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A STUDY OF THE TRAJECTORIES AND DIFFUSION PATTERNS OF
GROUND-GENERATED AIRBORNE PARTICULATES UNDER OROGRAPHIC
WIND FLOW CONDITIONS

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ABSTRACT

In late June and early July, 1956, a series of experiments were performed to determine the wind structure over an orographic barrier and to ascertain whether ground-generated aerosols reach cloud heights in such a situation. Zinc sulphide particles were dispersed in an oil fog from a ground-located fog generator and collections were made using airborne impactors. Particles were found at elevations of at least 14,000 feet at distances out to at least 20 miles. However, "plumes" were found to be considerably broader than had been anticipated and the structure of the wind over a mountain ridge is judged to be substantially more complex than has been assumed in cloud-seeding operations.

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I. INTRODUCTION.

Zinc sulphide pigment has been used by a number of investigators in the United States as an air tagging and tracing material. Detailed descriptions of these experiments have been given in the literature by Perkins et al (1952), Neiburger (1955), Falk et al (1954), Braham et al (1952), and Crozier and Seely (1955). With the exception of the last two, these experiments were performed using ground sampling points so that, while it was possible to get information on the horizontal trajectories, it was not possible to get any information on the vertical structure of the wind. The experiments reported by Braham et al and Crozier and Seely were performed at the New Mexico Institute of Mining and Technology and used airborne impactors for sampling. Additional work by Smith and Heffernan (1954) in Australia tracing ground-generated silver iodide smoke gives some information on the structure of aerosol plumes and the concentration distributions within them.

All of the aforementioned experiments were done over essentially level terrain. The general conclusion that may be reached from these experiments is that it is quite unusual to find plume widths, from a point source, exceeding the plume length. Moreover, very little of the ground-generated material may be expected to be found at altitudes over 5000 feet above terrain even at distances of several tens of miles from the source.

Although few would doubt that in an orographic situation with strong convection present, ground-generated aerosols would reach cloud base altitudes, this is a fundamental question in the matter of cloud-seeding with ground-generated silver iodide smoke. Moreover, since little basic data on the nature of

the circulation in the vicinity of an orographic barrier exists, it was felt that an air tracing experiment in such a situation would be a worthy one.

It was decided to study the dispersal pattern for tracer particles released at ground level into an air current that was not only moving against a sizeable orographic barrier but that was also characterized by relatively unstable lapse rate, thus further favoring chances of the particulates being swept to great altitudes. Such an experiment would constitute a decisive test of an existing question that has puzzled cloud-seeding experimenters: Do ground-released particles, under any conditions, reach cloud altitudes in distances of the order of a few miles of downwind travel? If the results were to be negative in such a test situation, this would have clarified this important issue immediately, in that a more favorable opportunity for rapid ascent would be difficult to find. If the results were positive, then it would be valuable to have the resultant quantitative information on heights and plume geometries.

II. LOCATION OF THE EXPERIMENT.

After consideration of many practical aspects, a generator site was chosen in Rincon Valley, about 20 miles southeast of the center of Tucson. Figure 1 is a map of the experimental area. As can be seen from the map, the generator site is in a fairly level area with two ridges about seven miles from the site. The ridges are roughly perpendicular to each other and are so situated with respect to the wind-rose for the month of June, when most of the runs were taken, that a ridge barrier would present itself for most anticipated variation in wind direction. Later experience showed that sustained surface flow in the direction of the ridges could not be expected until after noon of any particular day. Whether this is a consequence only of the topographic factors in the vicinity of the ridge is not known at this time, although the extent to which

this effect persists and its cause would be the subject of a very interesting experiment in itself. The prevailing westerly winds must ascend a barrier that averages over 3000 feet above the valley level, as can be seen from the accompanying maps.

Aerial photographs of the whole area were taken and terrain positions were spotted to be used as fixes for the sampling flights. These fixes are shown on the map as the numbered black circles. It was anticipated that control of the sampling flights would be from the ground, based on pilot balloon observations taken from the generator site. From the predicted air trajectories, fixes would be chosen, corresponding to the ends of cross-sections, and the airplane pilots would be directed, by radio, at what altitudes to fly the sampling runs. This technique was used throughout the experiment, and it is felt that it is doubtful that any other method, with the possible exception of radar control, would work.

A small hill, 230 feet above terrain, called Loma Alta was chosen for a second theodolite site. The elevation was thought to be necessary so that the second observer could see the pilot balloon releases. Two theodolites were also felt to be necessary since there was some doubt as to the reliability of the free-lift-calculated ascension rates used in pibal runs under the conditions of the experiment. Experience proved this to be a wise precaution, particularly since it was found to be very difficult to erect any sort of temporary shelter on the desert that would enable the balloon to be inflated to proper free-lift. The base-line was surveyed using a horizontal stadia technique, and found to be 3.085 miles long. Radio communication was also maintained between theodolite stations and the data were immediately radioed back to the generator site so that the pibal plots could be made up on the spot and the information given to the airplanes.

Figure 2 is a general view of the generator site activity.

III. THE GENERATOR OPERATION.

It was felt that the dispersal of the zinc sulphide tagging material should be accomplished by means of the fog generator technique mentioned by Braham et al (1952). In this method, zinc sulphide pigment is mixed with fog oil and dispersed using a military fog generator. Under ideal circumstances this gives a plume visible for the first few miles of its course. It was thought that the presence of the plume would be indispensable to proper direction of the airplane. However, experience showed that the surface winds had so little relation to the wind structure over the ridge that the plume was more deceptive than helpful. Frequent pibals are still felt to be indispensable but the visible plume is not necessary. Moreover, the increase in complexity in the logistics required by the handling of a large volume of oil and the general messiness of the fog generator would even further urge the elimination of this step. The better alternative would be the "dry duster" described by Braham et al (1952), by Perkins et al (1952) and by Neiburger (1955).

The fog generator used was the Navy, Model PF-102, pulse-jet, fog generator. This generator has a pair of gasoline pulse-jet engines and the fog oil is injected into a compartment heated by the exhaust of the gasoline engines. The oil is vaporized and the resulting vapor pours forth from nozzles whereupon it immediately condenses into a dense white fog. The generators normally vaporize about 100 gallons of oil per hour. However, it was found that in using them at about 3000 feet above their design elevation, they tended to "choke" themselves and it was necessary to throttle both the gasoline and oil feed rate down to about half their nominal values. It was also found that the margin between choking and fire danger became somewhat thinner under these circumstances.

The pigment was mixed directly into the fog oil in the field to avoid excessive settling. Anticipation of some difficulty in this direction necessitated

some advance planning that worked fairly well in practice. Rough calculation showed that each 55 gallon drum of oil would require eight pounds of pigment on the basis of 100 gallons per hour of oil consumption. (This mixing rate was later doubled when it was found that oil consumption could be maintained at only about one drum per hour.) Since the mass mean diameter of the pigment is about two microns it was felt that mixing eight pounds of the dry pigment into 55 gallons of oil every half hour would be difficult in the field. (This view was amply substantiated by Dr. R. R. Braham, Jr. who was associated with the New Mexico effort.) Therefore, it was decided to have a local paint manufacturer make a paste of eight pounds of pigment per three quarts of oil and put this up in gallon cans, one gallon of paste to be mixed into each drum of fog oil. Removable lid drums were used in the field and the mixing operation was easily accomplished with a standard electric mixer of the variety manufactured for mixing paints in drum lots. Negligible settling took place in the paste and five minutes of mixing appeared ample.

New Jersey Zinc Sales Company pigment NJZ 2267 was used. This is similar to NJZ 2266, more commonly used, with the exception that its range of particle sizes is smaller and it has been treated to improve its dry flowing properties. We used a figure of 5×10^{10} particles per gram as a good average of the reported particle count for NJZ 2266. From the experience of Crozier and Seely, 10^{11} particles dispersed per second was taken to be a good generation rate. Since eight pounds per hour corresponded to about half this rate due to the reduced oil consumption by the generator, eventually two gallons of paste were used per drum of oil. The pigment tended to clog the filters in the generators but by alternating generators between two that were available, it was possible to maintain continuity of the plume fairly well.

A check on the number of particles per gram was made by diluting a 50 cc. sample of a mixed drum of oil with another 55 gallons of oil and counting a few drops of the resulting mixture under a microscope. The result yielded 5×10^9 particles per gram. This order of magnitude discrepancy is disconcerting. However, Rosinski et al (1956), in a comparison of different techniques for determining the number of particles per unit mass of just these materials, finds similar discrepancies between sedimentation and dilution techniques in these size ranges. Their work suggests that agglomeration and failure to resolve small particles by direct count techniques leads to these discrepancies. Since direct counting is involved in the final analysis, presumably 10^{10} particles per second is a more realistic estimate of the effective generator output than 10^{11} is.

Figure 3 shows a fog generator in operation.

IV. THE AIR SAMPLING OPERATION.

Sampling was done by two impactors, in general, one mounted in a Piper Super Cub, Model PA-18, airplane and the other in a Piper Tri-Pacer, Model PA-22. In the case of the Super Cub, the impactor was mounted on the back of the pilot's seat and a three foot length of one-half inch thin-walled conduit was led out the window and fastened to a strut. The conduit had a gradual bend so that the plane of its open end was normal to the axis of the airplane. In the Tri-Pacer, the impactor was mounted on the rear door and a similar, but shorter, length of conduit led through a hole in the door directly to the outside air. Exhaust tubes from both impactors led to three inch venturis mounted close to the fuselages of the planes. Care was taken to insure that the intake tubes were clear of the airplane engine exhaust tubes and clear of the major portion of the prop wash.

One of the impactors was the one used in the New Mexico experiments reported by Crozier and Seely. The second impactor was constructed by the Cloud Physics group at the University of Chicago. Both impactors were identical in essential details. The New Mexico impactor was arranged with a microscope and ultra-violet light source to view the collections in flight. However, in the light planes over the mountains, turbulence made it impossible to make any effective use of the microscope. The impactors had 0.050 x 0.250 inch rectangular slits at the ends of their intake nozzles which were spaced about 0.050 inch from the collection strip. The strips were of 0.050 inch acetate plastic, one inch wide and 20 inches long. They were coated with a heated gelatin and glycerin mixture which remained slightly "sticky" on cooling. The strips were clamped in the impactors on a disk so that they have a cylindrical form. The disk is driven by a constant speed motor so that sampling is continuous at a linear speed of $1/8$ inch per minute.

An air-speed indicator was connected across the impactor to measure the pressure drop and hence the volume flow through the impactor orifice. The impactor was previously calibrated using a flow meter with the air speed indicator. Due to the fact that the air speed down the intake tube can be practically neglected with respect to the jet at the orifice, the air-speed indicator was found to give the linear speed through the orifice to within ten percent of the actual air-speed indicated over the whole range of the instrument. This is not a serious error since the particle counts are necessarily "rounded off" to the nearest count.

The venturis proved to be very helpful since they increased the volume flow, and hence the volume sampled, by more than a factor of two over that given by merely leaving the exhaust open to the static pressure within the plane or by simply hanging the exhaust tube outside. For future design purposes it is of

interest to note that, for all practical purposes, the indicated air speed in the impactor orifice was the same as the plane speed when the venturis were not used. At least, this was true in the speed range of 80 to 100 miles an hour where these planes were normally used.

With the venturis connected, the average speed in the orifice was 200 miles per hour, thus the volume flow through the orifice of the dimensions given averaged 48.5 liters per minute. If the plane were flying at 90 miles per hour, then the volume swept out by the one-half inch impactor tube would be 342 liters per minute. Since one minute intervals of the strips were counted, one particle on the strip under these circumstances represented about 21 particles per cubic meter.

Figure 4 shows the impactor mounting in the Super Cub.

V. THE ANALYSIS OPERATION.

The strips were counted under a microscope with 100X magnification. A General Electric BH-4 mercury vapor lamp was used as sub-stage illumination using the regular condensing system of the microscope. With this illumination far too much ultra-violet light came through the microscope eye piece. However, it was found that a polaroid analyzer filter placed between the objective and the eyepiece reduced the ultra-violet light to a comfortable level while still retaining sufficient contrast in the visible to make the smallest fluorescent particles discernible. Holders were attached to the microscope stage to hold the strips and the strips were counted by moving the drive screws of the mechanical stage. Some time was saved by attaching a motor drive to the stage, actuated by a foot switch. However, at best, the counting operation proved very tedious. It is felt that the system described by Parsons et al (1952) would be superior. In this case a piece of tape is fastened to a drum with the sticky side out. The drum is mounted in the impactor for the collection and

then is mounted on a similar motor driven arrangement for counting under the microscope. Parsons estimated that the time for counting varies from ten to thirty minutes for a strip which would be equivalent to the one used in the present investigation. The technique used in this study required a full day's tedious effort to count one strip, and it is questionable whether the reproducibility would approach that mentioned by Parsons.

VI. RESULTS.

In all, eight separate runs were made on eight different days. The first four days will have to be taken as "shake-down" runs, some sort of operational failure having shown up on each of these days. The results of operations taken to be successful are plotted in Figures 5 through 17. Figure 18 shows the temperature sounding for the four days. In each case, the flights are summarized on a base map, the flight lines shown between the appropriate terminating points. In addition, the pibal run nearest in time to the flights is plotted. The vectors shown are the velocity vectors for each thousand feet in elevation above sea level. The number opposite the vector identifies the elevation in thousands of feet. The surface vector is identified by the letter "S".

Accompanying the base maps are the analyses for each cross-section. On the left hand side of each plot is given the flight altitude of each traverse. The numbers in parentheses refer to the times of reversal of course above the end points. The numbers shown between the dashed borders are the actual particle counts, corrected for difference in air speed of the two air-planes used. The numbers outside of the dashed lines refer to the counts encountered in the turn and climb or descent between traverses. The numbers just under the dashed lines refer to the terminating points on the base maps.

A. June 26, 1956. The first completely successful flight from an operational point of view was on June 26, 1956. However, the pibal run showed that there was a complete shift in wind direction between the surface and 15,000 feet. It must be remembered that, in all cases, these pibal plots are not trajectories, but are vector plots. The trajectories would not be meaningful in this case since the pibals were filled so as to rise 1000 feet per minute and never really got over the ridges. This was a mistake and the balloons should have been filled so as to give very little lift.

Examination of the particle counts immediately reveals one fact that will prove characteristic of all the flights. The flight lines were planned to be roughly as long as the plume length, as suggested by the previous studies, and were hoped to be normal to the plume axis. Whether the latter condition was satisfied can never be learned from the data, but it seems clear that plume widths must be many times plume lengths in an orographic area, if, in fact, we can use the term "plume" at all.

On this flight, the closest line was about five miles from the generator at the center of the line and about 15 miles long. Particles were found in considerable abundance at the maximum altitude flown, 10,000 feet in this case. The particles seem somewhat more abundant in the first few thousand feet above the ground, but clearly no delineation of a "plume" was accomplished. The record of several pibal runs do not suggest excessive meandering of the plume although the rapid ascent rates would tend to mask any such effect.

The second cross-section at about 10 miles suggests that the center of gravity of the counts may be at around 8,000 feet, although this particular traverse is missing from the data. A twenty mile traverse did not serve to delineate any plume and concentrations in excess of 1000 particles per cubic meter were detected at the maximum altitude flown.

A thirty mile cross-section was flown 15 miles from the generator site. Heaviest particle concentrations were detected at the west end of the traverse at 11,000 feet. This seems consistent with the pibal run. A large number of particles reached the maximum altitude flown, 14,000 feet.

B. June 30, 1956. This operation was slightly hampered by having only one airplane available. In addition, light precipitation was falling intermittently throughout the test area and fairly heavy cumulus clouds were around the mountains. The pibal run and flight paths are shown in Figure 9. The results of the analysis are shown in Figures 10 and 11. The flights were thought to have been good ones since the plume, or fragments thereof, were visible on the low ridge about halfway between the generator site and point 11. The flight paths seem to have been fairly well chosen, yet the results are rather disappointing. One seems forced to conclude that either the plume was staying fairly close to the surface or the particles were being washed out. No data exists in any of the operation logs to suggest that everything wasn't operating satisfactorily. Since this was the only situation investigated which would be anything like a situation amenable to cloud seeding, it would have been much more satisfying to find the particles in abundance at the higher altitudes, although the possibility clearly exists that the great bulk of the particles were actually above the altitudes probed in the flights. However, such flights simply were not possible in the light plane that was used.

C. July 3, 1956. Only one plane was used in this flight. The winds were rather light and the plume was observed to hug the ground for about a mile and then rise almost vertically as is suggested in Figure 19. The map of the flights and the pibal, as shown in Figure 12, suggests that a very bad guess was made and that the pibal should have been relied on rather than the appearance of the visible plume. However, the plot of the results, Figure 13, is very interesting.

It suggests that the northern edge of the plume was essentially delineated. If this were the case, and the data are certainly in doubt here, then, if one cares to suggest that the axis of the plume was given by the pibal, then one could conclude that the plume was twenty miles wide at a distance of five miles from the source. This is not inconsistent with the data from the other runs, but it certainly suggests that a lot remains unknown about the nature of turbulent diffusion and dispersion in the vicinity of an orographic feature.

D. July 4, 1956. The flight paths and the pibal for this day are shown in Figure 14. The winds were quite light but better related to the topography than on some of the other runs. The results are shown on Figures 15, 16, and 17. Some mechanical difficulties caused loss of data on the run of Figure 15. This was unfortunate because the lower altitude flight of Figure 16 suggests that Figure 15 might have been very revealing as to just what happened to the large bulk of the particles just over the ridge. Figure 17 suggests that most of the particles stay in a stream after they leave the ridge and only a few are carried to lower levels after traversing the ridge. It is apparent in this run, again, that a 30 mile traverse only 10 miles from the source failed to delineate any plume.

It might be suggested that these tests could be rather badly influenced by contamination during the flights. This would seem to be ruled out by the fact that the area of the impactor strips immediately outside of the orifice area remained quite clear of particles and as soon as the planes left the general test area on their return to the airport the strips were clear. Admittedly the results leave a lot to be desired, but the physical situation proved much more complicated upon analysis than had been anticipated in the planning of the experiment.

VII. GENERAL CONCLUSIONS.

1. In clear air, ground-generated particles reach altitudes of at least 14,000 feet at distances out to at least 20 miles in an area influenced by orographic disturbances with adiabatic lapse rates extending to altitudes in excess of the mountain crest.
2. "Plumes" may be four times as wide as they are long after a relatively few miles. This is for conditions characterized by strong convection and not inversion.
3. The situation may be quite different if clouds are present, particularly if they are raining.
4. The term "targeting" as presently used by cloud-seeders may be practically meaningless and control areas must be selected with extreme care.

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Figure 1. Map of experimental area. The generator site is identified at point 9.

Figure 2. Typical generator site activity.

Figure 3. Fog generator in operation.

Figure 4. Impactor mounting arrangement in Piper Super Cub airplane.

June 26, 1956

Figure 5. Flight paths and pibal plot for June 26, 1956.

Figure 6. Particle counts for June 26, 1956 for flights between points 17 and 10.

Figure 7. Particle counts for June 26, 1956 for flights between points 14 and 18.

Figure 8. Particle counts for June 26, 1956 for flights between points 15 and 16.

June 30, 1956

Figure 9. Flight paths and pibal plot for June 30, 1956.

June 30, 1956

Figure 10. Particle counts for June 30, 1956 for flights between points 3 and 13.

June 30, 1956

Figure 11. Particle counts for June 30, 1956 for flights between points 19 and 18.

July 3, 1956

Figure 12. Flight paths and pibal plot for July 3, 1956.

Figure 13. Particle counts for July 3, 1956 for flights between points 4 and 19.

Figure 14. Flight paths and pibal plot for July 4, 1956.

July 4, 1956

Figure 15. Particle counts for July 4, 1956 for flights between points 1 and 12 on near side of ridge.

Figure 16. Particle counts for July 4, 1956 for flights between points 1 and 12 directly over ridge.

July 4, 1956

Figure 17. Particle counts for July 4, 1956 for flights between points 1 and 18 via point 6.

Figure 18. 2100Z radiosonde temperature soundings for Tucson on the flight days.

Figure 19. Side view of oil fog plume.