*Photogrammetric Technique for Studying Atmospheric Diffusion**

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ABSTRACT: *This paper describes a photogrammetric technique for studying atmospheric diffusion. Three type K-24 aerial cameras, operating simultaneously, photograph fog-oil smoke plumes emitted from a 111-foot stack. The photographs are analyzed by means of a photogrammetric analyzer which simulates actual field conditions. Measurements of the cross-sectional area of the plume, the rate of change of the cross-sectional area of the plume, i.e., its divergence, and a measure of the area covered by the meander of the plume's center line at various distances from the stack are presented.*

I. INTRODUCTION

THE Meteorology Group at the Argonne National Laboratory has developed a photogrammetric technique for obtaining data on atmospheric diffusion. This involves generating smoke consisting of fog-oil particles, injecting it into a stack, and photographing the smoke plume simultaneously from three sides with K-24 aerial cameras. With the information obtained from the photographs, the size and position of selected parts of the plume were determined.

There is a grave deficiency in the literature of studies of this nature since they are expensive and quite difficult, but are nevertheless essential for the verification of existing theories and current empirical practices. In industry, quantitative data on the diffusive capacity of the atmosphere are required for use in the selection of plant sites, for day-to-day operations, and for safeguarding health and property in case of a release of toxic materials [1].

II. EXPERIMENTAL EQUIPMENT

A. THE SMOKE GENERATOR

An Army Chemical Corps M-2 smoke generator was used to produce smoke consisting of fog-oil particles of the order of 0.3μ mean diameter. Smoke, consisting of particles of this size, is a useful visual tracer for studying atmospheric diffusion since it follows very nearly the motions of the air in which it is imbedded.

B. THE EXPERIMENTAL METEOROLOGY STACK

The Experimental Meteorology Stack receives the smoke from the smoke generator and emits it into the atmosphere. An extension pipe is used to couple the outlet nozzle of the M-2 smoke generator to the Experimental Meteorology Stack (Figure 1) at a point $6\frac{1}{4}$ feet above ground. The stack is 111 feet high and has an outer diameter of 18 inches and an inner diameter of 17.5 inches. Although the stack can be varied in height from 111 feet to 41 feet in 10-foot sections, these experiments were conducted with the stack at its full height.

In addition to varying the stack height it is possible to control the flow rate and concentration of the air-smoke mixture. This is accomplished by means of a set of louvered dampers regulating the air flow from a 4,500 CFM New York Blower driven by a $7\frac{1}{2}$ horsepower motor. A Hagan Ring Balance pressure differential recorder and orifice plate provide a continuous record of the flow rate. In carrying out the experiments, measurements were made for three flow rates: 1,500–2,000 CFM, 2,500–3,000 CFM, and 4,200–4,400 CFM.

Information concerning the temperature of the effluent is of importance for determining the height to which the plume will rise, and also its rate of diffusion near the stack [2, 3]. In the Experimental Meteorology Stack, temperature is measured by means of two pencil-type copper constantan thermo-

* Work performed under auspices of the Atomic Energy Commission.

couples inserted into the stack; one at 31 feet above ground and the other ½ foot from the top. Once during each minute the temperature at the 31-foot level is recorded for 40 seconds, and the temperature at the top level for 20 seconds alternately on a Minneapolis-Honeywell single point potentiometer recorder.

C. SMOKE PHOTOGRAPHY

Photographs of the smoke plumes were taken by three K-24 aerial cameras equipped with 161 mm., f 4.5 lenses. The K-24 camera uses $5\frac{1}{2}'' \times 56'$ film, and each picture frame is nominally $5'' \times 5''$. Two of the cameras were oriented facing each other with their optical axes elevated 30 degrees with respect to the horizontal plane, and photographed the smoke plume from opposite sides. These cameras are designated as the *A* and *B* cameras (see Figure 2). The third camera, designated as the *C* camera, was placed 40 feet from the stack and at a point equidistant to the two other cameras. It was directed vertically thus photographing the bottom of the plume. The plane containing the stack's axis, the *C* camera axis, and the midpoint of the 400-foot baseline is denoted as the vertical "datum" plane.

Before each run, camera locations were selected to allow the smoke plume to lie as close as possible to the datum plane. The area around the smoke stack has been surveyed, and the camera locations have been determined for 18 different 400-foot baselines. Consecutive baselines make an angle of 20 degrees with each other. The midpoints of the baseline lie on a circle having a radius of 80 feet with the stack as center.

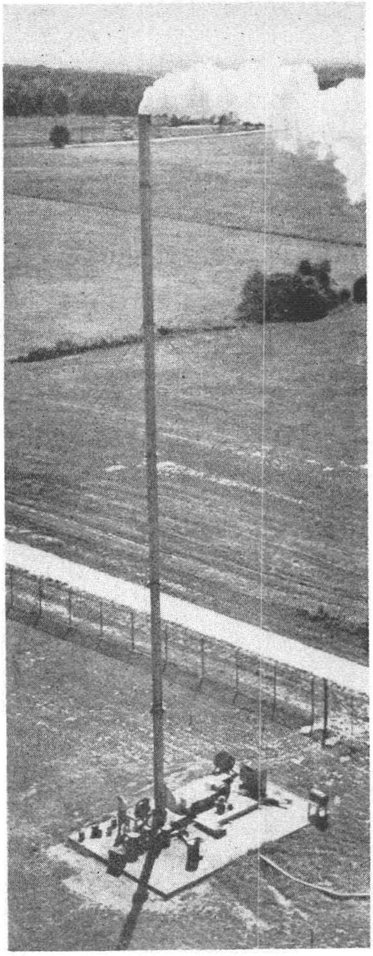

FIG. 1. The Experimental Meteorology Stack.

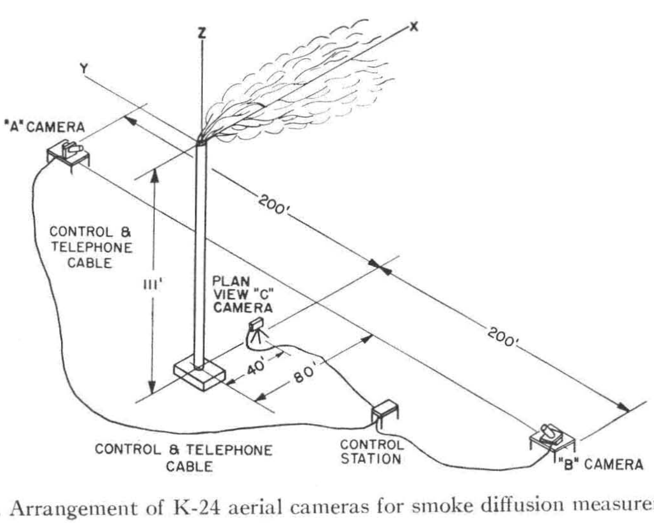

FIG. 2. Arrangement of K-24 aerial cameras for smoke diffusion measurements.

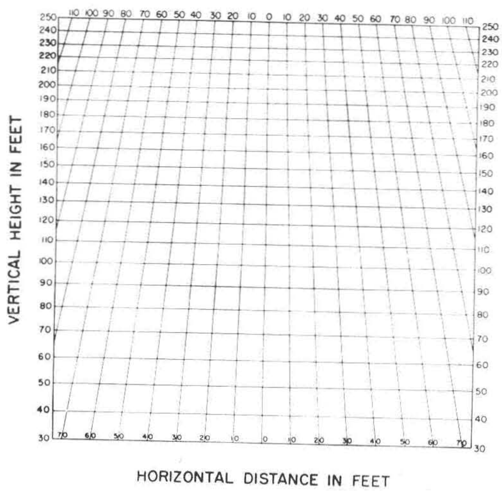

FIG. 3. Grid in the focal plane of the K-24 aerial camera located in the A or B position. The indicated values are true only for smoke lying in the datum plane. The distance from each camera to the datum plane is 200 feet and the elevation angle of each camera's axis is 30 degrees.

In order to facilitate the orientation of the *A* and *B* cameras and the analysis of the photographs the grid representing the datum plane shown in Figure 3 was constructed. The vertical lines converge and the horizontal lines are non-uniformly spaced on this grid because the optical axes of the *A* and *B* cameras were elevated 30 degrees. When the grid is projected on a vertical screen with a projector tilted 30 degrees with respect to the horizontal plane, the grid becomes rectangular. A transparent positive of the grid was sandwiched between two thin glass plates placed against the film in the camera. In orienting the *A* or *B* camera, the stack is made to lie along the appropriate 80-foot line. For positioning the *C* camera, a transparent copy of Figure 4 sandwiched between thin glass plates placed against the film is used. The *C* camera is positioned by placing the image of the stack along reference marker *R-R*.

The three cameras are synchronized electrically by means of a timer and an arrangement of relays. For this study a 15-second time interval between photographs was used, but the equipment allows selection of the time interval from 1 to 15 seconds. Although the photographs were taken automatically, it was necessary to station a person near each camera to advance the film manually. To facilitate the analysis, an Esterline-Angus Time of Event recorder was used to record automatically the fact that each camera took a photograph. One-second time markers were also recorded on the same chart. Thus, a complete record was made of the time and number of the photographs taken by each camera.

D. METEOROLOGICAL MEASUREMENTS

Meteorological conditions have a profound effect on the rate of atmospheric diffusion. The most important variables are the speed and direction of the wind and the atmospheric thermodynamic stability as indicated by the variation of temperature with height [4]. For a study of this kind it is necessary to measure wind and stability and it is desirable to measure a number of auxiliary weather variables. An ample amount of meteorological data was available for this work since the following meteorological measurements are recorded continuously at the Meteorology Laboratory:

(1) the wind speed and direction at six levels from $6\frac{1}{2}$ to 150 feet,
(2) temperature at five levels from $5\frac{1}{2}$ to 144 feet,
(3) dew point temperature at five levels from $5\frac{1}{2}$ to 131 feet,
(4) solar radiation on a horizontal surface,
(5) net radiation flux,
(6) soil temperature at seven levels from 1 cm to 29 feet, and
(7) other conventional meteorological variables such as precipitation and pressure.

The meteorological equipment used to make these measurements is described elsewhere [5, 6].

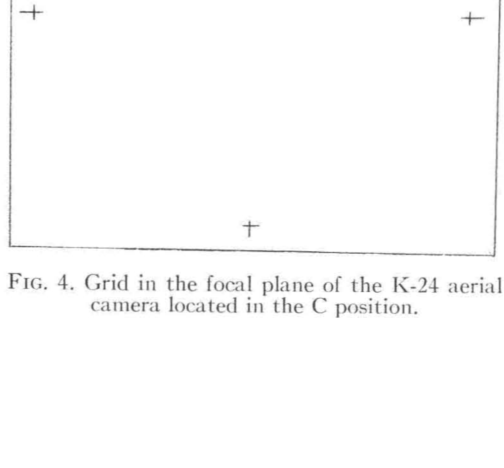

FIG. 4. Grid in the focal plane of the K-24 aerial camera located in the C position.

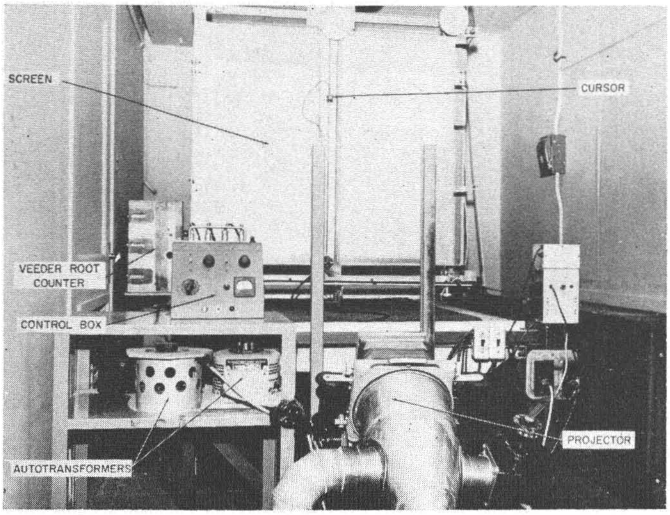

FIG. 5. The Photogrammetric Analyzer.

III. DATA ANALYSIS

A. THE PHOTOGRAMMETRIC ANALYZER

A photogrammetric analyzer (see Figure 5) for reducing the photographs was designed and constructed at the Argonne National Laboratory. It consists of the following components:

(1) Two Elwood projectors equipped with 161 mm., f 4.5 lenses on rack and pinion mounts. One projector is located behind the screen and is not visible in Figure 5. The angle of the mounts is adjustable.

(2) A 39″×46″ translucent screen mounted vertically on a table. The screen is composed of crystalene prepared tracing paper (N 198LX manufactured by the Keuffel and Esser Company), backed by a translucent beaded screen (type WDL manufactured by the Klearcite Screen Company).

(3) A cursor for locating any point on the screen.

(4) An electrical control unit for driving the screen perpendicular to itself and for driving the cursor vertically and horizontally. In addition, the control unit regulates the light intensity of the projector by autotransformers and contains a number of switches for operating the equipment.

(5) Three Veeder-Root counters for reading out the numerical values of the X, Y, and Z positions of any point on the screen. (A Cartesian coordinate system is used. The origin is at the top of the stack; X is the horizontal distance from the stack in the datum plane, Y is at right angles to the datum plane, and Z is the distance upward in the datum plane.) The Veeder-Root counters are driven by synchro receiver motors which are coupled to synchro transmitter motors attached to the screen and cursor.

B. PROCEDURE FOR REDUCING THE DATA

In analyzing corresponding photographs of the A and B cameras, the two images were projected simultaneously on opposite sides of the translucent screen. The film was adjusted so that the zero lines of the grids on the two photographs and the stack images coincided. It was further necessary to adjust the magnification of the projected images so that the distance between the stack and zero line corresponded to a reading of 80 feet as shown by the appropriate Veeder-Root counter. This was accomplished by changing the distances between the projectors and the screen.

With the analyzer properly aligned the cursor was moved to a point corresponding to a position in the field of 2.5 feet from the stack. The tops of the plume as seen by the A and B cameras at this distance were brought into coincidence by moving the screen, and the coordinates were recorded. Then the coordinates of the coincidence point for the bottom of the plume were determined. The process was repeated for a distance of 5.0 feet from the stack and for distances at intervals of 5 feet for the remainder of the plume.

For reducing the data of the vertically pointing C camera only one horizontally mounted projector was used. Through the use of markings on the film the magnification of the projected image was adjusted so that the cursor displacements, indicated by the Veeder-Root counter, were in calibration for points in the horizontal plane through the top of the stack. Since ordinarily the smoke plume did not lie in this plane but fluctuated about it, account had to be taken of this in the analysis. Therefore, before making measurements, the height of the plume's center line was determined from the A and B camera photographs. The screen was moved to correspond to the height of the horizontal plane intersecting the plume's center line at the distance under consideration and the coordinates of the edges of the plume as seen by the camera were recorded. Measurements were made at distances from the stack of 2.5 feet, 5.0 feet, and at interval-distances of 5.0 feet thereafter.

C. COMPUTATIONS

The measurements obtained from the photographs were manually punched on IBM cards and processed on an IBM 650 computer. In the analysis it was assumed that any intersection of the plume by a vertical plane was an ellipse. Since the analysis technique determined a quadrilateral in which the ellipse was inscribed, corrections were necessary to reduce this inaccuracy. The computer was programmed to provide the following parameters:

(1) Horizontal width—the horizontal dimension in the plane perpendicular to the center line at the point of measurement.

(2) Thickness—the plume's dimension at right angles to the horizontal dimension in the plane perpendicular to the plume's center line. If the center line deviated from the horizontal plane, the direction of the thickness length deviated from the vertical.

(3) Cross-sectional area—the area formed by the intersection of the plume with the plane perpendicular to its center line. Since the area is assumed to be elliptical, it is calculated by means of the expression

$$\frac{\pi \times \text{thickness} \times \text{horizontal width}}{4}.$$

(4) Height of center line above the stack.

A number of other pertinent plume parameters may be derived from these data as seen below.

D. SHORTCOMINGS OF THE TECHNIQUE

The photogrammetric technique described in this paper has provided useful data concerning the diffusion of a smoke plume. It does, however, suffer from a number of shortcomings. First, data cannot be obtained when there is an overcast because the contrast between the plume and sky is too small. However, with the use of colored smoke grenades and color photographs, usable photographs may be obtained under these conditions. It is desirable that measurements of the smoke plume be made to greater distances from the stack. This is quite feasible under stable conditions when the plume remains intact for many thousands of feet, but in the daytime when atmospheric mixing is pronounced, the plume diffuses very rapidly and may even come to the ground within one or two stack heights. Under these conditions, the plume is diffuse thus making the delineation of its boundary difficult. Finally, the analysis technique is quite laborious, though, with the use of automatic data reduction techniques, this difficulty can be eliminated.

IV. Sample of Analyses

A series of eight runs involving over 1,500 photographs were analyzed. These were made in the daytime under relatively unstable conditions, i.e. the rates of diffusion were high. The results of some of these studies are shown in Figures 6 to 8.

In each of these figures two curves are shown. These are called range curves since one represents the highest average values, and the other the lowest average values. Standard deviations are indicated by the vertical lines intersecting the curves.

Figure 6 shows the variation of the plume's cross-sectional area along the center line. The ratio of the cross-sectional area of the plume to that of the stack may be considered as a measure of atmospheric dilution [7]. Under this assumption, the upper curve indicates that the average concentration at 20 feet, along the plume's center line, is 2 per cent of that at the stack, and at 70 feet, 0.7 per cent; the lower curve indicates the corresponding percentages to be 4.3 per cent and 1.7 per cent.

The divergence of the plume's cross-sectional area may be defined as $1dA/AdS$ where A is the cross-sectional area and S is the distance along the plume's center line. This parameter indicates the rate at which the dilution changes. It is evident from the divergence curves (Figure 7) that the variation in divergence among the runs is relatively small, since corresponding points on the two curves are within one standard deviation. A characteristic feature of these curves is the sharp drop in divergence from high values near the stack to the nearly constant values beginning at about 20 feet or 13 stack diameters.

One may view the process by which gaseous materials within the atmosphere are diffused as consisting of two components:

(1) the diffusion of gaseous material about the center line of the plume due to small eddies, and

(2) the diffusion due to larger eddies which gives the plume a serpentine appearance or causes the entire plume to change position [8, 9]. A measure of the diffusion due to the larger eddies—the meander—may be defined as the elliptical area containing 95.55 per cent of the points of intersection of the plume center lines with a sphere of given radius centered at the stack. The calculation was made for spheres having radii of 2.5 feet, 5 feet, and multiples of 5 feet for the remainder of the visible plume. Curves showing this meander area for runs having the largest and smallest meander values are shown in Figure 8. Percentage-wise the variation of the meander area among the runs was larger than that for other variables. For example, at 70 feet the range was from 1,000 to 9,000 square feet.

V. Concluding Remarks

Only a few results of the analysis are presented above. Nevertheless, the photogrammetric technique described in this paper has provided some of the most detailed measurements available on the behavior of a smoke plume within several hundred feet from the

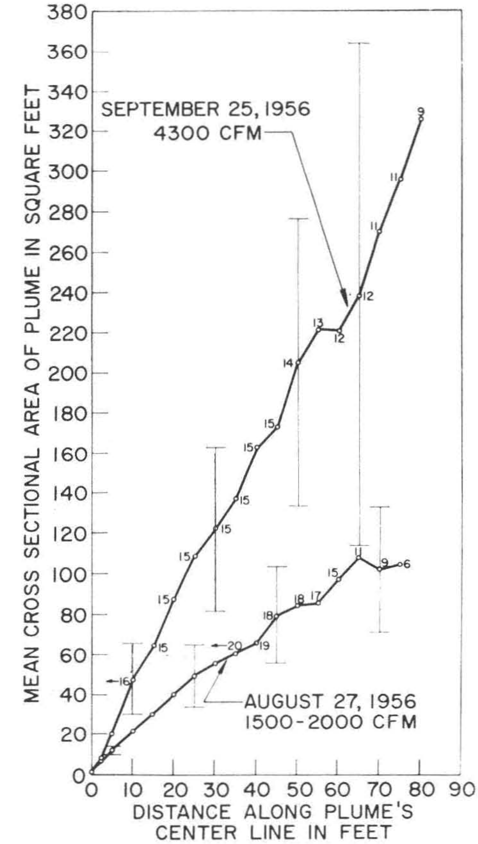

FIG. 6. Range curves of the mean cross-sectional area of the plume as functions of the distance along the plume's center line. Numbers refer to the number of cases used in computing the average. Unnumbered points have the same number of cases as the nearest numbered point.

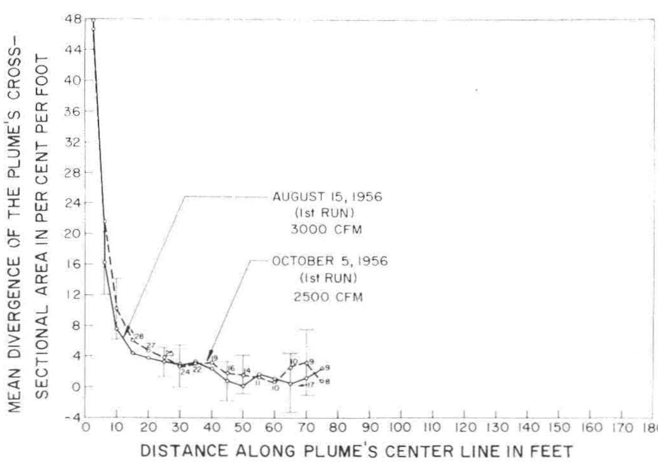

FIG. 7. Range curves of the mean divergences of the cross-sectional area of the plume in per cent per foot as functions of the distance along the plume's center line. See Figure 6 for the meaning of the numbers.

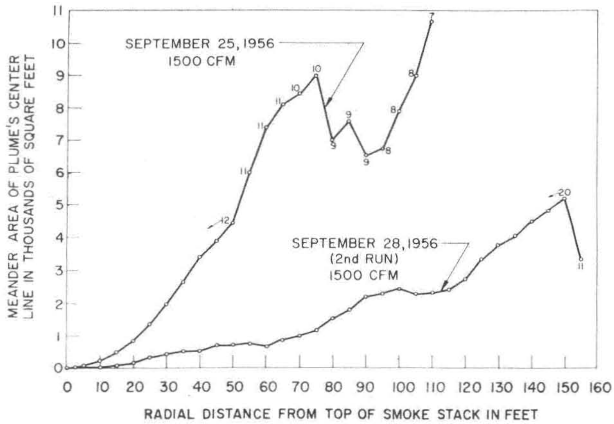

FIG. 8. Range curves of the meander area of the plume's center line as functions of the radial distance from the top of the smoke stack. See Figure 6 for the meaning of the numbers.

source. Many more different types of measurements are necessary. For example, more data are needed on the height of the plume rise as a function of meteorological conditions and of effluent temperature. A stack heater is now nearly completed to provide these data. Also an automatic film processing unit is now under design which will not only substantially reduce the analysis time, but will also eliminate some of the inaccuracies inherent in the analysis technique.

VI. ACKNOWLEDGEMENTS

In most meteorological field experiments the assistance of many individuals is necessary. Thanks are due to Dr. John E. Rose, Director of the Radiological Physics Division, who suggested the design for the photogrammetric analyzer and to Mr. Richard F. Selman who constructed it. Dr. Horace R. Byers of the University of Chicago, Meteorology Department, offered helpful counsel on many occasions during the course of this project. The contributions of Dr. Glenn R. Hilst of Travelers Insurance Company and Dr. Roderick D. M. Clark [10] of McDonnell Aircraft Company who worked on the design of the stack and photographing techniques during the early phases of the project are gratefully acknowledged, as is the invaluable assistance of Frank C. Kulhanek and Gunther A. Zerbe rendered during the field experiments.

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