelatin as a medium; however, it was observed in other media which will not record small droplet impressions (9 and 38).

There is poor correlation in the Meszaros (13) data between visibility and liquid water content as formulated by Eldridge (27). He employed

0.35 to 10μ radius droplets in the concentration range of about 400 to 8000 drops cm^{-3}. Eldridge emphasized the importance of small droplets in visibility by showing the increase in transmission with the omission of small sized droplets (less than 1μ radius).

Meszaros (13) credited the absorption by nuclei of radius equal to or greater than 0.15μ in the concentration of 1000 drops cm^{-3} with the decrease in visibility in fog to 140 m (average of several cases). She calculated visibility (V) to be approximately 2800 m for the corresponding observed distributions. Data (39) indicate that a particulate mass of 0.002μ gm cm^{-3} (liberal estimate from Figure 3 of Meszaros) would allow a greater than 9600 m visibility. Estimating the effect of particulate matter on the total visibility of the Meszaros fog from scattering and absorption one has

$$1/V_{calculated} = 1/V_{drops} + 1/V_{particles}$$

or

$$V_{calculated} = \frac{1}{1/2800 + 1/9600} = 2160 \text{ m}$$

V calculated in this way is 2160 m versus 140 m observed, or the decrease in V due to dust reduces the calculated visibility (2800 m) by a factor of less than 5 (liberal estimate) when a factor of 20 is needed to correlate observed and calculated V. May (28) viewed the absorption by particulates during fog as playing a minor role in deterioration of visibility in fog because when fog lifts, visibility goes up very markedly even though the same number of nuclei are present in the atmosphere. Thus, there is no alternative but to assume the presence of lower modal values in the distribution of fog droplets or haze from the Meszaros data.

Evans (37) found the mode to be between 5 and 40μ radius when employing an electrostatic fog collection technique which imparted a charge to droplets and impacted them on a film of PVA. Collection efficiency was given as 65% for the 1μ diameter droplets; however, reduced counts were obtained when wind exceeded 1 m sec^{-1}. The orientation of the instrument was also critical for obtaining drops from cloudy air and therefore the reliability of small droplet concentrations from Evans' data can be questioned.

Although MacCready's values compared well with those of H. Dessens (2), the efficiency of the web technique of Dessens becomes very poor near 2μ radius; thus the two evaluations may have been correct to near 2μ radius, but for droplets smaller than this value either datum is questionable.

Those who employed the Casella impactor with gelatin (11 and 28) found the median of fog drop distributions to lie from below 1 to 2.4μ radius. Reasons discussed above indicate that the absence of these low values in the Meszaros (13), Homma (36), Evans (37), and MacCready (2) data was due to media or instrumentation.

Web, Transmission Methods

The validity of the spider web method in collecting droplets down to 2.5μ radius was borne out by simultaneous visibility and drop size distribution measurements which were in close agreement (25, 26).

Eldridge (31) calculated that the number of drops that must have escaped capture by Arnulf's spider web technique was greater than 1000. This estimate was based on computer-determined distributions (40) and Junge's haze distributions (41). Eldridge (27) also employed infrared transmission techniques, correlating drop size with transmission measurements at several wavelengths.

All Media and Methods

The number of droplets estimated by Eldridge (27, 31) seems rather large (thousands cm^{-3}) compared to other values given in Table I. Dessens (25) correlated his measured distributions with visibility measurements and found only about 100 droplets cm^{-3}. Dessens reasoned that drops of small radii (less than 2.5μ) which were not caught by his spider web would not contribute significantly to reduced visibility. Subsequently, it was shown that this hypothesis was incorrect, using transmission calculations based on distributions of Eldridge (27). In fogs that he investigated, May (28) indicated that the existence of more small droplets was doubtful. He showed that the attenuation due to the small droplets he collected rarely accounted for more than 10% of the total attenuation and that in general an error of 10 times their number would be necessary for matching the observed and calculated visibilities.

Examination of fog near the coast almost invariably revealed some modes between 7 to 10μ radius (34, 35, 38). Therefore, it is possible that the primary mode was not observed because many droplets were below detection limits of methods employed. It is also possible that sea fog actually exhibits a mode between 7 to 10μ radius.

Evidence that the primary mode may have been missed is abundant; but there are no data showing a fog drop distribution mode from 7 to 10μ that correlate these distributions well with visibility.

Eldridge (27) indicated the possible lack of detection of small droplets in some fog drop size distribution studies. When oil was used, Kojima's (33) observation of a mode shift with evaporation of small drops into the oil or atmosphere can account for some of the observed modes near 7 to 10μ. The data of Keily (23), Diem (20), Eldridge (27), Arnulf (26), MacCready (2), Houghton (35), Homma (36), and Meszaros (13) showed a mode in the 7 to 10μ radius interval. The first four authors showed an approached mode below 2μ while the others noted only the mode at 7 to 10μ. Reasons given in the text indicate that collection methods or capture media could be at fault in the remaining works, causing a great number of small droplets to be overlooked.

B. Conclusions

Based on data reviewed here, visual measurement allowed size determinations to 0.5μ radius with 1300 droplets cm^{-3} maximum (28) while indirect methods showed sizes to 0.35μ diameter with approximately 10,000 droplets cm^{-3} maximum (31). Only one published article (28) listed thousands of observed droplets cm^{-3} in the range 0.45 to 0.75μ radius by visual methods, although Eldridge postulated that greater than this number would be present in all fogs, based on transmission measurements.

It appears then that either a great number of small droplets are missed by collection and replication, and/or factors other than scattering are important sources of transmission attenuation in fog.

PART III

DESCRIPTION OF EXPERIMENTS AND ANALYSES

With knowledge of the limitations of drop size distribution measurement techniques, two methods were selected for use. Thin Formvar and a vacuum impactor with oil were employed in experiments at Ft. Rucker, Alabama, during radiation fog. Formvar, gelatin, and vacuum impactors with fluid were used to document drop size distributions in advection fog at Arcata, California. Gelatin and Formvar slides were taken during an experiment as a comparison between the Formvar and gelatin media.

Experiments on the number and size of drops grown by hygroscopic particles produced by flares allowed determination of the growth and fall-out time (distance) of droplets.

A. Measurement of Fog Drop Size Distributions

Samples of the radiation fog at Ft. Rucker, Alabama, were made on 13 May 1968. This fog was sampled using the Formvar solution technique by Mr. J. R. Hicks of the U. S. Army Terrestrial Sciences Center (5). A drop of 5% Formvar in chloroform was spread on a standard microscope slide by spreading with another slide. Slide exposure time was 30 seconds.

Samples of advection fog droplets were taken at Arcata, California in June of 1968, employing the vacuum impactor with silicon fluid (9000 centipoise) and natural settling on gelatin and Formvar-coated standard microscope slides. Use of the vacuum impactor with a 100 cm^3 sample chamber revealed few drops. During the days of fog when vacuum sampling was carried out, only about 10 drops in 100 cm^3 of air were found. These were from 10 to 40μ in diameter.

Early tests with gelatin slides which had been prepared prior to the experiment did not record drop impressions well. Formvar-coated slides were employed for the next few days of fog, and then simultaneous Formvar and fresh gelatin slides were used. Because of the variable drying time of Formvar solutions and the evaporation of droplets due to low relative humidity present at Arcata, gelatin was employed as the collecting medium in the remainder of the tests. The slides taken at Arcata were exposed for one minute.

Weather conditions, sampling techniques and types of tests are summarized in the following table. Visibility (V) is given in meters, wind direction (dd) in tens of degrees from north, and speed (ff) in meters sec^{-1}.

TABLE II. Summary of Data Applicable to Fog Droplet Samples

Location	Date/Time	Slide Type	R.H.(%)	V(M)	dd/ff	Remarks
Ft. Rucker	5/13,0545	Formvar(F)	100	300	00/0.5	Dense clearing fog.
Arcata	6/18,0843-0910	F	94	800	29/2.5	
Arcata	6/24,0810-0900	F	100-86	200 21000	00/00 28/02	Very fast clearing.
Arcata	6/25,1220	Gelatin(G)	92	2500	24/5.5	
Arcata	6/26,0545-0549	G	96	1000	00/02	
Arcata	6/26,0615	G	-	-	-	Start "salty frog"* burn.
Arcata	6/26,0617	G	-	2000	-	Under "frog" smoke.
Arcata	6/26,0628	G	-	-	-	Down runway from "frog" under smoke.
Arcata	6/26,0630	F	-	-	-	In smoke on runway.
Arcata	6/26,0635	G	-	-	-	In smoke on runway.

Ft. Rucker Fog Drop Size Distribution

It was hoped that the number (n_i) of droplets cm^{-3} in a given size interval could be calculated from the following formula:

$$n_i\ cm^{-3} = n_i \text{ counted/Area counted x terminal velocity of drop x time slide exposed.}$$

* See following text for definition.

However, owing to the very low terminal velocities of the small drops counted, the formula gave inordinately high values of small drops.

Another method of making an approximation was employed. Wind speed was approximated at 0.5 m sec^{-1} and the small drops were assumed to move with the air. Using an efficiency of 100% for all droplets gave the distribution in column 3 of Table III.

The fog was slowly evaporating and reduced visibility to 300 m. An estimate of the fog drop size distribution from Eldridge's data (31) is indicated in column 4 of Table III.

TABLE III. Fog Drop Parameters of a Radiation Fog at Ft. Rucker, Alabama

$r(\mu)$	K_s	$n\ cm^{-3}$ (observed)	$n\ cm^{-3}$ (Eldridge, evolving fog, Dist. 5)	$r^2K_s(10^{-8})n$
0.35				
-0.5	3.8	12	1800	1800*
1	2	44	100	88
1.5	2.8	39	30	254
2	2	37	15	296
2.5	2.5	30	4	180
3	2	20	4	400
3.5	2	12	5	240
4	2	3	15	96
4.5	2	7		308
5	2	8	25	400
5.5	2	0		0
6	2	2		160

Except for small sizes, the size and number are in close agreement in the experimental values and those of Eldridge.

Calculation of visibility is possible from Koschmieder's formula (42),

$$V = 3.95/\sigma$$

* Estimated, see text.

where σ is $2\pi r_i^2 K_s n_i$, r_i is the average radius in the interval under consideration, n_i is number per volume in the interval, and K_s is the corresponding scattering coefficient. Values of K_s were approximated from Houghton and Chalker (43) at a wavelength of 0.55μ. Using the distribution in column 3, V = 600 m. Assuming the low number of 0.5μ size is due to poor collection efficiency and including the estimate of 1800 cm^{-3} from Eldridge's evolving fog distribution 5, where V = 0.29 km, the calculated visibility (V_c) is equal to approximately 300 m. The liquid water content (lwc) calculated in the conventional way using the observed distribution

$$\text{lwc} = 4/3\pi \sum_i r_i^3 n_i = 0.02 \text{ gm}^{-3} .$$

The omission of droplet sizes below 0.5μ radius contributed only 5% of the lwc in the above case; however, this omission caused calculated visibility to be incorrect by 100%.

Arcata Fog Drop Size Distribution

Distributions of fog droplets recorded on 18 June and 24 June 1968 at Arcata, California, are shown in Figures 10 and 11. These results are typical of distributions observed at Arcata, California, during morning hours of high relative humidity and near noon when relative humidity was less. The morning fog contained more small droplets with few large while the noon advection fog contained more large droplets. In both cases calculated (Ve) and observed (Vo) visibilities were different by a factor of 2 or greater. Perhaps this discrepancy can be attributed to poor collection of small drops.

To test the usefulness of pyrotechnically produced hygroscopic nuclei (44), a 240 g flare of NaCl and LiCl in a pyrotechnic mixture was burned. The pyrotechnic flare was referred to as a "salty frog". The heat of the burning "salty frog" flare and the heat of condensation of the condensed water on the hygroscopic components caused the pyrotechnically produced salts to rise. In all cases the nuclei thus produced and their condensate caused a decrease in visibility.

Since laboratory studies have shown the poor recording properties of gelatin-coated slides for droplets below 5μ radius when sampling by natural settling, the number of the droplets in this range can only be estimated from the measured distribution of other sizes. The drop size distributions during the test are shown in Figure 12.

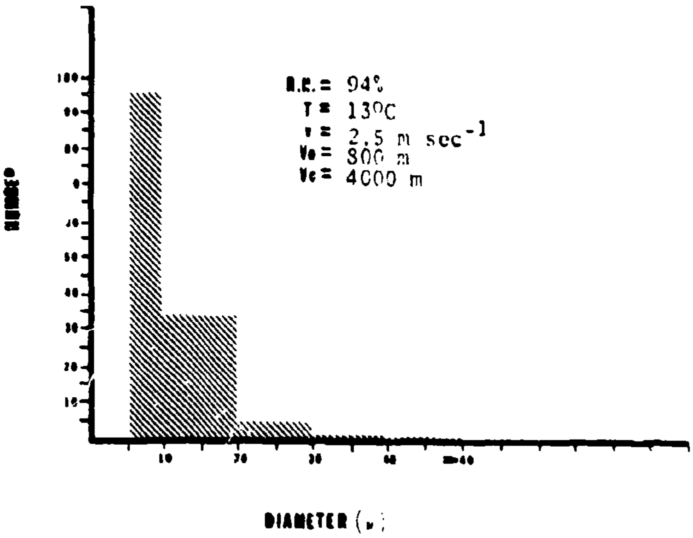


FIGURE 10. DROP SIZE DISTRIBUTION, JUNE 18, 0843 - 0910 HRS., AT ARCATA.

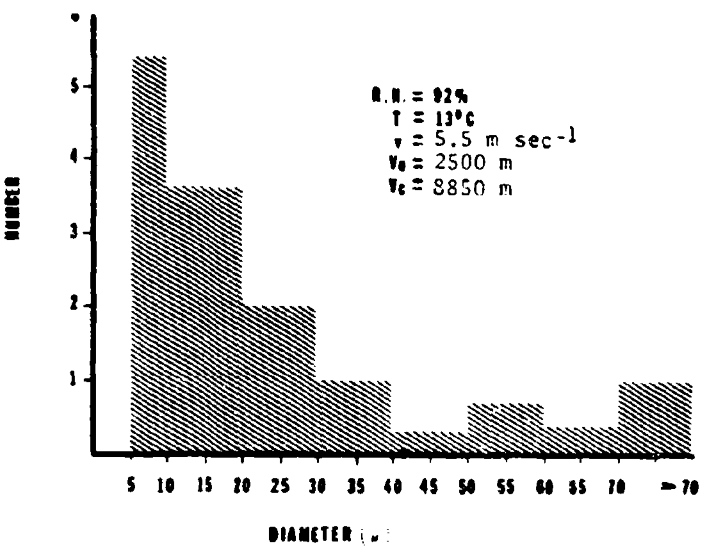


FIGURE 11. DROP SIZE DISTRIBUTION, JUNE 25, 1220 HRS., AT ARCATA.

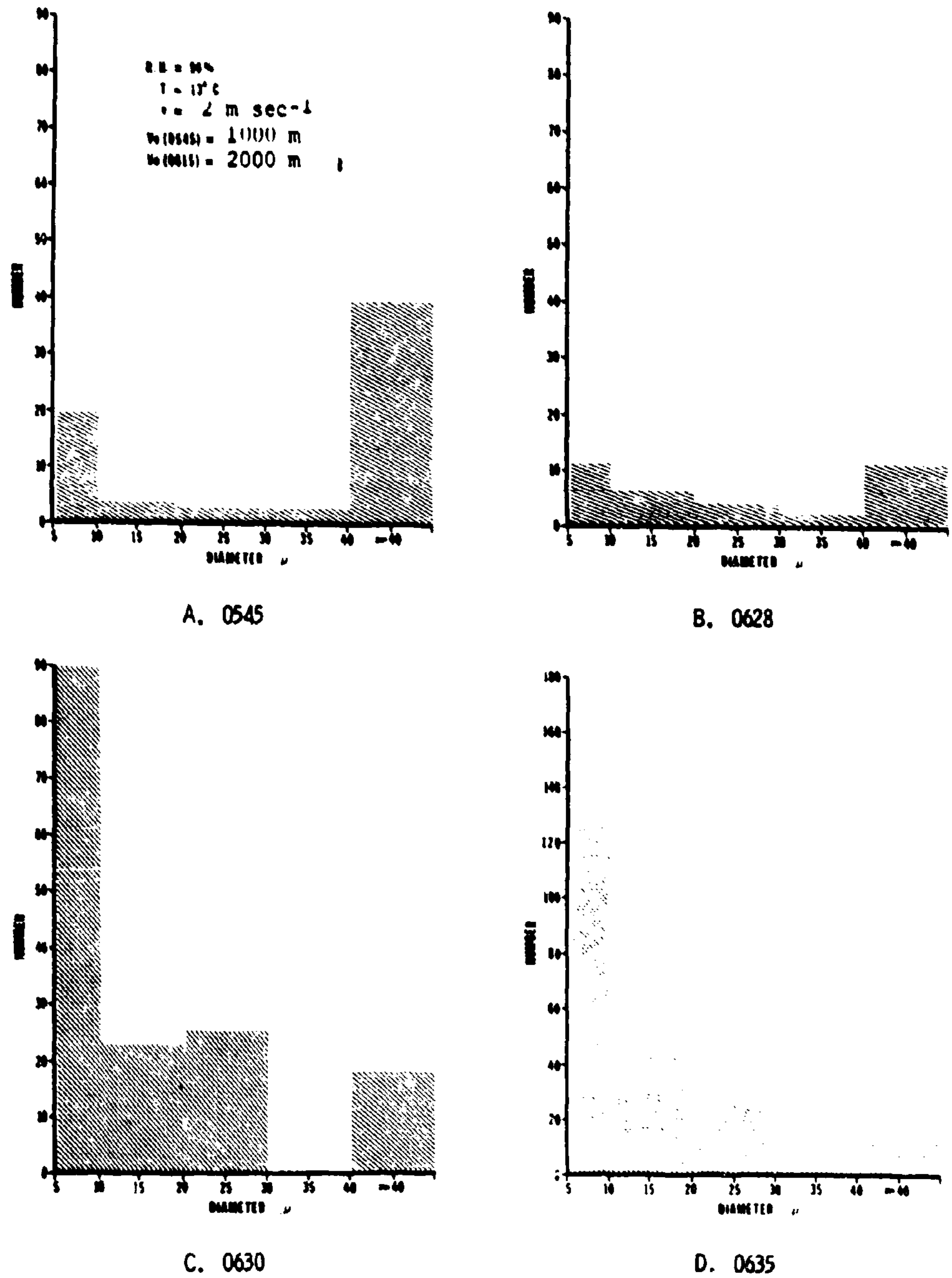


FIGURE 12. CHANGE IN DROP SIZE DISTRIBUTION AFTER SEEDING WITH PYROTECHNIC NUCLEI

The number of droplets in the 5 to 10μ diameter range is low in the distributions measured for 0545 to 0628 hours (Figures 12A and 12B). The increase in the small size fraction of droplets in the slides taken at 0630 and 0635 (15 and 20 minutes after ignition of the "salty frog") is evident in Figures 12C and 12D. Based on the size distributions of several pyrotechnically produced particles (particle mode diameter 0.2μ) which grow due to the condensation of water to a size of about 2 to 3μ, and Figures 12C and 12D, the estimated number of droplets of diameter below 5μ is very large. The numerous droplets of this and smaller sizes contribute greatly to reducing visibility, and their effect was pronounced in the vicinity of burning pyrotechnics.

B. Particle Size Distribution Downwind From Pyrotechnic Flares

Although some measurements of the particle size produced by pyrotechnic flares have been made, no studies of the growth and dispersion of these particles have been made under field conditions. Testing the pyrotechnics in nonfoggy but humid air allowed an estimate of particle growth without having to estimate which droplets were natural and which were artifically produced.

On 27 June, four types of pyrotechnic flares were burned on the beach near Arcata to determine their effectiveness in condensing water from the atmosphere and to estimate the diffusion of particles in a field condition. Relative humidity was 89%, wind speed was 1.1 m sec^{-1} blowing toward the beach from the sea. The direction and speed of the wind was determined by a portable anemometer and its varying direction over the terrain by a simple method. Soap bubbles were released from a location on the beach and these were carried along by the wind. Thus the turbulence, wind speed and direction could be estimated with distance.

Three participants in the experiment stationed themselves downwind of the pyrotechnic burn site at distances of 2, 5, and 14 m. Each participant held a gelatin coated microscope slide perpendicular to the path of each burning pyrotechnic smoke for one minute.

The four pyrotechnics were as follows:

Designation	Major Components	(Supplied by Manufacturer) Particle size mode diameter (μ)	No. of Particles per gram pyrotechnic
Olin Matheson X-1118	NaCl	2	-

Olin Matheson X-1121	$CaCl_2$	5	-
Crane Ammunition Depot WF-9	$MgCl_2$, NaCl	0.2	10^{14}
Crane Ammunition Depot WF-10	$AlCl_3$, NaCl	0.2	10^{14}

Although it was difficult to observe, a light fog rolled in from the sea. Before and after the burn, a one-minute sample of the fog was taken and the average counts subtracted from the distribution measured during the tests.

An area of 0.13 cm^2 was counted on each slide to determine the drop size distribution for droplets above 6μ diameter. A smaller area was counted for the 1 to 5μ sizes and the counts scaled to the 0.13 cm^{-2} area. Droplets were counted only for sizes 5μ diameter and greater. Both particles and droplets in the 1 to 5μ diameter range were counted since it was not possible to distinguish between the two in many cases.

The drop and particulate size distributions at the three stations are given for the four pyrotechnics in Figures 13 through 15. Figure 13 shows drop size summed over all three stations versus number of particles or drops downwind of 4 pyrotechnics. WF-9 produced more of almost all sizes, the exception being in the 1 to 5μ diameter size which was greater during the burn of the WF-10 pyrotechnic. The WF-10 produced more small (1 to 5μ diameter) particles and drops and fewer large (greater than 10μ diameter) drops than any of the other pyrotechnics. The NaCl and $CaCl_2$ flares were similar to each other; however, there were more large (greater than 30μ diameter) drops during the burn of the $CaCl_2$ flare than during the NaCl flare.

In Figure 14, distance from the pyrotechnic versus total number of particles and drops is shown. During the burn periods at 14 m more WF-9 particles or drops were found than in the case of the other three pyrotechnics. The $CaCl_2$ flare produced fewer particles or drops at any distance.

Figures 15A through 15D show the variation in particle and drop size with distance from the source of nuclei.

The NaCl size distribution change is more desirable than those obtained with the other pyrotechnics. That is, the number of small particles decreased while the number of large drops increased with

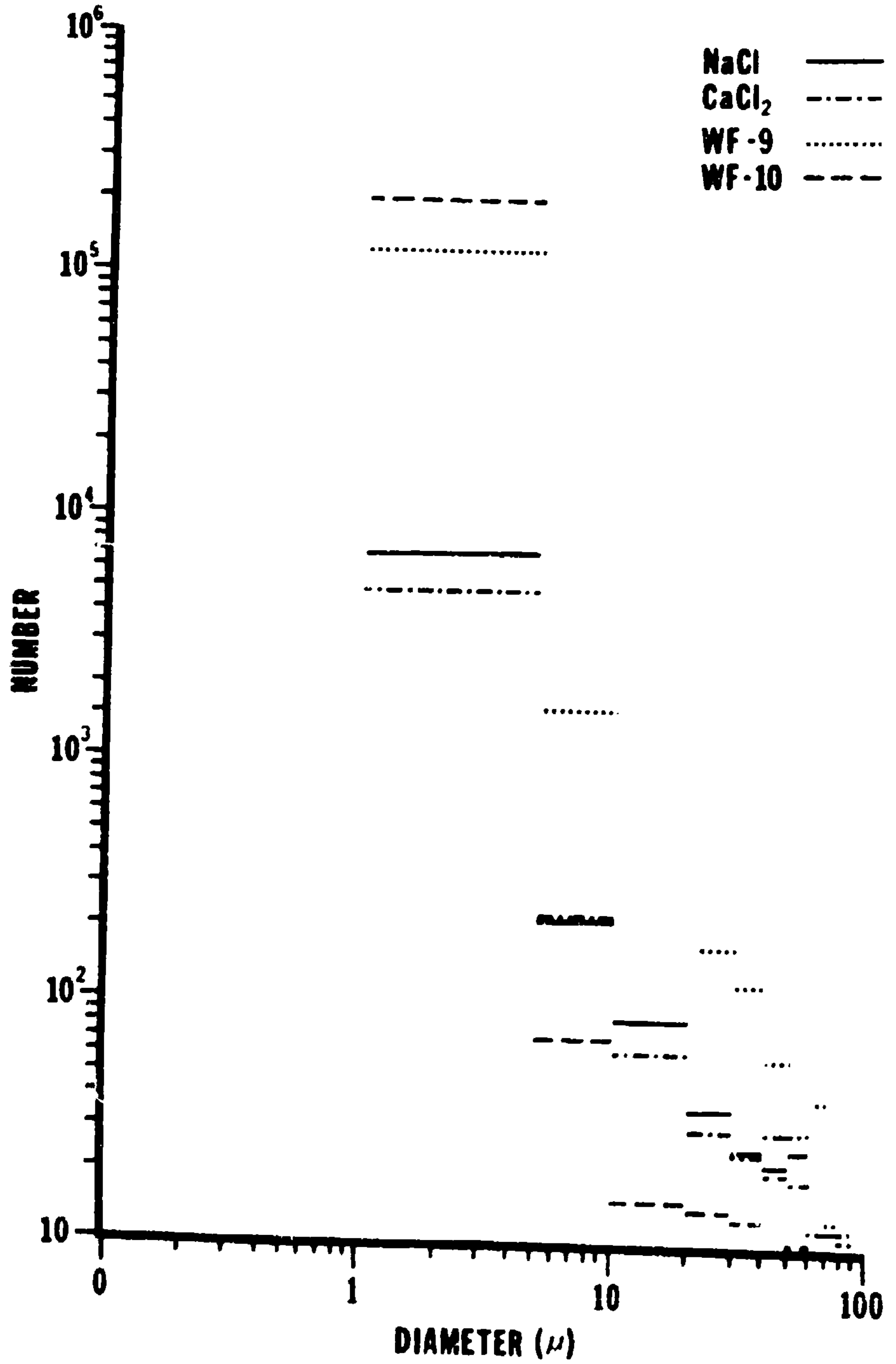


FIGURE 13. NUMBER OF DROPS OR PARTICLES VERSUS DIAMETER

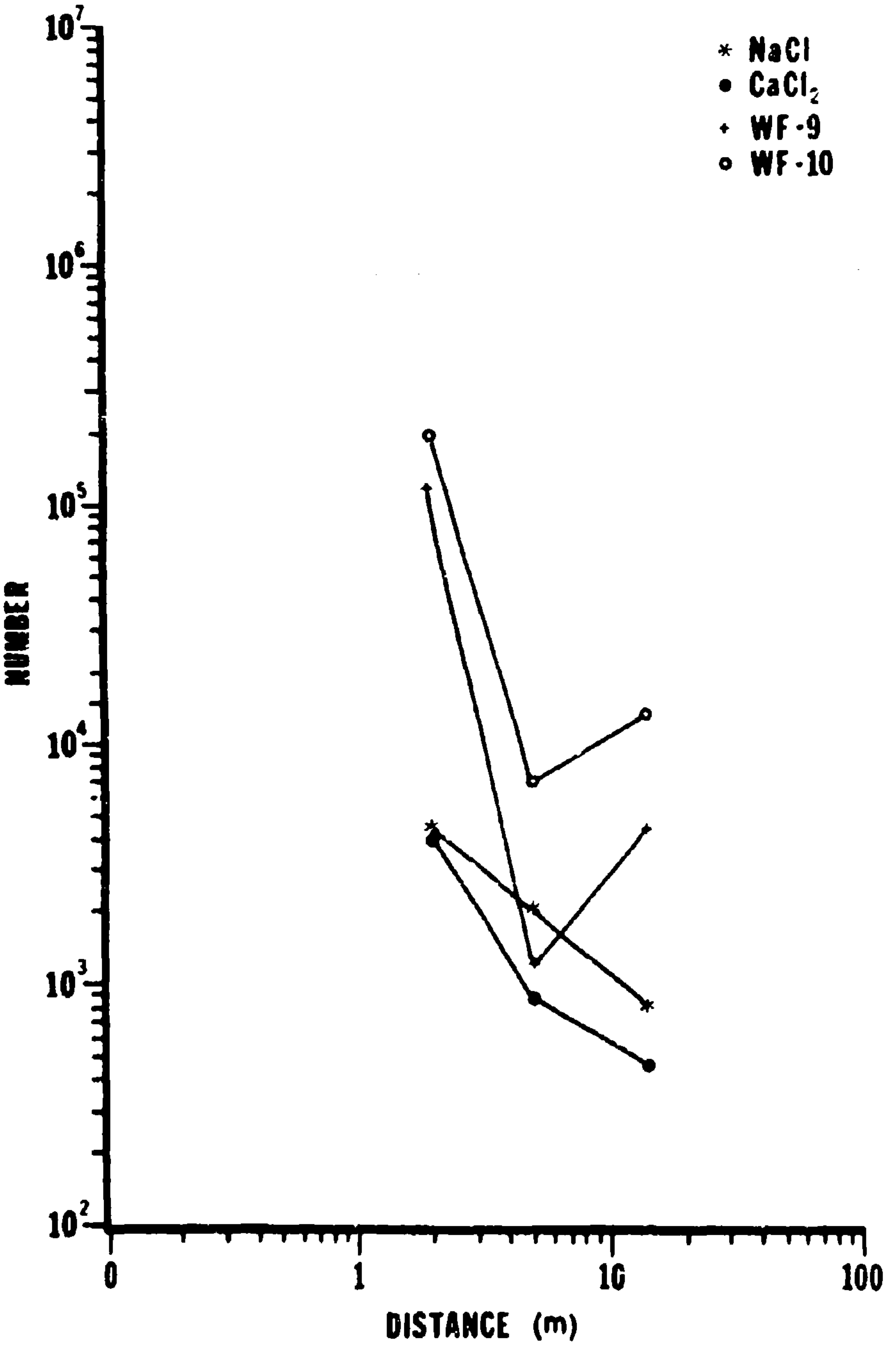
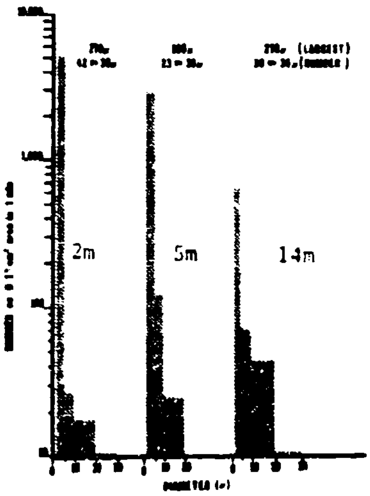
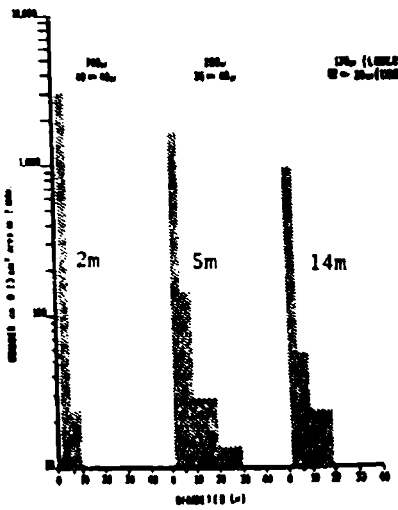


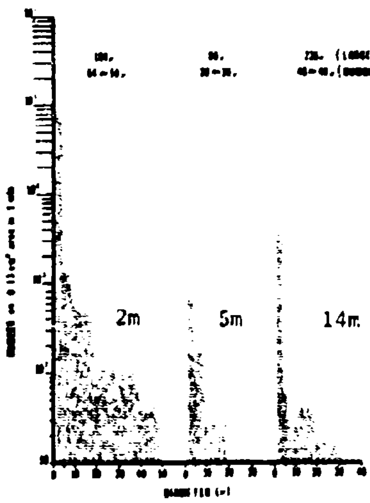
FIGURE 14. NUMBER OF DROPS OR PARTICLES VERSUS DISTANCE



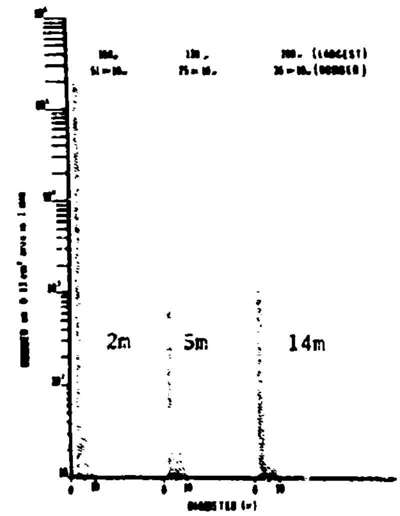
A. NaCl (X-1118)



B. $CaCl_2$ (X-1121)



C. $MgCl_2$, NaCl (WF-9)



D. $AlCl_3$, NaCl (WF-10)

FIGURE 15. SIZE DISTRIBUTION VERSUS DISTANCE FROM PYROTECHNIC FLARES

distance from (time after) burn, and the large drops ultimately fell to the ground. This behavior is not discernible in the WF-9 and WF-10 data (Figures 15C and 15D). It could be that the large sizes in the 2 m sample had fallen out by the time the smoke reached the 5 m station and that the particles or drops in the 1 to 5μ range had grown into larger sizes by the time the smoke reached 14 m.

The $CaCl_2$ pyrotechnic produced the least smoke while the WF-9 pyrotechnic produced the most smoke and eye irritation.

C. Conclusions

Correlation of drop size distribution with visibility when employing natural settling method with Formvar as a recording media was fair. Assumption of the presence of large numbers of small droplets as postulated by Eldridge yielded good agreement between calculated and actual visibility. Use of gelatin media to record fog droplet impressions always led to higher calculated visibilities than observed.

The use of pyrotechnically created hygroscopic particles as fog dispersing materials resulted in the deterioration of visibility and the increase of small sized droplets.

The WF-9 flare was most effective in producing large drops in the distance examined; however, the presence of the large number of small particles would prevent any increase in visibility which may have resulted from the removal of water droplets from an actual fog. The WF-10 flare was the poorest from both aspects: it produced too many small particles and caused very few large drops. NaCl and $CaCl_2$ fell between these two extremes. The $CaCl_2$ pyrotechnic produced the least number of small particles, caused the least impairment to visibility, and after WF-9 had the highest number of large drops. For these reasons, the $CaCl_2$ pyrotechnic was considered the best of the four pyrotechnics tested for fog dispersal purposes.

SUMMARY

A literature survey revealed that fog drop size distributions were method dependent. A laboratory study showed that neither impaction nor natural settling was entirely reliable. Capture or replication media which included PVA, gelatin, oil and silicon fluid do not always record droplet impressions or retain small droplets for lengthy periods. Lack of correlation between number of captured droplets and visibility was present in even the most careful determinations employing impaction methods. It appears th: either small droplets have not been captured and replicated or that factors other than scattering by water droplets contribute heavily to the deterioration of visibility in fog.

Pyrotechnically produced hygroscopic particles caused a persistent decrease in visibility in fog accompanied by an increase in the small droplet sizes fraction. The large number of small particles or droplets produced by four pyrotechnics, tested during a nonfog condition, would negate any visibility improvement brought about by removal of large water drops.

REFERENCES

1. Pearson, J. E., and Martin, G. E., "An Evaluation of Raindrop Sizing and Counting Techniques," Sc. Rpt. No. 1, Ill. State Water Survey and University of Illinois, ASTIA 146773, 116 pp. (1957).

2. MacCready, P. B., "The Continuous Particle Sampler at the Puy-de-Dome Comparison Conference," Bull. Obs. Puy-de-Dome, Ser. 2, 10, 19-29 (1962).

3. MacCready, P. B., and Williamson, R. E., "Continuous Particle Sampler Study Program," Final Report Meteorol. Res., Inc. for Naval Res. Lab., 50 p. (1963), AD643000.

4. Johnson, J. C., Physical Meteorology, M.I.T. and John Wiley and Sons, Inc., New York, p. 228 (1954).

5. Frisby, E. M., et al., "Resojet 2," Tech. Rpt. Atmos. Sciences Lab., U. S. Army Electronics Command, Ft. Monmouth, New Jersey, 48 pp. (1968).

6. MacCready, P. B., et al., Compte Rendu Du Meeting de Comparison des Capteurs de Gouttelettes, Bull. Obs. Puy-de-Dome, Ser. 2, No. 1, 1-18 (1962).

7. May, K. R., "The Cascade Impactor: An Instrument for Sampling Coarse Aerosols," J. Sc. Instru. (Brit.), 22, 187-195 (1945).

8. May, K. R., "The Measurement of Airborne Droplets by the Magnesium Oxide Method," J. Sci. Inst., 27, 128-130 (1950).

9. Rief, A. E., and Mitchell, C., "Size Analysis of Water Aerosols," Ann. Allergy, 17, 157-172 (1959).

10. Okita, T., "Water-Blue Film Methods for Measurement of Cloud and Fog Droplets," J. Meteorol. Soc. Japan (Tokyo), Ser. 2, 36, 164-165 (1958).

11. Liddell, H. F., and Wooten, N. W., "The Detection and Measurements of Water Droplets," Q. J. R. M. S., 83, 263-268 (1957).

12. May, K. R.,"Detecting Volatile Airborne Droplets," Nature, 183, 742-743 (1959).

13. Meszaros, A., "Concentration et Distribution Dimensionnelle de Gouttelettes de Brouillards Atmospheriques," J. Rech. Atmos., No. 2, 53-65 (1965).

14. Hosler, C. L., et al., "An Investigation of the Dynamics and Microphysics of Clouds," NSF Rpt. No. 10 and Final Report NSF GP-4743, Penn. State Univ., Dept. of Meteor., University Park, Pennsylvania, 61 p. (1967).

15. Farlow, N. H., "A Physiochemical System for Water Aerosol Measurement," J. Coll. Sc., 11, 184-191 (1956).

16. Farlow, N. H., and French, F. A., "Calibration of Liquid Aerosol Collectors by Droplets Containing Uniform Size Particles," J. Coll. Sc., 11, 177-183 (1956).

17. Koenig, L. R., and Spyers-Duran, P. A., "Simple Methods of Determining Water Drop Sizes by Means of Photographic Emulsions," Rev. Sci. Instr. (New York), 32, 909-913 (1961).

18. Dessens, J., "Un Capteur Classeur de Particles a Lame Unique," Bull. Obs. Puy-de-Dome, No. 1, 1-13 (1961).

19. Godard, S., "Measure des Gouttelettes de Nuage Avec un Film de Collargol," Bull. Obs. Puy-de-Dome, No. 2, 41-46 (1960).

20. Diem, M., "Messungen der Grösse von Wolkenelementen," Ann. Hyd. und Maritimen. Meteorol., 142-149 (1942).

21. Okita, T., "On the Mechanism of Dissipation of Fog by Model Wood," Low Temp. Sci., 11, 29-37 (1953).

22. Okita, T., "Studies of Physical Structure of Fog," J. Met. Soc. Japan, 49, No. 1, 40-49 (1962).

23. Keily, D. P., "Measurement of Drop Size Distribution and Liquid Water Content in Natural Clouds," M.I.T. Dept. of Meteor., Sci. Rpt. No. 6, Cambridge, Mass., 15 pp (1957).

24. Kumai, A., and Francis, K. E., "Size Distribution and Liquid Water Content of Fog Northwestern Greenland," U. S. Army Cold Regions Research and Engineering Laboratory Research Report 100, Hanover, New Hampshire, 13 pp (1962).

25. Dessens, H., "Brume et Noyaux de Condensation," Ann. de Geophys., 3, 68-86 (1947).

26. Arnulf, A., et al., "Transmission by Haze and Fog in the Spectral Region 0.35 to 10 Microns," J. Opt. Soc. Amer., 47, 491-498 (1957).

27. Eldridge, R. G., "Measurements of Cloud Drop-Size Distributions," Jour. Meteor., 14, 55-59 (1957).

28. May, K. R., "Fog Droplet Sampling Using a Modified Impactor Technique," Q. J. R. M. S., 87, 535-548 (1961).

29. Minervin, V. Ye., and Nikandrova, G. T., "Measuring the Spectrum of Cloud Droplets," Translation of "Ob izmerenii spektra oblachnykh kapel'," Trudy Tsentral'noy Aerologicheskoy Observatorii, No. 55, 18-31 (1964), NASA N65-27721, 20 pp. (1965).

30. O'Brien, H. W., and Kumai, M., "Electrically Operated Impactors for Hydrometeor Sampling," Cold Regions Research and Engineering Laboratory TR 170, Hanover, New Hampshire, 15 pp. (1965).

31. Eldridge, R. G., "Haze and Fog Aerosol Distributions," J. Atmos. Sci., 23, 605-613 (1966).

32. Kojima, K., and Yamaji, K., "Measurement of the Size Distribution of Fog Particles," Bull. No. 64, Forest Experimental Sta. Tokyo, 98-103 (1953).

33. Kojima, K., et al., "On the Size Distribution of Fog Particles in the Vicinity of a Fog-Preventing Forest," Studies on Fogs in Relation to Fog-Preventing Forest, Inst. Low Temp. Sci., Hokkaido University, Sapporo, Japan, 311-326 (1953).

34. Kojima, K., et al., "The Size Distribution of Fog Particles," Studies on Fogs in Relation to Fog-Preventing Forest, Inst. Low Temp. Sci., Hokkaido University, Sapporo, Japan, 303-309 (1953).

35. Houghton, H. G., "The Size and Size Distribution of Fog Particles," Physics, 2, 467-475 (1932).

36. Homma, T., et al., "Observations of Sea Fog and Drizzle at Nemro," J. Meteorol. Res. (Tokyo), 14, 72-79 (1962).

37. Evans, E. C., III, "An Electrostatic Fog Precipitator," Am. Ind. Hyg. Assoc. Quart., 18, 253-260 (1957).

38. Neiburger, M., and Wurtele, M., "On the Nature and Size of Particles in Haze, Fog and Stratus of the Los Angeles Region," Chem. Rev., 44, 321-335 (1949).

39. Chepil, W. S., and Woodruff, N. D., "Sedimentary Characteristics of Dust Storms: II. Visibility and Dust Concentration," Am. J. Sci. 255, 104-114 (1957).

40. Neiburger, M., and Chien, C. W., "Computations of the Growth of Cloud Drops by Condensation Using an Electronic Digital Computer," Washington, D. C., Am. Geophysical Union, Geophysical Monograph, No. 5, 191 (1960).

41. Junge, C., "The Size Distribution and Aging of Natural Aerosols as Determined from Electrical and Optical Data of the Atmosphere," J. Meteor., 12, 13-25 (1955).

42. Middleton, W. E. K., Vision Through the Atmosphere, University of Toronto Press, 104-105 (1963).

43. Houghton, H. G., and Chalker, W. R., "The Scattering Cross-Sections of Water Drops in Air for Visible Light," J. Opt. Soc. Amer., 39, 955-957 (1949).

44. Naval Weapons Center, "Foggy Cloud Operation Plan 4-68," Earth and Planetary Sciences Div., Res. Dept., Naval Weapons Center, China Lake, California, 44 p. (1968).

ATMOSPHERIC SCIENCES RESEARCH PAPERS

1. Webb, W.L., "Development of Droplet Size Distributions in the Atmosphere," June 1954.
2. Hansen, F. V., and H. Rachele, "Wind Structure Analysis and Forecasting Methods for Rockets," June 1954.
3. Webb, W. L., "Net Electrification of Water Droplets at the Earth's Surface," *J. Meteorol.*, December 1954.
4. Mitchell, R., "The Determination of Non-Ballistic Projectile Trajectories," March 1955.
5. Webb, W. L., and A. McPike, "Sound Ranging Technique for Determining the Trajectory of Supersonic Missiles," #1, March 1955.
6. Mitchell, R., and W. L. Webb, "Electromagnetic Radiation through the Atmosphere," #1, April 1955.
7. Webb, W. L., A. McPike, and H. Thompson, "Sound Ranging Technique for Determining the Trajectory of Supersonic Missiles," #2, July 1955.
8. Barichivich, A., "Meteorological Effects on the Refractive Index and Curvature of Microwaves in the Atmosphere," August 1955.
9. Webb, W. L., A. McPike and H. Thompson, "Sound Ranging Technique for Determining the Trajectory of Supersonic Missiles," #3, September 1955.
10. Mitchell, R., "Notes on the Theory of Longitudinal Wave Motion in the Atmosphere," February 1956.
11. Webb, W. L., "Particulate Counts in Natural Clouds," *J. Meteorol.*, April 1956.
12. Webb, W. L., "Wind Effect on the Aerobee," #1, May 1956.
13. Rachele, H., and L. Anderson, "Wind Effect on the Aerobee," #2, August 1956.
14. Beyers, N., "Electromagnetic Radiation through the Atmosphere," #2, January 1957.
15. Hansen, F. V., "Wind Effect on the Aerobee," #3, January 1957.
16. Kershner, J., and H. Bear, "Wind Effect on the Aerobee," #4, January 1957.
17. Hoidale, G., "Electromagnetic Radiation through the Atmosphere," #3, February 1957.
18. Querfeld, C. W., "The Index of Refraction of the Atmosphere for 2.2 Micron Radiation," March 1957.
19. White, Lloyd, "Wind Effect on the Aerobee," #5, March 1957.
20. Kershner, J. G., "Development of a Method for Forecasting Component Ballistic Wind," August 1957.
21. Layton, Ivan, "Atmospheric Particle Size Distribution," December 1957.
22. Rachele, Henry and W. H. Hatch, "Wind Effect on the Aerobee," #6, February 1958.
23. Beyers, N. J., "Electromagnetic Radiation through the Atmosphere," #4, March 1958.
24. Prosser, Shirley J., "Electromagnetic Radiation through the Atmosphere," #5, April 1958.
25. Armendariz, M., and P. H. Taft, "Double Theodolite Ballistic Wind Computations," June 1958.
26. Jenkins, K. R. and W. L. Webb, "Rocket Wind Measurements," June 1958.
27. Jenkins, K. R., "Measurement of High Altitude Winds with Loki," July 1958.
28. Hoidale, G., "Electromagnetic Propagation through the Atmosphere," #6, February 1959.
29. McLardie, M., R. Helvey, and L. Traylor, "Low-Level Wind Profile Prediction Techniques," #1, June 1959.
30. Lamberth, Roy, "Gustiness at White Sands Missile Range," #1, May 1959.
31. Beyers, N. J., B. Hinds, and G. Hoidale, "Electromagnetic Propagation through the Atmosphere," #7, June 1959.
32. Beyers, N. J., "Radar Refraction at Low Elevation Angles (U)," Proceedings of the Army Science Conference, June 1959.
33. White, L., O. W. Thiele and P. H. Taft, "Summary of Ballistic and Meteorological Support During IGY Operations at Fort Churchill, Canada," August 1959.
34. Hainline, D. A., "Drag Cord-Aerovane Equation Analysis for Computer Application," August 1959.
35. Hoidale, G. B., "Slope-Valley Wind at WSMR," October 1959.
36. Webb, W. L., and K. R. Jenkins, "High Altitude Wind Measurements," *J. Meteorol.*, 16, 5, October 1959.

37. White, Lloyd, "Wind Effect on the Aerobee," #9, October 1959.
38. Webb, W. L., J. W. Coffman, and G. Q. Clark, "A High Altitude Acoustic Sensing System," December 1959.
39. Webb, W. L., and K. R. Jenkins, "Application of Meteorological Rocket Systems," J. Geophys. Res., 64, 11, November 1959.
40. Duncan, Louis, "Wind Effect on the Aerobee," #10, February 1960.
41. Helvey, R. A., "Low-Level Wind Profile Prediction Techniques," #2, February 1960.
42. Webb, W. L., and K. R. Jenkins, "Rocket Sounding of High-Altitude Parameters," *Proc. GM Rel. Symp.*, Dept. of Defense, February 1960.
43. Armendariz, M., and H. H. Monahan, "A Comparison Between the Double Theodolite and Single-Theodolite Wind Measuring Systems," April 1960.
44. Jenkins, K. R., and P. H. Taft, "Weather Elements in the Tularosa Basin," July 1960.
45. Beyers, N. J., "Preliminary Radar Performance Data on Passive Rocket-Borne Wind Sensors," IRE TRANS, MIL ELECT, MIL-4, 2-3, April-July 1960.
46. Webb, W. L., and K. R. Jenkins, "Speed of Sound in the Stratosphere," June 1960.
47. Webb, W. L., K. R. Jenkins, and G. Q. Clark, "Rocket Sounding of High Atmosphere Meteorological Parameters," *IRE Trans. Mil. Elect.*, MIL-4, 2-3, April-July 1960.
48. Helvey, R. A., "Low-Level Wind Profile Prediction Techniques," #3, September 1960.
49. Beyers, N. J., and O. W. Thiele, "Meteorological Wind Sensors," August 1960.
50. Armijo, Larry, "Determination of Trajectories Using Range Data from Three Noncolinear Radar Stations," September 1960.
51. Carnes, Patsy Sue, "Temperature Variations in the First 200 Feet of the Atmosphere in an Arid Region," July 1961.
52. Springer, H. S., and R. O. Olsen, "Launch Noise Distribution of Nike-Zeus Missiles," July 1961.
53. Thiele, O. W., "Density and Pressure Profiles Derived from Meteorological Rocket Measurements," September 1961.
54. Diamond, M. and A. B. Gray, "Accuracy of Missile Sound Ranging," November 1961.
55. Lamberth, R. L. and D. R. Veith, "Variability of Surface Wind in Short Distances," #1, October 1961.
56. Swanson, R. N., "Low-Level Wind Measurements for Ballistic Missile Application," January 1962.
57. Lamberth, R. L. and J. H. Grace, "Gustiness at White Sands Missile Range," #2, January 1962.
58. Swanson, R. N. and M. M. Hoidale, "Low-Level Wind Profile Prediction Techniques," #4, January 1962.
59. Rachele, Henry, "Surface Wind Model for Unguided Rockets Using Spectrum and Cross Spectrum Techniques," January 1962.
60. Rachele, Henry, "Sound Propagation through a Windy Atmosphere," #2, February 1962.
61. Webb, W. L., and K. R. Jenkins, "Sonic Structure of the Mesosphere," *J. Acous. Soc. Amer.*, 34, 2, February 1962.
62. Tourin, M. H. and M. M. Hoidale, "Low-Level Turbulence Characteristics at White Sands Missile Range," April 1962.
63. Miers, Bruce T., "Mesospheric Wind Reversal over White Sands Missile Range," March 1962.
64. Fisher, E., R. Lee and H. Rachele, "Meteorological Effects on an Acoustic Wave within a Sound Ranging Array," May 1962.
65. Walter, E. L., "Six Variable Ballistic Model for a Rocket," June 1962.
66. Webb, W. L., "Detailed Acoustic Structure Above the Tropopause," *J. Applied Meteorol.*, 1, 2, June 1962.
67. Jenkins, K. R., "Empirical Comparisons of Meteorological Rocket Wind Sensors," *J. Appl. Meteor.*, June 1962.
68. Lamberth, Roy, "Wind Variability Estimates as a Function of Sampling Interval," July 1962.
69. Rachele, Henry, "Surface Wind Sampling Periods for Unguided Rocket Impact Prediction," July 1962.
70. Traylor, Larry, "Coriolis Effects on the Aerobee-Hi Sounding Rocket," August 1962.
71. McCoy, J., and G. Q. Clark, "Meteorological Rocket Thermometry," August 1962.
72. Rachele, Henry, "Real-Time Prelaunch Impact Prediction System," August 1962.

73. Beyers, N. J., O. W. Thiele, and N. K. Wagner, "Performance Characteristics of Meteorlogical Rocket Wind and Temperature Sensors," October 1962.

74. Coffman, J., and R. Price, "Some Errors Associated with Acoustical Wind Measurements through a Layer," October 1962.

75. Armendariz, M., E. Fisher, and J. Serna, "Wind Shear in the Jet Stream at WSMR," November 1962.

76. Armendariz, M., F. Hansen, and S. Carnes, "Wind Variability and its Effect on Rocket Impact Prediction," January 1963.

77. Querfeld, C., and Wayne Yunker, "Pure Rotational Spectrum of Water Vapor, I: Table of Line Parameters," February 1963.

78. Webb, W. L., "Acoustic Component of Turbulence," *J. Applied Meteorol.*, 2, 2, April 1963.

79. Beyers, N. and L. Engberg, "Seasonal Variability in the Upper Atmosphere," May 1963.

80. Williamson, L. E., "Atmospheric Acoustic Structure of the Sub-polar Fall," May 1963.

81. Lamberth, Roy and D. Veith, "Upper Wind Correlations in Southwestern United States," June 1963.

82. Sandlin, E., "An analysis of Wind Shear Differences as Measured by AN/FPS-16 Radar and AN/GMD-1B Rawinsonde," August 1963.

83. Diamond, M. and R. P. Lee, "Statistical Data on Atmospheric Design Properties Above 30 km," August 1963.

84. Thiele, O. W., "Mesospheric Density Variability Based on Recent Meteorological Rocket Measurements," *J. Applied Meteorol.*, 2, 5, October 1963.

85. Diamond, M., and O. Essenwanger, "Statistical Data on Atmospheric Design Properties to 30 km," *Astro. Aero. Engr.*, December 1963.

86 Hansen, F. V., "Turbulence Characteristics of the First 62 Meters of the Atmosphere," December 1963.

87. Morris, J. E., and B. T. Miers, "Circulation Disturbances Between 25 and 70 kilometers Associated with the Sudden Warming of 1963," *J. of Geophys. Res.*, January 1964.

88. Thiele, O. W., "Some Observed Short Term and Diurnal Variations of Stratospheric Density Above 30 km," January 1964.

89. Sandlin, R. E., Jr. and E. Armijo, "An Analysis of AN/FPS-16 Radar and AN/GMD-1B Rawinsonde Data Differences," January 1964.

90. Miers, B. T., and N. J. Beyers, "Rocketsonde Wind and Temperature Measurements Between 30 and 70 km for Selected Stations," *J. Applied Meteorol.*, February 1964.

91. Webb, W. L., "The Dynamic Stratosphere," *Astronautics and Aerospace Engineering*, March 1964.

92. Low, R. D. H., "Acoustic Measurements of Wind through a Layer," March 1964.

93. Diamond. M., "Cross Wind Effect on Sound Propagation," *J. Applied Meteorol.*, April 1964.

94. Lee, R. P., "Acoustic Ray Tracing," April 1964.

95. Reynolds, R. D., "Investigation of the Effect of Lapse Rate on Balloon Ascent Rate," May 1964.

96. Webb, W. L., "Scale of Stratospheric Detail Structure," *Space Research V*, May 1964.

97. Barber, T. L., "Proposed X-Ray-Infrared Method for Identification of Atmospheric Mineral Dust," June 1964.

98. Thiele, O. W., "Ballistic Procedures for Unguided Rocket Studies of Nuclear Environments (U)," Proceedings of the Army Science Conference, June 1964.

99. Horn, J. D., and E. J. Trawle, "Orographic Effects on Wind Variability," July 1964.

100. Hoidale, G., C. Querfeld, T. Hall, and R. Mireles, "Spectral Transmissivity of the Earth's Atmosphere in the 250 to 500 Wave Number Interval," #1, September 1964.

101. Duncan, L. D., R. Ensey, and B. Engebos, "Athena Launch Angle Determination," September 1964.

102 Thiele, O. W., "Feasibility Experiment for Measuring Atmospheric Density Through the Altitude Range of 60 to 100 KM Over White Sands Missile Range," October 1964.

103. Duncan, L. D., and R. Ensey, "Six-Degree-of-Freedom Digital Simulation Model for Unguided, Fin-Stabilized Rockets," November 1964.

104. Hoidale, G., C. Querfeld, T. Hall, and R. Mireles. "Spectral Transmissivity of the Earth's Atmosphere in the 250 to 500 Wave Number Interval," #2, November 1964.

105. Webb, W. L., "Stratospheric Solar Response," *J. Atmos. Sci.*, November 1964.

106. McCoy, J. and G. Clark, "Rocketsonde Measurement of Stratospheric Temperature," December 1964.

107. Farone, W. A., "Electromagnetic Scattering from Radially Inhomogeneous Spheres as Applied to the Problem of Clear Atmosphere Radar Echoes," December 1964.

108. Farone, W. A., "The Effect of the Solid Angle of Illumination or Observation on the Color Spectra of 'White Light' Scattered by Cylinders," January 1965.

109. Williamson, L. E., "Seasonal and Regional Characteristics of Acoustic Atmospheres," *J. Geophys. Res.*, January 1965.

110. Armendariz, M., "Ballistic Wind Variability at Green River, Utah," January 1965.

111. Low, R. D. H., "Sound Speed Variability Due to Atmospheric Composition," January 1965.

112. Querfeld, C. W., 'Mie Atmospheric Optics," *J. Opt. Soc. Amer.*, January 1965.

113. Coffman, J., "A Measurement of the Effect of Atmospheric Turbulence on the Coherent Properties of a Sound Wave," January 1965.

114. Rachele, H., and D. Veith, "Surface Wind Sampling for Unguided Rocket Impact Prediction," January 1965.

115. Ballard, H., and M. Izquierdo, "Reduction of Microphone Wind Noise by the Generation of a Proper Turbulent Flow," February 1965.

116. Mireles, R., "An Algorithm for Computing Half Widths of Overlapping Lines on Experimental Spectra," February 1965.

117. Richart, H., "Inaccuracies of the Single-Theodolite Wind Measuring System in Ballistic Application," February 1965.

118. D'Arcy, M., "Theoretical and Practical Study of Aerobee-150 Ballistics," March 1965.

119. McCoy, J., "Improved Method for the Reduction of Rocketsonde Temperature Data," March 1965.

120. Mireles, R., "Uniqueness Theorem in Inverse Electromagnetic Cylindrical Scattering," April 1965.

121. Coffman, J., "The Focusing of Sound Propagating Vertically in a Horizontally Stratified Medium," April 1965.

122. Farone, W. A., and C. Querfeld, "Electromagnetic Scattering from an Infinite Circular Cylinder at Oblique Incidence," April 1965.

123. Rachele, H., "Sound Propagation through a Windy Atmosphere," April 1965.

124. Miers, B., "Upper Stratospheric Circulation over Ascension Island," April 1965.

125. Rider, L., and M. Armendariz, " A Comparison of Pibal and Tower Wind Measurements," April 1965.

126. Hoidale, G. B., "Meteorological Conditions Allowing a Rare Observation of 24 Micron Solar Radiation Near Sea Level," *Meteorol. Magazine*, May 1965.

127. Beyers, N. J., and B. T. Miers, "Diurnal Temperature Change in the Atmosphere Between 30 and 60 km over White Sands Missile Range," *J. Atmos. Sci.*, May 1965.

128. Querfeld, C., and W. A. Farone, "Tables of the Mie Forward Lobe," May 1965.

129. Farone, W. A., Generalization of Rayleigh-Gans Scattering from Radially Inhomogeneous Spheres," *J. Opt. Soc. Amer.*, June 1965.

130. Diamond, M., "Note on Mesospheric Winds Above White Sands Missile Range," *J. Applied Meteorol.*, June 1965.

131. Clark, G. Q., and J. G. McCoy, "Measurement of Stratospheric Temperature," *J. Applied Meteorol.*, June 1965.

132. Hall, T., G. Hoidale, R. Mireles, and C. Querfeld, "Spectral Transmissivity of the Earth's Atmosphere in the 250 to 500 Wave Number Interval," #3, July 1965.

133. McCoy, J., and C. Tate, "The Delta-T Meteorological Rocket Payload," June 1964.

134. Horn, J. D., "Obstacle Influence in a Wind Tunnel," July 1965.

135. McCoy, J., "An AC Probe for the Measurement of Electron Density and Collision Frequency in the Lower Ionosphere," July 1965.

136. Miers, B. T., M. D. Kays, O. W. Thiele and E. M. Newby, "Investigation of Short Term Variations of Several Atmospheric Parameters Above 30 KM," July 1965.

137. Serna, J., "An Acoustic Ray Tracing Method for Digital Computation," September 1965.
138. Webb, W. L., "Morphology of Noctilucent Clouds," *J. Geophys. Res.*, 70, 18, 4463-4475, September 1965.
139. Kays, M., and R. A. Craig, "On the Order of Magnitude of Large-Scale Vertical Motions in the Upper Stratosphere," *J. Geophys. Res.*, 70, 18, 4453-4462, September 1965.
140. Rider, L., "Low-Level Jet at White Sands Missile Range," September 1965.
141. Lamberth, R. L., R. Reynolds, and Morton Wurtele, "The Mountain Lee Wave at White Sands Missile Range," *Bull. Amer. Meteorol. Soc.*, 46, 10, October 1965.
142. Reynolds, R. and R. L. Lamberth, "Ambient Temperature Measurements from Radiosondes Flown on Constant-Level Balloons," October 1965.
143. McCluney, E., "Theoretical Trajectory Performance of the Five-Inch Gun Probe System," October 1965.
144. Pena, R. and M. Diamond, "Atmospheric Sound Propagation near the Earth's Surface," October 1965.
145. Mason, J. B., "A Study of the Feasibility of Using Radar Chaff For Stratospheric Temperature Measurements," November 1965.
146. Diamond, M., and R. P. Lee, "Long-Range Atmospheric Sound Propagation," *J. Geophys. Res.*, 70, 22, November 1965.
147. Lamberth, R. L., "On the Measurement of Dust Devil Parameters," November 1965.
148. Hansen, F. V., and P. S. Hansen, "Formation of an Internal Boundary over Heterogeneous Terrain," November 1965.
149. Webb, W. L., "Mechanics of Stratospheric Seasonal Reversals," November 1965.
150. U. S. Army Electronics R & D Activity, "U. S. Army Participation in the Meteorological Rocket Network," January 1966.
151. Rider, L. J., and M. Armendariz, "Low-Level Jet Winds at Green River, Utah," February 1966.
152. Webb, W. L., "Diurnal Variations in the Stratospheric Circulation," February 1966.
153. Beyers, N. J., B. T. Miers, and R. J. Reed, "Diurnal Tidal Motions near the Stratopause During 48 Hours at WSMR," February 1966.
154. Webb, W. L., "The Stratospheric Tidal Jet," February 1966.
155. Hall, J. T., "Focal Properties of a Plane Grating in a Convergent Beam," February 1966.
156. Duncan, L. D., and Henry Rachele, "Real-Time Meteorological System for Firing of Unguided Rockets," February 1966.
157. Kays, M. D., "A Note on the Comparison of Rocket and Estimated Geostrophic Winds at the 10-mb Level," *J. Appl. Meteor.*, February 1966.
158. Rider, L., and M. Armendariz, " A Comparison of Pibal and Tower Wind Measurements," *J. Appl. Meteor.*, 5, February 1966.
159. Duncan, L. D., "Coordinate Transformations in Trajectory Simulations," February 1966.
160. Williamson, L. E., "Gun-Launched Vertical Probes at White Sands Missile Range," February 1966.
161. Randhawa, J. S., Ozone Measurements with Rocket-Borne Ozonesondes," March 1966.
162. Armendariz, Manuel, and Laurence J. Rider, "Wind Shear for Small Thickness Layers," March 1966.
163. Low, R. D. H., "Continuous Determination of the Average Sound Velocity over an Arbitrary Path," March 1966.
164. Hansen, Frank V., "Richardson Number Tables for the Surface Boundary Layer," March 1966.
165. Cochran, V. C., E. M. D'Arcy, and Florencio Ramirez, "Digital Computer Program for Five-Degree-of-Freedom Trajectory," March 1966.
166. Thiele, O. W., and N. J. Beyers, "Comparison of Rocketsonde and Radiosonde Temperatures and a Verification of Computed Rocketsonde Pressure and Density," April 1966.
167. Thiele, O. W., "Observed Diurnal Oscillations of Pressure and Density in the Upper Stratosphere and Lower Mesosphere," April 1966.
168. Kays, M. D., and R. A. Craig, "On the Order of Magnitude of Large-Scale Vertical Motions in the Upper Stratosphere," *J. Geophy. Res.*, April 1966.
169. Hansen, F. V., "The Richardson Number in the Planetary Boundary Layer," May 1966.

170. Ballard, H. N., "The Measurement of Temperature in the Stratosphere and Mesosphere," June 1966.
171. Hansen, Frank V., "The Ratio of the Exchange Coefficients for Heat and Momentum in a Homogeneous, Thermally Stratified Atmosphere," June 1966.
172. Hansen, Frank V., "Comparison of Nine Profile Models for the Diabatic Boundary Layer," June 1966.
173. Rachele, Henry, "A Sound-Ranging Technique for Locating Supersonic Missiles," May 1966.
174. Farone, W. A., and C. W. Querfeld, "Electromagnetic Scattering from Inhomogeneous Infinite Cylinders at Oblique Incidence," *J. Opt. Soc. Amer.* 56, 4, 476-480, April 1966.
175. Mireles, Ramon, "Determination of Parameters in Absorption Spectra by Numerical Minimization Techniques," *J. Opt. Soc. Amer.* 56, 5, 644-647, May 1966.
176. Reynolds, R., and R. L. Lamberth, "Ambient Temperature Measurements from Radiosondes Flown on Constant-Level Balloons," *J. Appl. Meteorol.*, 5, 3, 304-307, June 1966.
177. Hall, James T., "Focal Properties of a Plane Grating in a Convergent Beam," *Appl. Opt.*, 5, 1051, June 1966
178. Rider, Laurence J., "Low-Level Jet at White Sands Missile Range," *J. Appl. Meteorol.*, 5, 3, 283-287, June 1966.
179. McCluney, Eugene, "Projectile Dispersion as Caused by Barrel Displacement in the 5-Inch Gun Probe System," July 1966.
180. Armendariz, Manuel, and Laurence J. Rider, "Wind Shear Calculations for Small Shear Layers," June 1966.
181. Lamberth, Roy L., and Manuel Armendariz, "Upper Wind Correlations in the Central Rocky Mountains," June 1966.
182. Hansen, Frank V., and Virgil D. Lang, "The Wind Regime in the First 62 Meters of the Atmosphere," June 1966.
183. Randhawa, Jagir S., "Rocket-Borne Ozonesonde," July 1966.
184. Rachele, Henry, and L. D. Duncan, "The Desirability of Using a Fast Sampling Rate for Computing Wind Velocity from Pilot-Balloon Data," July 1966.
185. Hinds, B. D., and R. G. Pappas, "A Comparison of Three Methods for the Correction of Radar Elevation Angle Refraction Errors," August 1966.
186. Riedmuller, G. F., and T. L. Barber, "A Mineral Transition in Atmospheric Dust Transport," August 1966.
187. Hall, J. T., C. W. Querfeld, and G. B. Hoidale, "Spectral Transmissivity of the Earth's Atmosphere in the 250 to 500 Wave Number Interval," Part IV (Final), July 1966.
188. Duncan, L. D. and B. F. Engebos, "Techniques for Computing Launcher Settings for Unguided Rockets," September 1966.
189. Duncan, L. D., "Basic Considerations in the Development of an Unguided Rocket Trajectory Simulation Model," September 1966.
190. Miller, Walter B., "Consideration of Some Problems in Curve Fitting," September 1966.
191. Cermak, J. E., and J. D. Horn, "The Tower Shadow Effect," August 1966.
192. Webb, W. L., "Stratospheric Circulation Response to a Solar Eclipse," October 1966.
193. Kennedy, Bruce, "Muzzle Velocity Measurement," October 1966.
194. Traylor, Larry E., "A Refinement Technique for Unguided Rocket Drag Coefficients," October 1966
195. Nusbaum, Henry, "A Reagent for the Simultaneous Microscope Determination of Quartz and Halides," October 1966.
196. Kays, Marvin and R. O. Olsen, "Improved Rocketsonde Parachute-derived Wind Profiles," October 1966.
197. Engebos, Bernard F. and Duncan, Louis D., "A Nomogram for Field Determination of Launcher Angles for Unguided Rockets," October 1966.
198. Webb, W. L., "Midlatitude Clouds in the Upper Atmosphere," November 1966.
199. Hansen, Frank V., "The Lateral Intensity of Turbulence as a Function of Stability," November 1966.
200. Rider, L. J. and M. Armendariz, "Differences of Tower and Pibal Wind Profiles," November 1966.
201. Lee, Robert P., "A Comparison of Eight Mathematical Models for Atmospheric Acoustical Ray Tracing," November 1966.
202. Low, R. D. H., et al., "Acoustical and Meteorological Data Report SOTRAN I and II," November 1966.

203. Hunt, J. A. and J. D. Horn, "Drag Plate Balance," December 1966.
204. Armendariz, M., and H. Rachele, "Determination of a Representative Wind Profile from Balloon Data," December 1966.
205. Hansen, Frank V., "The Aerodynamic Roughness of the Complex Terrain of White Sands Missile Range," January 1967.
206. Morris, James E., "Wind Measurements in the Subpolar Mesopause Region," January 1967.
207. Hall, James T., "Attenuation of Millimeter Wavelength Radiation by Gaseous Water," January 1967.
208. Thiele, O. W., and N. J. Beyers, "Upper Atmosphere Pressure Measurements With Thermal Conductivity Gauges," January 1967.
209. Armendariz, M., and H. Rachele, "Determination of a Representative Wind Profile from Balloon Data," January 1967.
210. Hansen, F. V., "The Aerodynamic Roughness of the Complex Terrain of White Sands Missile Range, New Mexico," January 1967.
211. D'Arcy, Edward M., "Some Applications of Wind to Unguided Rocket Impact Prediction," March 1967.
212. Kennedy, Bruce, "Operation Manual for Stratosphere Temperature Sonde," March 1967.
213. Hoidale, G. B., S. M. Smith, A. J. Blanco, and T. L. Barber, "A Study of Atmospheric Dust," March 1967.
214. Longyear, J. Q., "An Algorithm for Obtaining Solutions to Laplace's Titad Equations," March 1967.
215. Rider, L. J., "A Comparison of Pibal with Raob and Rawin Wind Measurements," April 1967.
216. Breeland, A. H., and R. S. Bonner, "Results of Tests Involving Hemispherical Wind Screens in the Reduction of Wind Noise," April 1967.
217. Webb, Willis L., and Max C. Bolen, "The D-region Fair-Weather Electric Field," April 1967.
218. Kubinski, Stanley F., "A Comparative Evaluation of the Automatic Tracking Pilot-Balloon Wind Measuring System," April 1967.
219. Miller, Walter B., and Henry Rachele, "On Nonparametric Testing of the Nature of Certain Time Series," April 1967.
220. Hansen, Frank V., "Spacial and Temporal Distribution of the Gradient Richardson Number in the Surface and Planetary Layers," May 1967.
221. Randhawa, Jagir S., "Diurnal Variation of Ozone at High Altitudes," May 1967.
222. Ballard, Harold N., "A Review of Seven Papers Concerning the Measurement of Temperature in the Stratosphere and Mesosphere," May 1967.
223. Williams, Ben H., "Synoptic Analyses of the Upper Stratospheric Circulation During the Late Winter Storm Period of 1966," May 1967.
224. Horn, J. D., and J. A. Hunt, "System Design for the Atmospheric Sciences Office Wind Research Facility," May 1967.
225. Miller, Walter B., and Henry Rachele, "Dynamic Evaluation of Radar and Photo Tracking Systems," May 1967.
226. Bonner, Robert S., and Ralph H. Rohwer, "Acoustical and Meteorological Data Report - SOTRAN III and IV," May 1967.
227. Rider, L. J., "On Time Variability of Wind at White Sands Missile Range, New Mexico," June 1967.
228. Randhawa, Jagir S., "Mesospheric Ozone Measurements During a Solar Eclipse," June 1967.
229. Beyers, N. J., and B. T. Miers, "A Tidal Experiment in the Equatorial Stratosphere over Ascension Island (8S)", June 1967.
230. Miller, W. B., and H. Rachele, "On the Behavior of Derivative Processes," June 1967
231. Walters, Randall K., "Numerical Integration Methods for Ballistic Rocket Trajectory Simulation Programs," June 1967.
232. Hansen, Frank V., "A Diabatic Surface Boundary Layer Model," July 1967.
233. Butler, Ralph L., and James K. Hall, "Comparison of Two Wind Measuring Systems with the Contraves Photo-Theodolite," July 1967.
234. Webb, Willis L., "The Source of Atmospheric Electrification," June 1967.

235. Hinds, B. D., "Radar Tracking Anomalies over an Arid Interior Basin," August 1967.
236. Christian, Larry O., "Radar Cross Sections for Totally Reflecting Spheres," August 1967.
237. D'Arcy, Edward M., "Theoretical Dispersion Analysis of the Aerobee 350," August 1967.
238. Anon., "Technical Data Package for Rocket-Borne Temperature Sensor," August 1967.
239. Glass, Roy I., Roy L. Lamberth, and Ralph D. Reynolds, "A High Resolution Continuous Pressure Sensor Modification for Radiosondes," August 1967.
240. Low, Richard D. H., "Acoustic Measurement of Supersaturation in a Warm Cloud," August 1967.
241. Rubio, Roberto, and Harold N. Ballard, "Time Response and Aerodynamic Heating of Atmospheric Temperature Sensing Elements," August 1967.
242. Seagraves, Mary Ann B., "Theoretical Performance Characteristics and Wind Effects for the Aerobee 150," August 1967.
243. Duncan, Louis Dean, "Channel Capacity and Coding," August 1967.
244. Dunaway, G. L., and Mary Ann B. Seagraves, "Launcher Settings Versus Jack Settings for Aerobee 150 Launchers - Launch Complex 35, White Sands Missile Range, New Mexico," August 1967.
245. Duncan, Louis D., and Bernard F. Engebos, "A Six-Degree-of-Freedom Digital Computer Program for Trajectory Simulation," October 1967.
246. Rider, Laurence J., and Manuel Armendariz, "A Comparison of Simultaneous Wind Profiles Derived from Smooth and Roughened Spheres," September 1967.
247. Reynolds, Ralph D., Roy L. Lamberth, and Morton G. Wurtele, "Mountain Wave Theory vs Field Test Measurements," September 1967.
248. Lee, Robert P., "Probabilistic Model for Acoustic Sound Ranging," October 1967.
249. Williamson, L. Edwin, and Bruce Kennedy, "Meteorological Shell for Standard Artillery Pieces - A Feasibility Study," October 1967.
250. Rohwer, Ralph H., "Acoustical, Meteorological and Seismic Data Report - SOTRAN V and VI," October 1967.
251. Nordquist, Walter S., Jr., "A Study in Acoustic Direction Finding," November 1967.
252. Nordquist, Walter S., Jr., "A Study of Acoustic Monitoring of the Gun Probe System," November 1967.
253. Avara, E. P., and B. T. Miers, "A Data Reduction Technique for Meteorological Wind Data above 30 Kilometers," December 1967.
254. Hansen, Frank V., "Predicting Diffusion of Atmospheric Contaminants by Consideration of Turbulent Characteristics of WSMR," January 1968.
255. Randhawa, Jagir S., "Rocket Measurements of Atmospheric Ozone," January 1968.
256. D'Arcy, Edward M., "Meteorological Requirements for the Aerobee-350," January 1968.
257. D'Arcy, Edward M., "A Computer Study of the Wind Frequency Response of Unguided Rockets," February 1968.
258. Williamson, L. Edwin, "Gun Launched Probes - Parachute Expulsion Tests Under Simulated Environment," February 1968.
259. Beyers, Norman J., Bruce T. Miers, and Elton P. Avara, "The Diurnal Tide Near the Stratopause over White Sands Missile Range, New Mexico," February 1968.
260. Traylor, Larry E., "Preliminary Study of the Wind Frequency Response of the Honest John M50 Tactical Rocket," March 1968.
261. Engebos, B. F., and L. D. Duncan, "Real-Time Computations of Pilot Balloon Winds," March 1968.
262. Butler, Ralph and L. D. Duncan, "Empirical Estimates of Errors in Double-Theodolite Wind Measurements," February 1968.
263. Kennedy, Bruce, et al., "Thin Film Temperature Sensor," March 1968.
264. Bruce, Dr. Rufus, James Mason, Dr. Kenneth White and Richard B. Gomez, "An Estimate of the Atmospheric Propagation Characteristics of 1.54 Micron Laser Energy," March 1968.

265. Ballard, Harold N., Jagir S. Randhawa, and Willis L. Webb, "Stratospheric Circulation Response to a Solar Eclipse," March 1968.
266. Johnson, James L., and Orville C. Kuberski, "Timing Controlled Pulse Generator," April 1968.
267. Blanco, Abel J., and Glenn B. Hoidale, "Infrared Absorption Spectra of Atmospheric Dust," May 1968.
268. Jacobs, Willie N., "Automatic Pibal Tracking System," May 1968.
269. Morris, James E., and Marvin D. Kays, "Circulation in the Arctic Mesosphere in Summer," June 1968.
270. Mason, James B., "Detection of Atmospheric Oxygen Using a Tuned Ruby Laser," June 1968.
271. Armendariz, Manuel, and Virgil D. Lang, "Wind Correlation and Variability in Time and Space," July 1968.
272. Webb, Willis L., "Tropospheric Electrical Structure," July 1968.
273. Miers, Bruce T., and Elton P. Avara, "Analysis of High-Frequency Components of AN/FPS-16 Radar Data," August 1968.
274. Dunaway, Gordon L., "A Practical Field Wind Compensation Technique for Unguided Rockets," August 1968.
275. Seagraves, Mary Ann B., and Barry Butler, "Performance Characteristics and Wind Effects for the Aerobee 150 with VAM Booster," September 1968.
276. Low, Richard D. H., "A Generalized Equation for Droplet Growth Due to the Solution Effect," September 1968.
277. Jenkins, Kenneth R., "Meteorological Research, Development, Test, and Evaluation Rocket," September 1968.
278. Williams, Ben H., and Bruce T. Miers, "The Synoptic Events of the Stratospheric Warming of December 1967 - January 1968," September 1968.
279. Tate, C. L., and Bruce W. Kennedy, "Technical Data Package for Atmospheric Temperature Sensor Mini-Loki," September 1968.
280. Rider, Laurence J., Manuel Armendariz, and Frank V. Hansen, "A Study of Wind and Temperature Variability at White Sands Missile Range, New Mexico," September 1968.
281. Duncan, Louis D., and Walter B. Miller, "The Hull of a Channel," September 1968.
282. Hansen, Frank V., and Gary A. Ethridge, "Diffusion Nomograms and Tables for Rocket Propellants and Combustion By-Products," January 1968.
283. Walters, Randall K., and Bernard F. Engebos, "An Improved Method of Error Control for Runge-Kutta Numerical Integration," October 1968.
284. Miller, Walter B., "A Non-Entropy Approach to Some Topics in Channel Theory," November 1968.
285. Armendariz, Manuel, Laurence J. Rider, and Frank V. Hansen, "Turbulent Characteristics in the Surface Boundary Layer," November 1968.
286. Randhawa, Jagir S., "Rocket Measurements of the Diurnal Variation of Atmospheric Ozone," December 1968.
287. Randhawa, Jagir S., "A Guide to Rocketsonde Measurements of Atmospheric Ozone," January 1969.
288. Webb, Willis L., "Solar Control of the Stratospheric Circulation," February 1969.
289. Lee, Robert P., "A Dimensional Analysis of the Errors of Atmospheric Sound Ranging," March 1969.
290. Barber, T. L., "Degradation of Laser Optical Surfaces," March 1969.
291. D'Arcy, E. M., "Diffusion of Resonance Excitation Through a One-Dimensional Gas," March 1969.
292. Randhawa, J. S., "Ozone Measurements from a Stable Platform near the Stratopause Level," March 1969.
293. Rubio, Roberto, "Faraday Rotation System for Measuring Electron Densities," March 1969.
294. Olsen, Robert, "A Design Plan for Investigating the Atmospheric Environment Associated with High Altitude Nuclear Testing," March 1969.
295. Monahan, H. H., M. Armendariz, and V. D. Lang, "Estimates of Wind Variability Between 100 and 900 Meters," April 1969.
296. Rinehart, G. S., "Fog Drop Size Distributions - Measurement Methods and Evaluation," April 1969.

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) U. S. Army Electronics Command Fort Monmouth, New Jersey	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

FOG DROP SIZE DISTRIBUTIONS - MEASUREMENT METHODS AND EVALUATION

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

Gayle S. Rinehart

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
April 1969	39	44

8a. CONTRACT OR GRANT NO. b. PROJECT NO. c. Task No. 1T061102B53A-20 d.	9a. ORIGINATOR'S REPORT NUMBER(S) ECOM-5247 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Distribution of this report is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Atmospheric Sciences Laboratory U.S. Army Electronics Command White Sands Missile Range, New Mexico

13. ABSTRACT

In connection with evaluating fog modification efforts, several published methods of measuring the size distribution of fog droplets were reviewed. An evaluation cast doubt on the validity of the gelatin, Formvar, and polyvinyl alcohol, and oil collection media for recording droplets less than 4μ diameter. Efficiency of several collection methods appeared to be poor for less than 4μ diameter droplets when lack of drop size distribution correlation with visibility measurement was considered.

During a fog dispersal test, pyrotechnically produced hygroscopic reagents were observed to cause an increase in the number of concentrations of the small sized droplets of a natural fog.

During nonfog conditions, several types of pyrotechnic flares containing different hygroscopic reagents were tested for usefulness as fog modification agents. Measurement of drop and particle size distributions downwind from the ignition point of these pyrotechnics revealed that the effect of small droplet sizes in decreasing visibility in air of high humidity would negate the improvement made by removal of large size drops.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

UNCLASSIFIED
Security Classification

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
1. Weather Modification 2. Fog 3. Drop Size Distributions 4. Replication 5. Capture Methods 6. Recording Media						

UNCLASSIFIED
Security Classification