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AFCRL 468

Air force surveys in geophysics

No. 134

Area-dosage relationships and time of tracer arrival in the Green Glow Program

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OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
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AREA-DOSAGE RELATIONSHIPS AND TIME OF TRACER ARRIVAL IN THE GREEN GLOW PROGRAM

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May 1961

Project 1448
Task 86441

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ABSTRACT

An empirical relationship between the area in which a given dosage is equalled or exceeded and the value of the dosage itself is developed using Green Glow data. It is found that the logarithm of the area is nearly a linear function of the logarithm of the dosage divided by the source strength and multiplied by a representative wind speed. These results differ only slightly from similar results obtained from Prairie Grass data.

Observations of the time of first arrival of the tracer near ground level at distances of 8 and 16 miles from the source indicate that the tracer material which first arrives has travelled with a wind speed greater than the surface wind (about 15 ft). It would be necessary to have wind speed measurements between 50 and 100 ft above ground in order to estimate the time of first arrival at these distances even though the source is no higher than 15 ft.

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PREFACE

During the Summer of 1959 a series of diffusion experiments, jointly sponsored by the U.S. Air Force and the U.S. Atomic Energy Commission, was conducted on the Hanford reservation of the Commission in southeastern Washington. The program had been nicknamed Green Glow, a name which reflects the use of a pigment tracer that exhibits a green fluorescence under ultraviolet light.

The following organizations participated in the program:

1. Hanford Laboratories Operation, Hanford Atomic Products Operation, General Electric Company
2. Texas A & M Research Foundation
3. 6th Weather Squadron, 4th Weather Group, Air Weather Service
4. Geophysics Research Directorate, Air Force Cambridge Research Center

The objective of the experiments was to determine, as a function of meteorological conditions, the horizontal and vertical diffusion patterns of a particulate tracer emitted continuously from a source near ground level. The horizontal patterns were sought out to a distance of about 16 miles and the vertical patterns to a distance of about 2 miles.

The purpose of this Survey is to provide answers to the following specific questions of significance to the Air Force:

1. For a given mean dosage of a pollutant, what is the size of the area downwind from the source within which the given mean dosage is exceeded?
2. What type of wind information is necessary to determine the time of first arrival of a tracer at distances of the order of 8 to 16 miles?

Following an introductory section on a description of the site and the experimental procedures, Sections 2 and 3 will contain answers to the two questions given above. The answer to the first question, in particular, is an abbreviation of a more detailed analysis to be included in a Geophysical Research Note now in preparation. The diffusion and meteorological data and a more complete description of the equipment and the field and laboratory procedures will be included in a forthcoming Geophysical Research Paper.

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AREA-DOSAGE RELATIONSHIPS AND TIME OF TRACER ARRIVAL IN THE GREEN GLOW PROGRAM

1. A DESCRIPTION OF THE EXPERIMENTAL PROGRAM

1.1 Characteristics of the Site

The Green Glow program was conducted during June, July, and August of 1959 at the Hanford reservation of the U.S. Atomic Energy Commission near Richland, Washington. This area is located in southeastern Washington in a semi-arid climate. The reservation is roughly bounded on the north and east sides by the Columbia River and on the south and west by the Rattlesnake Hills and Yakima Ridge. The maximum height of the mountains approaches 3500 ft above sea level, whereas the major part of the reservation lies about 400 to 700 ft above sea level. Figure 1 is a topographic map of the area showing the location of the sampling grid and other observing points to which reference will be made later.

The sampling grid is indicated in Fig. 1 by segments of circles all centered about the point marked "Source." The tick marks along the arcs show the positions of the samplers. Within 4 miles of the source the ground is relatively flat, with slightly rolling hills or ridges a bit more frequent in the region between 4 and 16 miles of the source. The most prominent feature of the topography within the sampling grid is the drop in general level of terrain about 4.5 miles southeast of the source.

Most of the reservation is covered by desert grass and sagebrush. The sagebrush often grows to a height of about 4 or 5 ft, but has an average height of about 3 ft.

The grid was laid out to take advantage of the nighttime drainage wind, which is a climatological feature of the area. On clear nights

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(Authors' manuscript approved 4 April 1961.)

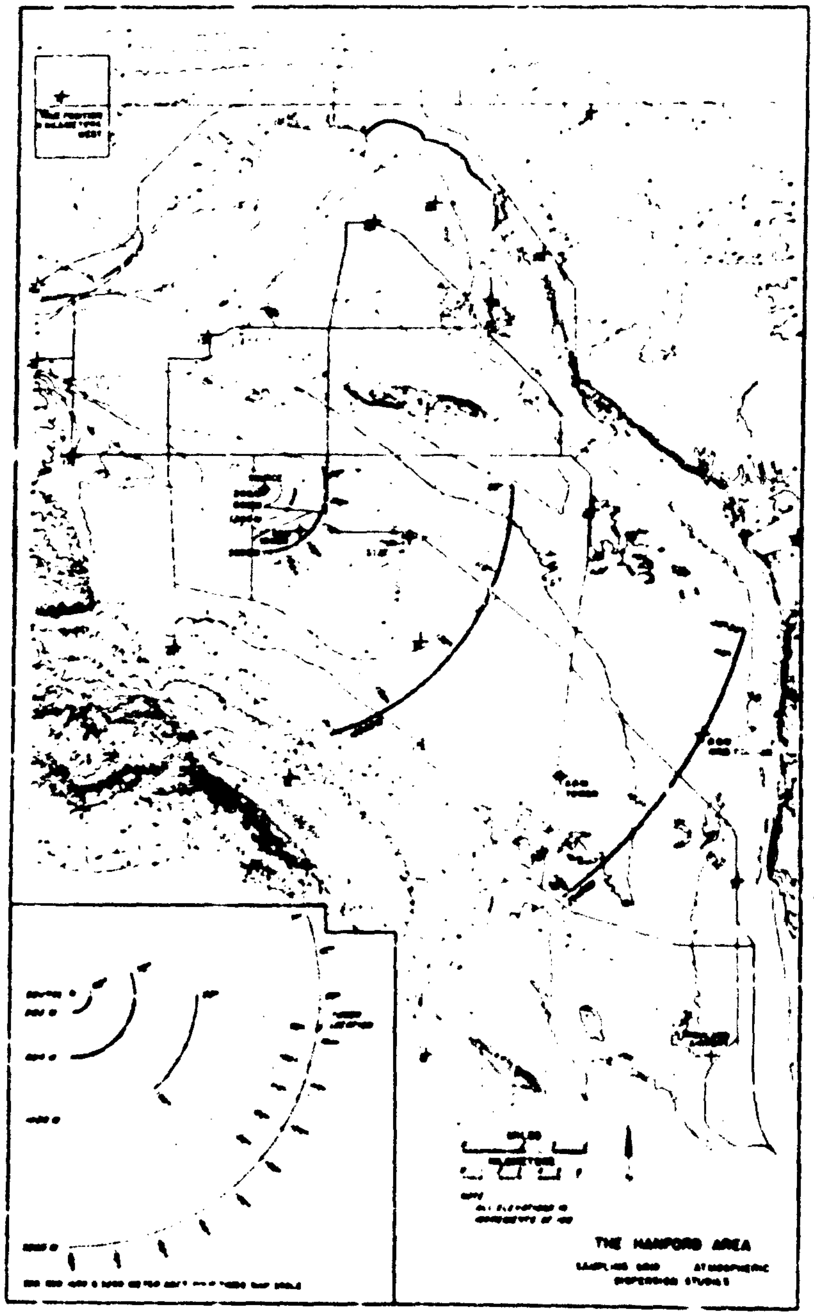

FIG. 1 Map of Hanford reservation and sampling network

with relatively stagnant weather patterns (features common to this area in summer), fairly persistent winds blow from northwest to southeast, beginning in late evening and continuing until after sunrise.

1.2 Experimental Design

The design of the diffusion experiments to be described was a joint venture undertaken by personnel of the Geophysics Research Directorate and the Hanford Laboratories Operation. The conduct of the diffusion experiments and the reduction of the diffusion data were the responsibility of the Hanford Laboratories Operation. Also participating in these phases of the program were personnel of the Geophysics Research Directorate, the Texas A & M Research Foundation, and the Air Weather Service.

The samplers were laid out along arcs according to the plan shown in Table 1. These samplers were all 1.5 meters above ground.

TABLE 1. Characteristics of sampling network

Arc	Distance (km)	Distance (miles)	Sampler Spacing (degrees)	Arc Length (degrees)	Flow Rate (ℓ sec^{-1})
1	0.2	0.12	2	90	0.148
2	0.8	0.50	2	90	0.153
3	1.6	0.99	1	48	0.232
4	3.2	1.99	1	70	0.513
5	12.8	7.95	0.5	75	1.963
6	25.6	15.91	0.25	37.25	1.980

During the first few experiments participating personnel found that the original layout of samplers could be improved to obtain better definition of cloud width. Therefore, between Runs 10 and 11, 22° of sampling arc were added to the north end of the 200-m arc, 20° to the north end of the 800-m arc, and 19° to the north end of the 3200-m arc. These changes were effected by removing like distances from the southern ends of these arcs. These changes did result in better cloud definition. They are incorporated in Fig. 1.

In addition to the ground sampling network, towers were erected at five points on each of the four inner arcs. These towers were located at azimuth angles 98°, 106°, 114°, 122°, and 130°. (See insert, Fig. 1.) Each tower had 15 samplers with the top level increasing from 27 m on the 200-m arc to 42 m on the 800-m, and to 62 m on the 1600- and 3200-m arcs.

To determine the arrival time of the pigment on the two outer arcs, drum samplers were placed at various positions on these arcs. These drum samplers provide a time record of the deposition of pigment on a revolving drum; and this information can be used to determine the length of time it takes the pigment to travel from the source to the sampler. Some results obtained from these samplers will be discussed in Section 3.

1.3 Experimental Procedures

The tracer used in this study was a fluorescent zinc sulfide pigment (U.S. Radium Corp. No. 2210) which has a geometric mean particle diameter of about 2.5 microns. The pigment was suspended in a tank filled with water and emitted simultaneously from two dispensers (Todd Insecticidal Fog Applicators) placed side by side on the ground. The nozzles of the dispensers had to be pointed upward to allow the pigment to clear nearby sagebrush. As a result, the effective source height was about 3 to 5 m. Between 0.6 and 3.6 kg of pigment were emitted during each release, the total emission time being 30 minutes on almost all of the releases.

The pigment was collected on membrane filters about 2 inches in diameter in the sampler positions given in Table 1 and on the towers described in Section 1.2. Air was drawn through the filters at different rates on each arc, the rates increasing with distance from the source, again as indicated in Table 1. Flow rates on the towers were the same as on the ground samplers at the respective arcs.

After the pigment was emitted for 30 minutes, the dispensers were shut off; but the samplers were turned off only after a suitable delay to allow the cloud of particles to fully pass the respective arcs. The filters were collected, new ones inserted to prepare for the next release, and the exposed filters taken to a laboratory for assaying. This assaying was accomplished by exposing each filter to a source of alpha particles. When the pigment particles are struck by alpha particles, the ensuing light-flashes are detected and accumulated on a counter.

The original assaying system was calibrated by comparing the number of scintillations obtained from selected filters with visual counts obtained with the aid of a microscope. The results were then expressed in terms of numbers of particles on the filters. However the system did not provide the accuracy required because of the uncertainties in the microscope counting. In addition the protracted high volumetric sampling rates at the outer arcs caused considerable foreign matter to be collected on the filters, introducing additional complexities in the assaying procedures. Consequently further development of the sample assaying system was required.

The sample assaying system finally used was as follows. When the filters were relatively free of dust, the zinc sulfide particles were activated on the filter by a fixed-strength source of plutonium alpha particles and the resulting scintillations counted as described earlier. For dusty filters and for calibrating the assaying technique described above, the filters were dissolved and exposed to white light and the resulting phosphorescence was measured in an automatic liquid scintillation counter. A correction factor for the effect of dust in the sample was determined from turbidity measurements on the vial with a calorimeter.

In all, 27 releases were made during the Green Glow program, all at night. Because wind shifts occasionally occurred during a run, which carried the cloud outside the sampling network, not all the runs were considered successful. Almost no useful information was available from 3 runs while several more have only limited usefulness. However the goal, a minimum of 15 useful runs, was exceeded.

1.4 Meteorological Measurements

In order to relate the results of the dispersion tests to ambient meteorological conditions, as well as to estimate the amount of time necessary for the pigment to traverse the sampling network, certain meteorological data are also necessary. These data were provided by several installations. Near the source, winds and temperatures at 50-ft intervals were available from the 410-ft meteorological tower. In addition a 78-ft portable mast provided data on wind and temperature at six levels to give a better picture of the atmosphere near the ground. Both towers were operated by General Electric personnel.

Two complete micrometeorological stations were operated by the Texas A & M Research Foundation at distances of approximately 2 and 13 miles from the source.

Besides wind and temperature, wet-bulb temperatures were available from eight heights up to 32 m at each Texas A & M station. Measurements of radiation, soil heat flux, soil temperatures, and the standard weather observations were also made at these locations.

The General Electric Company also operated a wind station network consisting of wind speed and direction sensing instruments mounted about 23 ft above the ground. The wind readings were automatically transmitted to a building near the dispensers, where they were recorded. In Fig. 1 the locations of these stations are shown by the large crosses with arabic numbers beside them.

Upper-air observations were provided by a rawinsonde team from the 6th Weather Squadron, 4th Weather Group, Air Weather Service. Their station was located about 4.5 miles from the source and is marked as GMD-1 Station in Fig. 1. In general the plan called for a balloon to be released about 1 hour prior to the planned emission time, one released at emission time, and one released 1 hour after emission. Data were taken up to 8000 ft during each of these releases.

2. PREDICTION OF AREA-DOSAGE

2.1 Introduction

The purpose of this section is to describe and summarize the results of an analysis designed to obtain estimates of the area within which a specified level of pollution would be exceeded downwind of a continuous point source of pollution. The method of analysis is essentially the same as that used by Elliott[2] in studying the same problem using data collected during Project Prairie Grass.[1]

Strictly speaking, the results of this study are applicable only to the Hanford reservation and only for a pollutant similar to the zinc sulfide tracer used. However, comparisons with the Prairie Grass results indicate that some generalizations are possible. These will be discussed later.

2.2 Method of Analysis

The values of dosage observed at each sampler for each arc were plotted on a grid proportional to the actual sampling grid used at the Hanford site. These values were plotted for 18 of the 27 tracer releases made. The other nine releases were rejected for a variety of reasons, the most common being failure of the tracer to remain within the sampling network during the experiment.

After these values of dosage were plotted, the highest values observed on selected arcs were determined by inspection. The arcs selected were those approximately 1, 2, 8, and 16 miles from the source. Isopleths of these dosages were drawn; and the area within these isopleths was then measured with a planimeter. Figure 2 shows a typical pattern obtained for the peak dosage at 16 miles.

Since differing amounts of pigment were released during different releases, observed values of dosage (D) were divided by the total amount of pigment emitted (E). During the analysis of Prairie Grass data, it was found that the inclusion of the wind speed in the final prediction scheme resulted in significant improvement. (An examination of Sutton's equation suggests that this would be the case.)

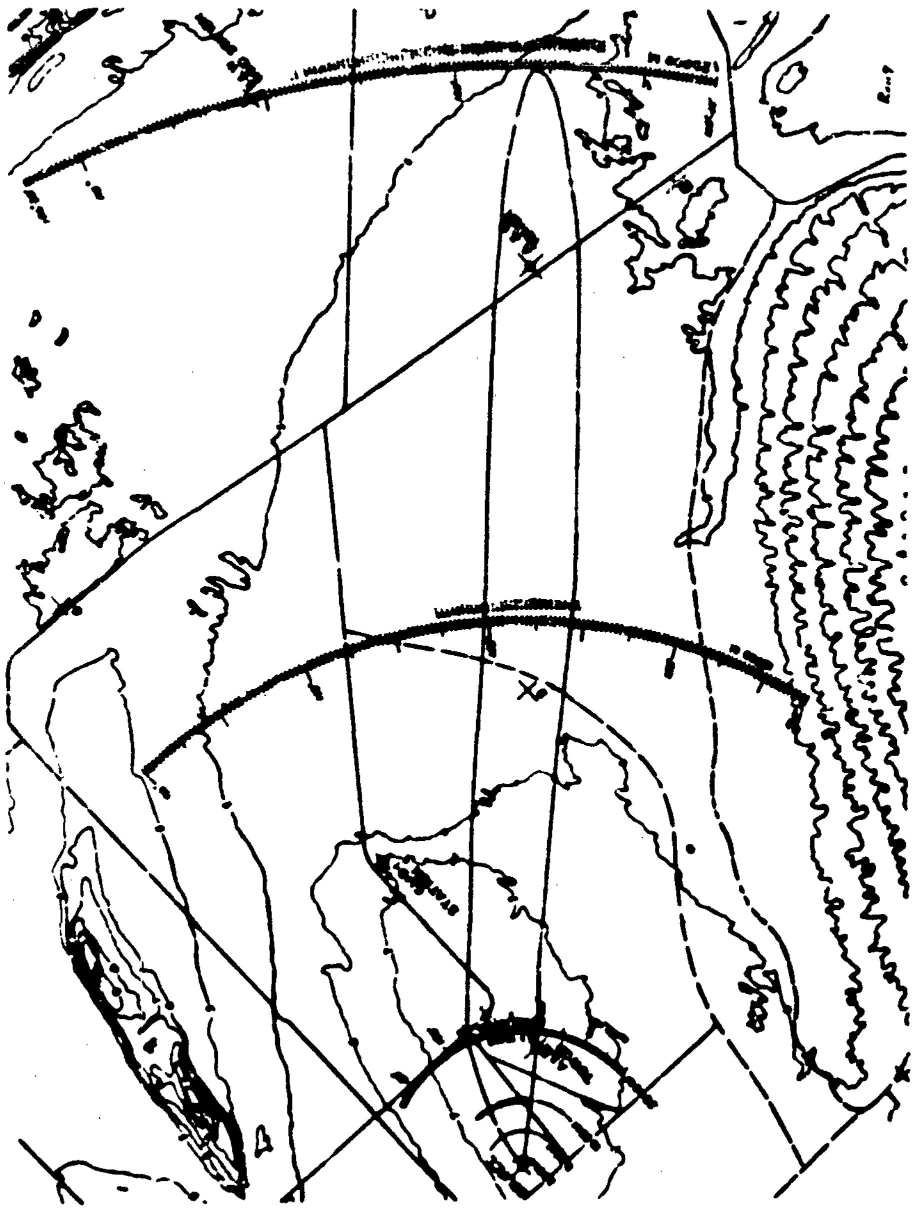

FIG. 2 Typical isopleth of dosage

Therefore, the values of D/E were multiplied by the wind speed (U) observed at 2 m above the ground. Finally the values of DU/E were plotted on logarithmic paper against the values of area (A) enclosed by D.

2.3 Results

Figure 3 shows the results of this analysis. The values of A are in (meters)^2 and the values of DU/E are in (meters)$^{-2}$. Results of the Prairie Grass analysis are also shown for comparison. (Only those points for nighttime gas releases at Prairie Grass are presented.) One can see that the values from each set of experiments tend to lie along a straight line although the lines are not the same for the two different sets. In order to see this more clearly, least squares regression lines were computed for both sets of points. These lines are indicated in Fig. 3. Their equations are

$$\text{(Green Glow)} \qquad A = 10.3\left(\frac{DU}{E}\right)^{-0.95} \tag{1}$$

and

$$\text{(Prairie Grass)} \qquad A = 33.1\left(\frac{DU}{E}\right)^{-0.91} \tag{2}$$

The exponents of Eqs. (1) and (2) are almost the same and, in fact, no statistically significant difference can be ascribed. The fact that the two lines do not lie along one another is not too surprising in view of the differences between the two sets of experiments. Differences in vegetation, terrain, tracers used, and source height could all lead to differences in the results. The fine particles used as a tracer at Green Glow could give different rates of deposition compared to the gas tracer used at Prairie Grass. In addition, when measurements from towers were available at Green Glow, it was frequently found that the maximum D observed along a given arc was

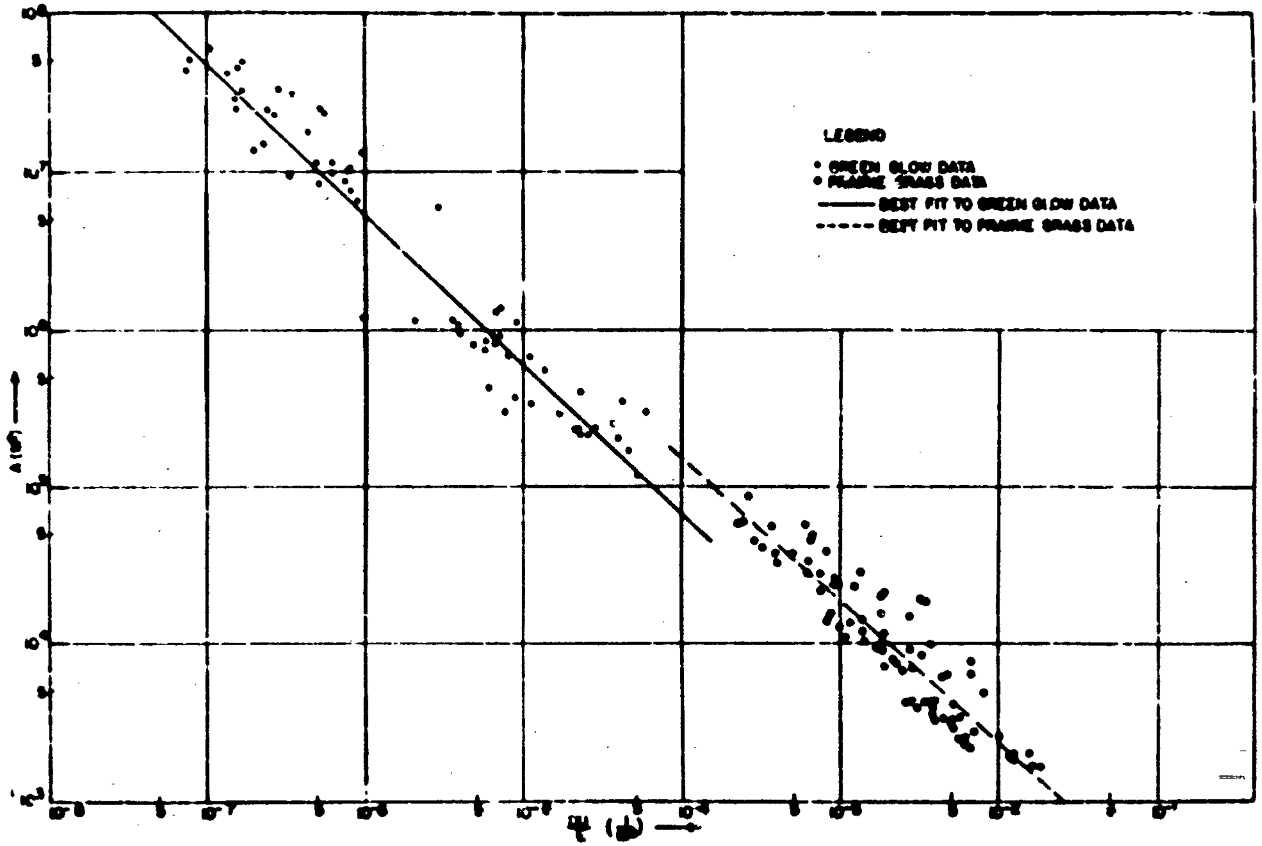

FIG. 3 Area vs. DU/E showing Green Glow and Prairie Grass results

not near the ground, as it appeared to be at Prairie Grass, but was found at greater heights. This fact would also contribute to differences between Green Glow and Prairie Grass. However the significant fact is that the lines are essentially parallel, indicating that basically the effects of the atmosphere are the same in the two experiments.

2.4 Discussion of Accuracy

It is not sufficient to simply consider the regression line (or prediction equation) without considering some measure of the accuracy of the prediction.

The standard error of estimate of the regression line computed from the Green Glow data indicates that the range 0.60 to 1.66 times the predicted area embraces the observed area about two-thirds of the time. Similarly the range 0.36 to 2.76 times the predicted area embraces the observed area about 95 percent of the time. These ranges may seem extreme, but one must recall that the total range of areas observed was almost 3 orders of magnitude. These limits are somewhat larger than the comparable limits about the Prairie Grass line, due in part to the less accurate determination of the values of D at the outer arcs and the greater difficulty in determining A. Section 2.6 "Appendix" contains an example of the use of this scheme in actual practice.

Another factor affecting the relationship between A and DU/E is the atmospheric stability. Generally, those points derived from measurements made in the most stable conditions tended to fall above the regression line (larger areas for the same values of DU/E) while those derived from less stable conditions tended to fall below the regression line (smaller areas for the same values of DU/E). This result was even more evident in the Prairie Grass data. However, with the Green Glow data, at great distances from the source (8 and 16 miles) the separation of points by stability was not so great as with the points closer to the source. This may be a reflection of the greater difficulty in defining a relevant stability parameter to apply during much longer travel times involved at Green Glow. It was not judged that the slight improvement in prediction made by including a stability parameter warranted the inclusion of it in this scheme. Furthermore, to apply such a correction one would need measurements of vertical temperature gradient which are not normally available at standard weather stations. These results do indicate that further study of the affects of stability on clouds traveling for long distances would be helpful.

In addition to defining the area enclosed by a given isopleth, it would be highly desirable to be able to specify the shape of this area. Figure 2 suggests that the shape is somewhat elliptical and this appears to be a fair approximation. Thus, if one can determine the maximum distance downwind of the source that a given value of D will reach, one can obtain a crude estimate of the maximum width of the isopleth by dividing the predicted area by the quantity ($\pi/4$ x maximum downwind distance). Results of this study indicate that such a procedure would, on the average, overestimate the maximum width by about 10 to 20 percent but individual values could be in error by as much as +60 or 70 percent to -20 percent. This maximum width is found about halfway between the source and the maximum downwind distance.

At best this method of determining the shape is crude and should be used with caution. Furthermore, results of Prairie Grass indicate that in unstable conditions or with short emission times, the shape of the area may be far from elliptical and the method should not be used. Also, if the mean wind direction is not constant with distance, the shape will be distorted and the results of this method quite misleading. All in all, this scheme for estimating the shape can at best serve only as a rough guide.

2.5 Extension of Results to Other Conditions

The question of whether these results can be applied in other conditions and for greater distances than those involved in this study must be considered. In the following discussion the views expressed are only educated guesses based upon the authors' experiences with diffusion data.

The similarity of the exponents in Eqs. (1) and (2) leads one to have some confidence in further extrapolation. Without much doubt we feel the results would be valid to distances of 30 to 40 miles. With somewhat less confidence we feel the results should be a fair guide out to distances of 50 to 60 miles. Beyond this we are reluctant to make any statement. Remember that all these extrapolations are based upon the assumption that the wind blows in about the same direction and speed over the whole distance, the terrain remains roughly uniform, the general level of vegetation remains about the same, and the pollutant has about the same characteristics as the tracer used. In reference to the matter of vegetation, it may be that, other things being the same, a wind speed (U) measured at some lower elevation (say 1 m) might produce a better estimate of the area if the vegetation height is on the order of a few centimeters rather than about 1-m high as at the Hanford reservation.

A point which must be emphasized is the matter of terrain. Our present knowledge of wind regimes in mountainous areas is meager. All the above conclusions may be poor predictors at best if the pollutant cloud enters or is released in fairly rough terrain. Funneling effects and local circulations can so distort the wind field and subsequent diffusion patterns that any of our current diffusion models would be inadequate to describe the results.

2.6 Appendix

This gives an example of the use of the results of this section in determining the area enclosed by a given isopleth of dosage. Figure 4 shows the regression line (Eq. [1]), of Fig. 3, replotted without the data points. In addition the slanting dashed lines represent the plots of the limits of one standard error. In other words about two-thirds

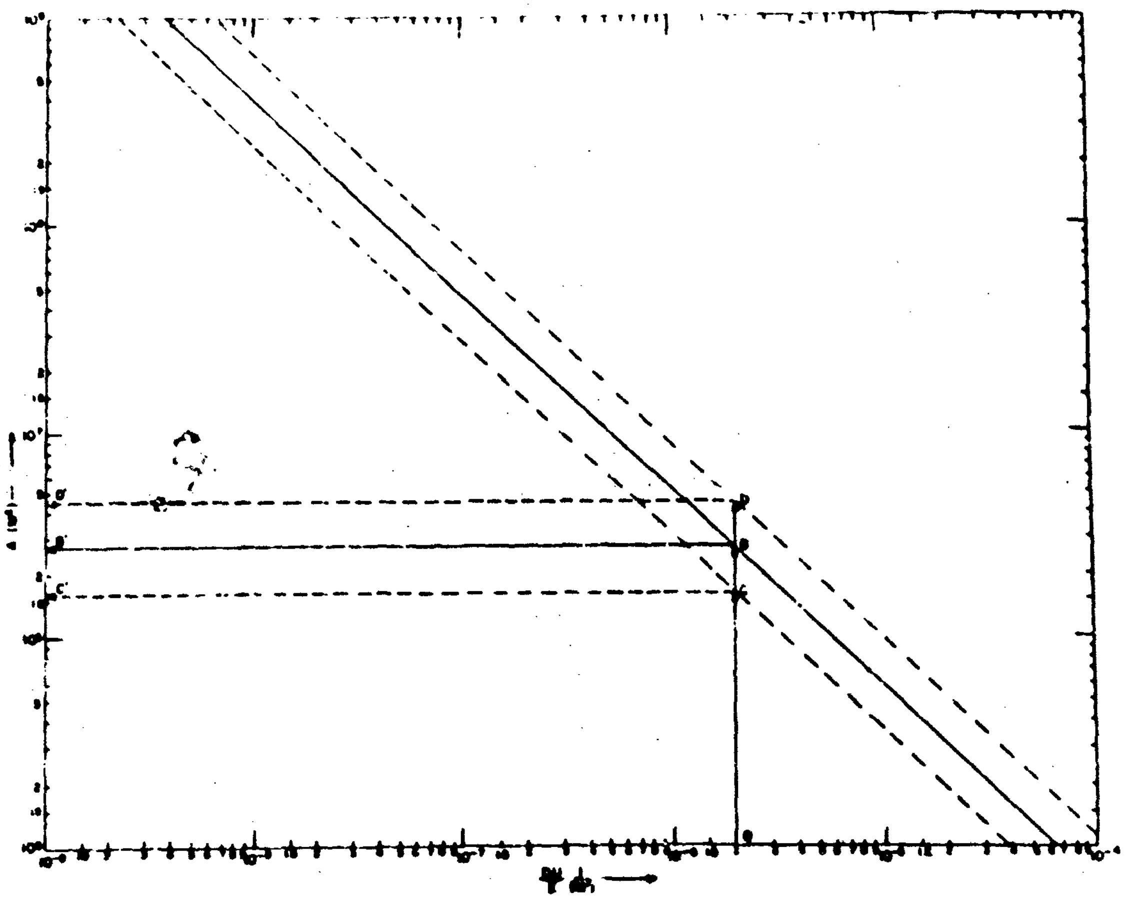

FIG. 4 Example of estimation of area for a given dosage

of the cases should fall between the two dashed lines. They outline the range -40 percent to +66 percent of the value found on the solid line.

As an example, for a given emission (E) and a wind speed (U) at 2 m above ground, we wish to estimate the area enclosed by a given dosage (D). Let us assume that $\frac{DU}{E}$ is then computed to be $2 \times 10^{-6}\ m^{-2}$. This value is entered as the abscissa (Point Q in Fig.4). The ordinate erected at Q intersects the solid line at B, the ordinate of which is $2.7 \times 10^{6}\ m^{2}$. This value represents the best estimate of the area enclosed by $\frac{DU}{E} = 2.0 \times 10^{-6}\ m^{-2}$. This is also the area enclosed by D for the given values of E and U. The intersection of line QB with the lower dashed line (Point C) gives an area of $1.6 \times 10^{6}\ m^{2}$ and the intersection of the extension of line QB with the upper dashed line (Point D) gives an area of $4.5 \times 10^{6}\ m^{2}$. Thus we say that about two-thirds of the areas enclosed by an isopleth whose value is $2.0 \times 10^{6}\ m^{-2}$ will lie between $1.6 \times 10^{6}\ m^{2}$ and $4.5 \times 10^{6}\ m^{2}$. Actually the ratios D'/B' and B'/C' are both equal to 1.66. If we further wished to estimate the values of the areas between which 95 percent of the cases will occur we can multiply the value $B' = 2.7 \times 10^{6}\ m^{2}$ by $(1.66)^{2}$ and divide B' by $(1.66)^{2}$ obtaining a range of about $1 \times 10^{6}\ m^{2}$ to $7.4 \times 10^{6}\ m^{2}$, within which 95 percent of the areas should lie.

3. TRACER ARRIVAL TIMES AT 8 AND 16 MILES

3.1 Introduction

This section provides an estimate of the information necessary to determine the time of first arrival near ground level of a tracer at distances of 8 to 16 miles from the source. The results of this study are based upon analyses of data obtained from drum samplers placed along the 8- and 16-mile arcs of the Green Glow sampling grid. Pigment is drawn into these samplers and impacted on a tape attached to a revolving drum. The drum is turned slowly at a known rate and the pattern of pigment deposition on the tape provides a means of estimating the time of first arrival of significant quantities of tracer material at the sampler.

This study is concerned with determining the time after release of pigment at the source that significant quantities of pigment first arrived at the sampler. Arrival time was defined to be the time of the beginning of a continuous reception containing about 98 percent of the material. Because particles could become lodged in the intake tube during a given run (although all possible care was taken in cleaning the drums between runs) and subsequently appear on the drum in the next run, it was not always easy to define the exact beginning of the reception of pigment. A further error could be introduced by lack of precise knowledge of when the drum was first turned on. This, coupled with the errors of about 2 minutes in actually reading the drum, could produce an over-all uncertainty of as much as 5 or 6 minutes in determining the actual time of arrival of the pigment. Despite these possible errors significant results were obtained.

In addition to the drum sampler data, wind speeds, wind directions, and temperatures were available from the various meteorological installations discussed in Section 1. The wind data were used to construct theoretical trajectories of the plume so that the time of first arrival at an arc could be correlated with the wind speeds at various heights.

3.2 Method of Analysis

Of the 27 runs made during the Green Glow program, drum sampler data were available for 18 runs out to 8 miles from the source and for 10 runs out to 16 miles from the source. However some of the data could not be used in these studies because the samplers were not turned on soon enough at one or both arcs. This is evident from the traces when pigment appeared on the drum immediately after the samplers were turned on, leaving one in doubt about the time of first arrival. For this reason the number of runs with useful data was reduced to 12 for travel to 8 miles and to 5 for travel to 16 miles.

Estimates of travel times to the two arcs were made using the mean winds observed at various levels during the diffusion experiments. Winds at 50 and 100 ft above the ground were recorded on the meteorological tower and a 15 ft wind was determined by interpolation between 7 ft and 50 ft levels. Fifteen feet was chosen because it is close to the estimated source height. It was assumed that the pigment traveled in a straight line from the generator to the samplers on the arcs. Since the wind did change somewhat in direction during the travel time, another set of travel times was computed to 8 and 16 miles. The 23-ft wind directions reported by the wind-station network plus the 15 ft tower wind speeds and the wind speeds and directions of the Texas A & M stations were combined in a streamline analysis to give an estimate of the travel time of a particle remaining in the 15 to 20-ft layer.

3.3. Results

Table 2 shows the comparison between the theoretical trajectories computed assuming the particles were transported in a straight line with the 15 ft tower wind and assuming they were transported along the streamlines as discussed in the preceding subsection. Inspection reveals little difference between the travel times computed by the two methods for distances out to 8 miles. However for travel to 16 miles

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TABLE 2. Initial arrival times (minutes after first release) of pigment at 8 and 16 miles from source observed (T_o) and computed from 15-ft source wind (T_{15}) and from 15-ft streamlines T_{traj}

Run No.	8 MILES			16 MILES		
	T_o	T_{15}	T_{traj}	T_o	T_{15}	T_{traj}
6	42	48	48			
7	77	107	96			
8	39	72	68			
10	24	34	32			
14	96	130	113			
15	56	96	82			
17	20	37	42			
18				68	83	119
19	21	31	37			
21				76	91	121
22	30	42	49			
23				51	75	82
25	28	42	45	48	76	78
26	40	44	46	64	95	108
S1	24	36	37			

there is a tendency for the streamline method to produce somewhat longer travel times (but not in each case), as might be expected. This result does show the effects of variations in speed and direction along the travel path.

Table 3 compares the observed travel time (T_o) with the travel times computed from the winds at 15, 50, and 100 ft as determined from the tower observations. The columns marked T_o give the observed travel times to the respective arcs. The columns marked T_{15}/T_o, T_{50}/T_o, and T_{100}/T_o give the ratios of the travel times computed from the winds at the heights represented by the subscripts and the observed travel times. The column marked SR gives the Stability Ratio (see Section 2.3, Eq. 1).

TABLE 2. Observed initial arrival time (T_o); ratios of arrival times computed from 15-ft wind speed (T_{15}), 50-ft wind speed (T_{50}) and 100-ft wind speed (T_{100}) to T_o; and Stability Ratio (SR).

	8 MILES				16 MILES				
Run No.	T_o	T_{15}/T_o	T_{50}/T_o	T_{100}/T_o	T_o	T_{15}/T_o	T_{50}/T_o	T_{100}/T_o	SR
6	42	1.14	0.84	0.68					0.57
7	77	1.39	0.73	0.60					1.7
8	39	1.84	1.34	0.92					1.4
10	34	1.42	1.08	0.90					0.22
14	76	1.35	0.78	0.52					12.0
15	56	1.71	1.06	0.83					3.2
17	20	1.85	1.41	1.14					0.12
18					68	1.22	0.93	0.76	0.56
19	21	1.48	1.16	0.99					0.06
21					76	1.20	0.90	0.74	0.14
22	30	1.40	1.07	0.93					0.47
23					51	1.47	1.14	0.96	0.11
25	28	1.50	1.16	0.98	48	1.58	1.22	1.06	0.13
26	40	1.10	0.84	0.71	64	1.48	1.06	0.89	0.21
31	24	1.50	1.20	1.04					0.06

A ratio of computed travel time at some height to the observed travel time which is greater than 1.0 indicates that the pigment arrived at the arc sooner than would have been expected were the pigment transported with the wind at the particular height, and conversely if the ratio is less than 1.0. One can see immediately that the pigment always arrived sooner than the wind near the source height (15 ft) would have indicated. In only 4 of the 12 observations of travel to 8 miles did the pigment arrive later than would have been indicated by the 50 ft wind speed and in one case arrived sooner than would have been indicated by the 100 ft wind speed. These results indicate that, on the average, a wind speed measured somewhere between 50 and 100 ft is necessary to specify the first time of arrival. In fact, for Run 17 the wind data showed that the 150 ft wind speed would have been necessary to specify first time of arrival. Although there are but half the number of observations of 16-mile travel time these results seem to hold at this distance as well.

One can easily understand what happens. The pigment cloud diffuses upward as well as outward by the action of turbulence. The pigment which first arrives at an outer arc has initially been diffused to a height of somewhere in the neighborhood of 100 ft and travels along at this height. Some of this pigment is diffused downward again by turbulence and first reaches the ground at the outer arcs before the bulk of the main cloud arrives.

This fact suggests that there might be some relationship between T_h / T_o and stability, where T_h refers to the travel time computed from the wind at height h. This suggestion arises because very stable conditions tend to suppress vertical mixing so that with a fixed speed at a height of 15 ft we might expect shorter arrival times if the atmosphere is near neutral than if the atmosphere is quite stable. The nature of the data and the relatively small number of observations do not permit one to use refined statistical procedures to test this hypothesis. However, one can use the rank correlation techniques to gain some qualitative insight into the correctness of the hypothesis. This method measures the degree of association between the order of one variate and that of another when arranged in ascending or descending values. In this case we can use the technique to determine if high values of the ratio of computed to actual travel time are associated with low values of stability, or to determine if low values of stability (near neutral) cases are associated with travel at effective travel heights greater than those associated with high values of stability.

When values of T_{15}/T_o are compared with SR, the answer is statistically inconclusive with some indication that there is a relationship. When T_{50}/T_o and T_{100}/T_o are compared with SR, the relationship is clear, the effective travel height increasing with decreasing stability.

5.4 Summary and Conclusions

This study has shown that pigment released at about 15 ft above the ground arrived at distances of 8 and 16 miles downwind sooner than was expected on the basis of wind speeds measured at 15 ft. The study indicates that the pigment which first arrived at these distances had traveled with the wind found generally between 50 ft and 100 ft but may even have traveled in some cases with the 150-ft wind. Which height is most appropriate seems to depend upon the stability of the air, the pigment traveling at effectively lower heights with stronger stabilities.

Since all runs were made at night under stable conditions no quantitative results are available for daytime conditions. In the daytime the resulting exposures at the ground are less; but, with everything else the same, it may very well be that the first pigment would travel with winds appropriate to the 150 or 200 ft levels, or perhaps higher.

While this study indicates that wind measurements at 50 ft and 100 ft would be desirable, we recognize that such measurements might not easily be available. When they are not available, the wind speed at 15 ft probably should be doubled (for safety) to obtain an estimated arrival time at some point between 8 and 16 miles downwind from the source.

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Observations of the time of first arrival of the tracer near ground level at distances of 8 and 16 miles from the source indicate that the tracer

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