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ANNUAL REPORT FOR 1968
TO THE USAEC
DIVISION OF BIOLOGY AND MEDICINE
VOLUME II: PHYSICAL SCIENCES
PART 1. ATMOSPHERIC SCIENCES

November 1969

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PACIFIC NORTHWEST LABORATORY
ANNUAL REPORT FOR 1968
to the
USAEC Division of Biology and Medicine
VOLUME II: PHYSICAL SCIENCES
Part 1. Atmospheric Sciences

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PACIFIC NORTHWEST LABORATORY
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Part 1. Atmospheric Sciences

RESULTS OF FIELD INVESTIGATIONS OF THE EFFECT OF
SOURCE HEIGHT AND STABILITY ON ATMOSPHERIC EXPOSURE

P. W. Nickola

A series of field tracer releases was conducted during stable atmospheric conditions. The tracer release height was 85 ft. Tracer sampling occurred at an elevation of 5 ft above ground level at distances between 0.4 and 12.8 km. Results from these field tests are presented in the form of normalized tracer exposures versus travel time for several thermal stratifications of the atmosphere. These results are compared with similar results from releases at elevations of 23 and 185 ft.

The development of effective field techniques at Hanford for dispersal and for sample collection and assay of atmospheric tracers has permitted the comparison of field results with existing diffusion models, and, where necessary, the modification of these models or development of further models to describe the observed atmospheric distribution of tracer.

Diffusion from a ground level source has received considerable attention at Hanford -- particularly in the potentially more hazardous situation of a stable atmosphere.

Diffusion from elevated sources has also been investigated for neutral to unstable atmospheres. Results from these studies have been reported in previous research and development annual reports and elsewhere. However, with but a few exceptions, there has been minimal field investigation of diffusion resulting from release of tracer from elevated sources during stable atmospheric conditions. During 1968 our effort was directed toward filling this gap in the experimental data.

In the summer and fall of 1968, a total of 25 field tracer releases was made from the 85 ft elevation on the 400-ft Meteorology Tower. In order to enhance the probability of releases during stable atmospheres, experiments were made at night. As many as 515 tracer sampling filters were exposed during each release on concentric arcs (or along roads approximating concentric arcs) at distances of 0.4, 0.8, 1.2, 1.6, 2.2, 3.2, 5.0, 7.0, and 12.8 km from the source tower. A known flow rate was initiated through each of these filters prior to the initiation of tracer generation. Generation of tracer, fluorescent powder No. 2210 (FP 2210), lasted 30 min during each experiment. Vacuum on the filters was maintained until well past the time that calculations based on surface level wind speed revealed that all tracer should have passed.

The thousands of filters exposed during the test series resulted in a great number of samples with detectable amounts of FP 2210. In nearly all of the experiments a second tracer, fluorescein, was released during the same interval as the FP 2210 tracer. In 11 instances, the fluorescein was released at ground level; in 13 instances, the release height was 185 ft. Additionally, from one to five devices capable of recording concentration of FP 2210 on a real-time basis were operated during 19 of the 25 field experiments. About 35 usable strip charts were generated by these samplers. Detailed wind and temperature measurements were made at five

locations on the diffusion grid. At year's end, the considerable volume of data generated from these field experiments has not been completely reduced and analyzed.

The results presented here involve the relationship between plume centerline exposure (E_{CL}) at ground level and travel time. Ground level is defined as an elevation of 5 ft. Travel time is defined as the time it takes a given element of tracer to travel from the source to the sampling location.

In 1965, Simpson⁽¹⁾ presented results from a small number of field experiments which related E_{CL} to travel time for aloft releases in stable atmospheres. The release heights were 23 ft and 185 ft. He grouped his results by rather arbitrary thermal stability classifications which he labeled "slightly stable," "moderately stable," and "very stable." The Hanford field experiments carried out in 1968 were also grouped by Simpson's stability classes. Since a few of the tests were less stable than his "slightly stable" category, "neutral" and "unstable" categories were added. The stability classifications are based on the temperature difference between the 200-ft elevation and the 3-ft elevation, and are defined as follows:

Very Stable	$\Delta T > 7.5 \text{ }^{\circ}\text{F}$
Moderately Stable	$7.5 \geq \Delta T > 2.5$
Slightly Stable	$2.5 \geq \Delta T > 0.5$
Neutral	$0.5 \geq \Delta T > -0.5$
Unstable	$-0.5 \geq \Delta T$

Simpson graphed the limits of the zones into which the observed field

data fell. For the sake of graphical clarity, however, only an average value between his extremes is presented in Figure 1. Simpson's data from the 23-ft release height are shown by the dashed lines, and the 185-ft data are shown by the dotted line. The solid curves are those generated from the 1968 summer-fall experiments. The graphed E_{CL} values have been normalized to unit mass of emitted tracer (Q) and multiplied by the mean wind speed ($\bar{U}$). The wind speed used was that measured at the geometric mean between the heights of release and sampling.

FIGURE 1. Normalized Plume Centerline Exposure at Ground Level Versus Travel Time

This family of empirical curves forms a reasonably congruous whole. It is seen that for a given height of release (H), the maximum normalized values of the observed exposure decrease with increasing stability. Recall that E_{CL} is measured near the earth's surface, and hence not at the centerline of the plume -- which is aloft. The plume centerline exposure at any selected transport time would no doubt increase with increasing stability.

Figure 1 also shows that the travel time required to reach the maximum ground level centerline exposure increases with increasing stability and increasing release height. Neither of these observations is unexpected; however, these empirical curves do present the opportunity to quantitatively estimate these relationships.

Theory specifies that for a given stability the normalized values should approach each other as the travel time increases -- irrespective of source height. Certainly the graph shows that the effects of source height are more pronounced at smaller travel times. With the likely exception of the "moderately stable" data for a source height of 185 ft, the empirical curves for a given stability class could reasonably be extrapolated to converge at large travel times.

A great deal of data was generated during the summer-fall 1968 field program and much remains to be done beyond the preliminary results reported here. Future analyses will include classification of data by the more sophisticated stability

parameter of Richardson number, examination of the relationship between exposure and distance pursued, and investigation of the relationships between short term and mean concentrations at various locations with respect to the plume centerline.

REFERENCE

1. C. L. Simpson. "A Model of Diffusion and Transport for a Continuous Release in a Stable Atmosphere," Hanford Radiological Sciences Research and Development Annual Report for 1964, Part I Atmospheric Physics, BNWL-36 I, pp 1.1-1.7. Battelle-Northwest, Richland. Washington, January 1965.

PEAK-TO-MEAN CONCENTRATION RATIOS AS A FUNCTION OF CROSSWIND
POSITION WITHIN THE MEAN PLUME AND THE RATIO OF THE DURATION
OF THE MEAN TO DURATION OF THE PEAK*

J. V. Ramsdell, Jr. and W. T. Hinds**

Diffusion data obtained from four short duration continuous releases of ^{85}Kr are analyzed to examine concentration fluctuations at various positions on a fixed sampling grid. Following a discussion of the effects of atmospheric stability and distance from the source on concentration fluctuations, a detailed study is made of the magnitude of the fluctuations as a function of: 1) crosswind position within the mean plume, and 2) the ratio of the duration of the mean concentration to that of the fluctuation (time ratio).

In particular, peak-to-mean concentrations are found to be an exponential function of the normalized crosswind position within the mean plume, although the relationship differs in form from that derived by Gifford in 1960. A single power law is found to be inadequate to fully describe the relationship between peak-to-mean ratios and the time ratio; however, at time ratios greater than 4 the experimental relationship follows an approximate power law. The data suggest that peak-to-mean ratios estimated for positions near the mean centerline by Gifford (1960) are significant underestimates.

A working model for estimating peak-to-mean concentration ratios which combines the exponential and power law relationships is given.

INTRODUCTION

Data collected during initial testing of the ^{85}Kr tracer system described by Lashock⁽¹⁾ and Ludwick *et al.*⁽²⁾ were analyzed to examine concentration fluctuations within a time-averaged plume. Concentration fluctuations were determined for numerous fixed positions in space and

are represented in the analysis by the ratios of the maximum short-duration concentration in a plume at a point to the mean concentration in the same plume at the point. The maximum short-duration concentration is referred to as the peak concentration. The term **peak concentration** should not be confused with the term centerline concentration which is used as a reference to concentration, peak or mean, at a specific crosswind position in a plume.

In 1960, Gifford⁽³⁾ used his atmospheric diffusion model to theoretically examine peak-to-mean concentration ratios (P/M). Assuming 1) a Gaussian distribution both for

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the positions of the centerlines of plume segments about a mean position and for the material within a plume segment; 2) equal lateral and vertical diffusion rates, and 3) that the variance of material about the centerline of the mean plume is equal to the sum of the variances of the material about the plume segment centerlines and the variance of the segment centerlines about the mean centerline, Gifford's theoretical relationship is:

$$\frac{P}{M} = \frac{\sigma_y^2}{\bar{Y}^2} \exp \left[\frac{1}{2} \left(\frac{y}{\sigma_y} \right)^2 \right] \quad (1)$$

where

σ_y^2 is the variance of material about the mean centerline

$\bar{Y}^2$ is the average variance of material about the segment centerlines,

and

y is the displacement of the receptor from the mean plume centerline.

Experimental examination of this relationship is undertaken in the following sections.

DATA

Four continuous tracer releases were made during periods of relatively constant atmospheric stability; the significant meteorological and diffusion parameters for these releases are summarized in Table 1. The source consisted of a cylinder from which ^{85}Kr was released at a constant rate of approximately 1 Ci/min at an effective height of 1 m. The mean background activity for the releases was 1.216 counts/sec with a mean standard deviation of 0.205 count/sec. Typically, the maximum activity within the plume (averaged over a 38.4 sec sampling period) was of the order of 170 counts/sec at 200 m and 25 counts/sec at 800 m. Calibration of the sensors indicated

TABLE 1. Test Parameters

Release	Duration ^(a) Release	Richardson ^(b) Number	Wind Speed ^(c)	σ_u ^(d)	σ_θ ^(e)	Duration ^(f) at 200 m	σ_y ^(g) 200 m	Duration ^(f) at 800 m	σ_y ^(g) 800 m
1	15 + 28	+0.20	1.2	0.22	6.7	45	5.8	41	4.8
2	15 + 05	-0.022	7.7	1.5	9.8	25	12	24	14
3	9 + 58	-0.31	4.1	1.1	13	17	6.8	7	4.6
4	19 + 51	+0.046	2.6	0.60	7.3	34	7.1	31	5.9

(a) Duration of release in min and sec

(b) Average value for the release period computed for the layer between 1.5 and 12.2 m

(c) Wind speed in m/sec at 1.5 m averaged for duration of release

(d) Standard deviation 1.5 m wind speed in m/sec (5 sec readings about the mean direction during generation)

(e) Standard deviation of 1.5 m wind direction in degrees (5 sec readings about the mean direction during generation)

(f) Number of 38.4 sec time intervals having concentration at any point on the sampling are at least double the ambient background concentration

(g) Standard deviation of crosswind distribution of mean concentration in degrees

that 9.2 counts/sec are approximately equal to $1 \mu\text{Ci}/\text{m}^3$.

The plume was considered to be present at a sampling arc only during those consecutive sampling periods in which at least one sampler indicated an activity greater than twice the background level.

The standard deviations of the crosswind distribution of tracer in the mean plume (σ_y) were computed for each test and sampling arc and are included in Table 1. When the plume was contained within the limits of the arc, the computation of the σ_y was straightforward. In several instances, significant portions of the mean plume missed an arc although the axis of the mean plume was contained within the arc. To compute σ_y in these cases, the plume was assumed to be symmetrical about the indicated centerline. The apparent discrepancy between σ_y and σ_θ for release 2 was induced by a wind direction shift at the end of the generation period.

A quasi-cylindrical coordinate system was established for each test as follows. The reference axis of the system had its origin at the source point and passed through the mean plume centerline at each arc and as a result was generally not straight. The position of each sampler in this coordinate system was identified by arc, absolute value of the angular separation, y , from the reference axis, and height. The crosswind position of each sampler was normalized by taking the ratio y/σ_y which identifies the position of the sampler in the mean plume. Ident-

tification by simple specification of a linear or angular distance from the mean centerline is not satisfactory.

Peak concentrations of varying duration were determined by averaging the concentration for 1, 2, 3, 4, 5, 8 and 15 consecutive sampling periods and selecting maxima. P/M and corresponding ratios of duration of the mean to the duration of the peak (time ratio, T/t) were then calculated for each sampler. The use of P/M ratios normalizes the magnitude of the peak concentrations for variations in the generation rate between tests, while the time ratio normalizes for variations in the duration of release.

RESULTS AND DISCUSSION

The proper grouping of data for analysis posed a problem as, in general, relationships have been found between peak-to-mean concentration ratios and 1) distance from the source, 2) atmospheric stability, 3) crosswind position within the mean plume, and 4) the time ratio. The effect of each of these variables on the peak-to-mean ratios calculated for the ^{85}Kr tests will be examined in some detail. In addition, the effect of crosswind position on the magnitude of the peak concentration will be examined.

Variation of Peak-to-Mean Concentrations with Distance and Stability

As the data were obtained at only two distances and from only four

tests, no attempt was made to determine, quantitatively, the relationships between peak-to-mean ratios and either distance or stability. Rather, the statistical propriety of grouping the data from the distances and atmospheric stabilities was examined.

Gifford (1959, 1960) indicated a sizeable decrease in the magnitude of off-axis P/M ratios with increasing distance from the source and therefore specifically limits much of the discussion in his 1960 paper⁽³⁾ to distances between 100 and 400 m from the source. Initial examination of the ^{85}Kr data did not indicate the expected decrease of P/M ratios from 200 to 800 m. This impression was supported statistically.

A relationship between P/M ratios and gustiness types, which are a function of atmospheric stability, has been indicated by several writers^(4,5,6). With this in mind, the data were examined for grouping by stability. Peak-to-mean ratios were found to differ significantly between stable and unstable atmospheric conditions. In general, P/M ratios tend to be higher during unstable conditions than during stable conditions, in agreement with the findings of Singer⁽⁴⁾ and Martin⁽⁶⁾. The stable and unstable data groupings were maintained for the following detailed analysis of relationship between P/M ratios and crosswind position.

Peak-to-Mean Ratios Versus Cross-Wind Position in the Mean Plume

Figure 1 shows the experimental peak-to-mean ratios as a function of

FIGURE 1. Peak-to-Mean Concentration Ratios as a Function of Normalized Crosswind Position at Time Ratios Near Eight

normalized crosswind position. The form of the relationship shown in Figure 1 may be stated as:

$$\frac{P}{M} = A \exp \left[b \left(\frac{Y}{\sigma_y} \right) \right] \quad (2)$$

Table 2 lists the unbiased estimates of A, b and the correlation coefficient, r, for data from both distances for the individual releases and for each of the data groupings. In addition, the number of data points included in the determination of the parameters and the critical value (5% level) of the correlation coefficient are included for each set of parameters. All correlation coefficients, with the exception of

TABLE 2. Unbiased Estimates of Parameters for the Functional Relationship Between P/M and y/σ_y for a time ratio about 8

Data Grouping	Distance	a	b	r	n	Critical Value of r (5% level)
Release 1	200	3.26	0.299	0.741	14	0.532
	800	2.72	0.129	0.423	12	0.576
Release 2	200	2.52	0.514	0.821	19	0.456
	800	2.78	0.370	0.655	14	0.532
Release 3	200	2.55	0.481	0.724	14	0.532
	800	--	--	--	--	--
Release 4	200	2.79	0.302	0.679	19	0.456
	800	2.99	0.355	0.827	14	0.532
Stable Tests	200	2.96	0.307	0.705	33	<0.349
	800	2.91	0.231	0.528	26	0.388
Unstable Tests	200	2.49	0.515	0.803	33	<0.349
	800	2.55	0.370	0.724	14	0.532
Stable Tests	--	2.91	0.281	0.633	59	<0.27
Unstable Tests	--	2.54	0.488	0.783	47	<0.288
All Tests	--	2.77	0.350	0.688	106	<0.195

that for Release 1 at 800 m, are well above the critical values. The low correlation coefficient for the data from 800 m in Test 1 is caused by a single low P/M ratio at y/σ_y of 2.69. Had this point been eliminated, though not meeting the statistical criteria for rejection, the parameters would have been: $A = 2.44$, $b = 0.257$ and $r = 0.786$.

Equation (2) is similar to (1) with the exception of the exponent on (y/σ_y) in the exponential term. The data for the unstable tests are presented in Figure 2 with the theoretically and experimentally derived curves, as unstable atmospheric conditions most nearly meet the assumptions of Gifford's theoretical derivation. For comparison, the experimentally derived coefficient (2.5) was used in calculation of the theoretical curve. Clearly, the theoretical formulation of the relationship between P/M and

y/σ_y yields significant overestimates of P/M ratios as the distance from the centerline increases much beyond a y/σ_y of 1.

FIGURE 2. Experimentally Derived Relationship Between Peak-to-Mean Concentration Ratios and Normalized Crosswind Position Compared with Gifford's Theoretically Derived Relationship

The Magnitude of Peak Concentrations Versus Crosswind Position

Perhaps a more meaningful relationship for evaluating the magnitude of peak concentrations is found by examining the ratio of the peak concentration at various crosswind positions to the mean concentration at the centerline of the mean plume. Following Gifford's discussion,⁽³⁾ the peak-to-centerline mean (P/M_{CL})

concentration ratio may be expressed, for the one dimensional case, as

$$\frac{P}{M_{CL}} = \frac{\sigma_y^2}{Y^2} \exp \left[-\frac{1}{2} \frac{(y-\bar{y})^2}{\frac{Y^2}{2}} \right] \quad (3)$$

Where the $(y-\bar{y})^2$ term represents the square of the distance between a sampler and the centerline of the plume segment. (In this case, both y and $\bar{y}$ must be signed rather than absolute values.) Within the limits of meandering of the plume segment centerlines, the peak concentration at a sampler can be assumed to occur when the centerline of a plume segment coincides with the position of the sampler. In this range the P/M_{CL} ratio is constant at σ_y^2/Y^2 . Beyond the meandering limits of the segment centerlines, P/M_{CL} concentrations would be expected to decrease as in Equation (3). This behavior of P/M_{CL} ratios as a function of crosswind position is not discernible from either Equation (1) or (2).

The P/M_{CL} ratios have been calculated for the unstable tests and are presented as a function of the crosswind position in Figure 3. The data clearly show the region of constant P/M_{CL} ratios and the rapid decrease in P/M_{CL} ratios at the edge of the mean plume. The region of constant P/M_{CL} indicates that, for a T/t of about 8, the meander of the short term centerline was limited to the range of crosswind positions $y/\sigma_y < 1.5$. It is interesting to note that this is approximately the same range of crosswind positions for which Gifford's theoretical formulation Equation (1) conforms to the data as shown in Figure 2.

FIGURE 3. Peak-to-Centerline Mean Concentration Ratios as a Function of Normalized Crosswind Position, Data from Unstable Tests at Time Ratios of About Eight

Peak-to-Mean Ratios as a Function of the Time Ratio

If peak-to-mean ratios are considered to be some unknown function of crosswind position and time ratio, the preceding discussion has been concerned with an evaluation of the partial derivative of P/M with respect to y/σ_y . In this section, the discussion will center on the evaluation of the partial of P/M with respect to T/t , for each of the crosswind position ranges, $y/\sigma_y \leq 0.70$, $0.71 \leq y/\sigma_y \leq 1.40$ and $y/\sigma_y \geq 1.41$.

To avoid analysis of possibly insignificant data groupings, the mean values of P/M ratios at T/t near 8 for

the crosswind groupings were compared and found to be significantly different. When the average P/M ratios for each of the crosswind ranges for the stable tests were compared with the corresponding averages for the unstable tests, the differences were found to be insignificant. The stable and unstable data were therefore combined for the evaluation of the relationship between P/M and T/t. Average P/M ratios and standard deviations are shown in Figure 4 for each range of crosswind positions and time ratios 1.6 through 22.

An examination of Figure 4 shows a systematic departure of ^{85}Kr P/M ratios from a simple power law suggested by Gifford⁽³⁾ and Hinds⁽⁷⁾ as the relationship between P/M ratios and T/t. The experimental relationship between P/M and T/t for each of the crosswind groupings has two regions. For values of T/t > 4, a power law with a constant of proportionality between 1.5 and 2 fits the data in each grouping, while as the time ratio approaches 1, the relationship between P/M and T/t departs from the power law from with P/M ratios decreasing to 1 at a T/t of 1. If, indeed, the constants of proportionality for the power law relationships have values other than 1, then the region of departure from the power law form T/t near 1 would be necessary because at a T/t of 1, P/M ratios must be 1 by definition. The fact that the experimental curves in Figure 4 show a consistent departure from a single power law relationship at approximately the same T/t value gives an additional measure of confidence to the analysis.

FIGURE 4. Peak-to-Mean Concentration Ratios as a Function of the Time Ratio

Figure 5 compares ^{85}Kr P/M ratios with the curves offered by Gifford to describe the relationship between P/M ratios and T/t. In accordance with Gifford's assumption that diffusion in the horizontal and vertical are approximately equal, the dashed curve in Figure 5 labeled "Gifford Ground Source" may be considered to represent the relationship between P/M ratios and T/t at the axis of the mean plume. The dashed curve labeled "Gifford Elevated Source" may then be thought of as representing the relationship at a point an

FIGURE 5. Experimental Relationship Between Peak-to-Mean Concentration Ratios and the Time Ratio Compared with Prior Estimates by Gifford (1960).

arbitrary vertical or horizontal distance from the centerline.

Peak-to-mean ratios between the plume axis and the arbitrary off-axis distance would be expected to fall between these lines. The experimental curves derived from the ^{85}Kr data are in agreement with the expectation. However, the separation between the curve for $y/\sigma_y \leq 0.70$ and the "Ground Source" curve is larger than might be expected.

As Gifford's curves have often been quoted, an examination of the discrepancy between the "Ground Source" curve and the experimental data was considered essential: review of the data cited by Gifford indicated that the ^{85}Kr estimates of expected axial P/M ratios are, indeed, correct.

A Working Model

In the previous section it was suggested that the relationships between P/M ratios and y/σ_y and T/t might be thought of as partial derivatives of an unknown function. Attempts to determine this function have as yet been unsuccessful. However, the product of an exponential function of y/σ_y and power function of T/t provides a fair approximation of P/M ratios for T/t ratios between 3 and 30. This relationship is:

$$P/M = 1.5 (T/t)^{0.30} \exp [b(y/\sigma_y)] \quad (4)$$

where the value of b , taken from Table 2, is 0.28 for stable conditions and 0.49 for unstable conditions. Although Equation (4) is tentative, and theoretically unsatisfying, it will yield results that are useful.

CONCLUSIONS

Throughout the analyses of these data the fact that peak-to-mean concentration ratios are a stochastic variable has been evident. The variability is clearly seen in each of the figures in which the individual data points have been shown and in Figure 4. Csanady⁽⁸⁾ has published a thorough discussion of this stochastic behavior.

A final cautionary note is in order at this time, for data from only four diffusion tests have been presented. The results and conclusions, though often in numerical form, should be regarded as tentative

and their extrapolation will yield uncertain results.

Despite the variability of peak-to-mean ratios, the following conclusions have been reached from the analyses presented here:

- There is little if any decrease in the magnitude of P/M ratios between 200 and 800 m from a ground source.
- Peak-to-mean ratios are significantly related to atmospheric stability.
- The functional relationship between P/M and (y/σ_y) is significantly different than that proposed by Gifford.
- The magnitudes of the peak concentrations experienced in a mean plume are greatest near the mean axis and are relatively constant in a range either side of the axis.
- A single power law is not adequate to fully describe the relationship between P/M and T/t, although for T/t greater than 4 a power law does fit the data.
- Peak-to-mean concentration ratios estimated from Gifford's "Ground Source" curve are significantly lower than those experienced.

Additional analyses of these data are in progress and future expanded experiments are anticipated.

REFERENCES

1. J. J. Lashock. "Electronic Design and Construction of a Noble Gas Atmospheric Tracer System," Pacific Northwest Laboratory Annual Report for 1967, to the USAEC Division of Biology and Medicine, Volume II: Physical Sciences, Part 3. Atmospheric Sciences, BNWL-715-3. Battelle-Northwest, Richland, Washington, October 1968.
2. J. D. Ludwick, J. J. Lashock, R. E. Connally, and P. W. Nickola. "Automatic Real-Time Monitoring of ^{85}Kr Utilizing the 4096 Memory of a Multiparameter Analyzer," Pacific Northwest Laboratory Annual Report for 1967, to the USAEC Division of Biology and Medicine, Volume II: Physical Sciences, Part 3. Atmospheric Sciences, BNWL-715-3. Battelle-Northwest, Richland, Washington, October 1968.
3. F. Gifford. "Peak to Average Concentration Ratios According to a Fluctuating Plume Dispersion Model," Intern. J. Air Pollution, vol. 3, pp. 253-260. 1960.
4. Irving A. Singer. "The Relationship Between Peak and Mean Concentrations," J. Air Pollution Control Assoc., vol. 11, pp. 336-341. 1961.
5. Irving A. Singer, K. Imai, and R. G. Del Campo. "Peak-to-Mean Concentration Ratios for Various Terrain and Vegetation Cover," J. Air Pollution Control Assoc., vol. 13, pp. 40-42. 1963.
6. James E. Martin. The Correlation of Wind Tunnel and Field Measurements of Gas Diffusion Using Krypton-85 as a Tracer. University of Michigan, 1965. (Ph.D. Thesis)
7. W. T. Hinds. "Peak-to-Mean Concentration Ratios from Ground Level Sources in Building Wakes," Atmos. Environment, vol. 3. 1969.
8. G. T. Csanady. "Concentration Fluctuations in Turbulent Diffusion," Journal of the Atmospheric Sciences, vol. 24, pp. 21-28. 1967.

ATMOSPHERIC TURBULENCE STUDIES

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Seventeen turbulence experiments were performed with the Hanford Wind Component Meter, measuring temperature and the three components of the wind at various heights up to 24.4 m during widely varying stability conditions. Simultaneous measurements were made of the mean profiles of temperature and wind speed and direction. During four of these experiments, the WCM was at 3 m and a sonic anemometer-thermometer was at 60 m, which gave data that are useful for further determination of the height dependence of turbulence characteristics and for determination of the vertical divergence of meteorological fluxes. A third sonic instrument has been added at an intermediate level for experiments which will allow inclusion of the divergence of the vertical flux of turbulent kinetic energy in the turbulent energy budget. Reduction of the test data has only recently begun.

Studies of atmospheric turbulence during the past year have mainly consisted of fast response measurements of the three components of the wind and the temperature at various heights up to 24.4 m and during widely varying stability conditions. These tests utilized the Hanford Wind Component Meter⁽¹⁾ (WCM) as the primary turbulence sensor and the Hanford Portable Mast System⁽²⁾ for simultaneous recording of the mean temperature and the mean wind speed and direction. Four of the tests also utilized a three-dimensional sonic anemometer-thermometer at a height of 60 m in addition to the wind component meter at 3 m. These simultaneous, fast response measurements at two widely separated heights were designed to further investigate the

height dependence of turbulence characteristics and as an initial investigation of the vertical divergence of the fluxes of momentum, sensible heat and turbulent kinetic energy. Finally, a third sonic anemometer-thermometer has been added at an intermediate level in preparation for further measurements which will allow inclusion of the divergence of the vertical flux of turbulent kinetic energy in the turbulent kinetic energy budget. Reduction of the single and dual level test data has only recently begun, but preliminary results of this analysis have been utilized in the design of the planned experiments.

Six stable and five unstable tests, each of approximately one hour duration, were run with the

wind component meter during the period of February to April, 1968. These tests were performed in the vicinity of the 400-foot Hanford Meteorology Tower and utilized the 80-foot Hanford Portable Meteorological Mast to mount the wind component meter and to measure the mean temperature and the mean wind speed and direction at heights of 2.5, 5, 10, 20, 40, and 80 feet. The electronic signal processing equipment for the portable mast system and the wind component meter, a paper punch tape system for recording the mean data, and a 7-channel AMPEX FR 1100 FM tape recorder for logging turbulence data were located in a nearby air-conditioned trailer. Table 1 lists the height of the wind component meter, the mean wind at that height, and the gradient Richardson number between 5 and 50 feet for this group of experiments.

TABLE 1. *Eighty-ft Tower Experiment Summary*

Test	Height of WCM, ft	$\bar{U}_m/\text{sec}$	Ri
B-1	10	2.9	0.07
B-2	10	1.9	0.1
B-3	5	1.5	0.3
B-4	20	3.5	0.08
B-5	40	5.8	0.04
B-6	80	4.6	0.05
USB-1	10	2.8	-1.1
USB-3	20	6.4	-0.03
USB-4	40	3.1*	-1.3
USB-6	80	5.0	-0.09
USB-7	80	10.3	-0.09

* Estimated from 400-ft tower data.

During the fall of 1968, a remote field site was set up in cooperation with the U. S. Air Force TOLCAT study about 1600 m ESE of the 400 ft Meteorology Tower. In addition to fulfilling the requirements of the TOLCAT study, this site has the advantages of a more homogeneous fetch and the availability of the 200-foot towers of the Hanford diffusion grid, which are easily adaptable for experimentation over a greater range of heights. The necessary power is supplied by a diesel-driven electrical generator of 30 kW capacity. The Hanford portable mast system is mounted at heights of 1, 2, 4, 8, 16, 32, and 46 m and the associated electronic signal processing and the paper punch tape recording equipment is located nearby in an air-conditioned shed. The electronic signal processing equipment for the turbulence sensors and an AMPEX FR 1300 FM tape recorder for data logging are also located nearby in an air-conditioned trailer.

Six tests were run at this site during November and December of 1968 with the wind component meter at a height of 3 m. Four of these tests had an additional fast response instrument, a sonic anemometer-thermometer, at a height of 60 m in order to investigate the dependence of turbulence statistics and spectra on height and to measure the vertical divergence of the fluxes of momentum, sensible heat and turbulent kinetic energy. The wind component meter was located adjacent to the tower on a small 10 ft mast and the sonic was located on a 20 ft hori-

zontal boom designed for versatility of positioning and for minimum cross section to avoid perturbing the wind. These tests incorporated a smaller stability range than the February-April series; Table 2 summarizes the stability conditions during the runs at the 200-foot tower site. An additional sonic anemometer-thermometer has been added at the 16 m level in preparation for further experiments which are intended to allow inclusion of the divergence of the vertical turbulent kinetic energy flux in an evaluation of the turbulent kinetic energy budget.

TABLE 2. 200-foot Tower Experiment Summary

Test	Stability	Height of Turbulence Instrumentation
2	Unstable, Neutral Stable	3 m, 60 m
3	Stable	3 m
4	Unstable, Stable	3 m, 60 m
5	Neutral, Stable	3 m, 60 m
6	Neutral, Unstable	3 m
7	Stable	3 m, 60 m

Analyses of these data are performed on a Beckman Ease 1132 analog computer⁽¹⁾ and will be aimed at the study of two subjects. The first of these is the relation between the fluxes of sensible heat and momentum and the mean profiles of temperature and horizontal wind as a function of stability. This matter is currently unresolved and there are few data available that include directly

measured Reynolds fluxes. The second subject of study is the modeling of turbulence spectra as a function of stability. It was proposed⁽³⁾ to link diabatic power spectra for the vertical wind component in the inertial subrange by normalizing the wave number, $nz/\bar{U}$, with the ratio of the dissipation to the mechanical energy production, $\epsilon Ky/U_*^3$. The normalized dissipation may be evaluated from the turbulent energy budget equation for horizontally homogeneous, two dimensional flow. This method met with limited success, but was handicapped in several respects that are alleviated in the current data. In addition to covering a wider range of stabilities than prior data, the current data will allow direct evaluation of the sensible heat flux, the divergence of the vertical flux of turbulent kinetic energy, and, perhaps, the time derivative of the turbulent kinetic energy.

Although data analysis has only recently begun, the preliminary results have already been useful in setting up the planned three-level experiments. Finite values of $\bar{w}$, the measured mean vertical velocity, indicate that greater care is necessary to perform the difficult task of orienting the sonic anemometer within $\pm 0.3^\circ$ in the vertical. Measurements were also made of the misalignments among the three, nominally orthogonal, measurement axes of the sonic anemometer to permit corrections to the data where they are required and to again provide guidelines for the precision needed during mounting of the instruments.

The experiments and the subsequent analysis outlined above are designed to increase our knowledge of the structure of the planetary boundary layer and thus to improve the means of predicting radionuclide dispersion and transport within and through this surface layer. Knowledge of the structure of atmospheric turbulence as a function of mean meteorological conditions is necessary for modeling of the diffusion process important in horizontal radionuclide transport. The vertical transport of radionuclides between the ground and heights at which synoptic scale transport becomes significant can be understood from the similar vertical exchange of momentum, moisture, and sensible heat.

REFERENCES

1. C. E. Elderkin. Experimental Investigation of the Turbulence Structure in the Lower Atmosphere, BNWL-329, Battelle-Northwest, Richland, Washington, December 1966.
2. P. W. Nickola. "Improvements in Micrometeorological Instrumentation," Hanford Radiological Sciences Research and Development Annual Report for 1964, BNWL-36, pp. 1.78-1.80, Battelle-Northwest, Richland, Washington, January 1965.
3. C. E. Elderkin. "Atmospheric Turbulence Studies," Pacific Northwest Laboratory Annual Report for 1967 to the USAEC Division of Biology and Medicine, Volume I: Physical Sciences, Part 3, Atmospheric Sciences, BNWL-715-3, Battelle-Northwest, Richland, Washington, October 1968.

EXPERIMENTAL STUDIES IN PRECIPITATION SCAVENGING

M. A. Wolf and M. T. Dana

Silver iodide test data were compiled and showed a well-defined relationship between washout coefficients and precipitation rates in rain. Test data from snow scavenging present more scatter but reveal a relationship which does not differ markedly from that in rain. Further analysis of washout coefficients derived in previous tests of dry-generated fluorescent dye showed good agreement with theoretical values based on experimental collection efficiencies. The development of a capability for particle size control was undertaken to extend the precipitation scavenging studies of particle size effects. Measurements of raindrop electric charge data collected at a site on the Olympic Peninsula of Washington indicated predominantly positive charges. Calculated precipitation electric currents best describe the raindrop electrification, although the raindrop charge spectrometer transducer apparently does not effectively sample the entire raindrop spectrum.

SILVER IODIDE SCAVENGING

The assay of three silver iodide scavenging tests conducted at Quillayute Air Field on the Olympic Peninsula of Washington in March 1968 brought to five the number of these tests conducted in rain. They also extended the range of rainfall rate in which these tests were conducted from 0.8 to 10.4 mm/hr. The washout coefficients calculated from assayed precipitation on the 100 ft arcs are presented in Figure 1 for the three tests at Quillayute, and the two previous ones at the Rimrock Lake site in the Washington Cascade Mountains. The scatter about the line of unit slope, which linearly relates washout coefficient and rainfall rate, is seen to be quite small. The "best fit" line to the fluorescein data obtained during the same test series under the assumptions previously reported,⁽¹⁾ is in-

cluded in Figure 1 to contrast the washout of these two materials.

The dry deposition of these materials provides a further comparison

FIGURE 1. Silver Iodide Washout Coefficients

of silver iodide with fluorescein. While fluorescein washout coefficients were previously shown⁽¹⁾ to be large by as much as a factor of four due to dry deposition, silver iodide coefficients were increased by less than a factor of two at the more distant arcs, as shown in Table 1. In fact, calculated deposition velocities for silver iodide were less than one percent of the values for fluorescein. This might be attributed to the low inertia of the submicron silver iodide particles which would reduce surface impaction.

Also shown in Figure 1 are the data points for silver iodide scavenging by snow at the Rimrock Lake site. Despite a wider scatter of the snow scavenging data, there is no significant difference of washout coefficient in snowfall of comparable precipitation rate.

SOLUBLE DYE SCAVENGING

The results of the scavenging of dry-generated fluorescein, which were reported previously,⁽¹⁾ are appropriate to this tracer without reference to its particle size only if the removal is independent of size. However, washout dependence on particle size is well established,^(2,3,4) and the results are meaningful only when the size is specified. A subsequent sizing of the dry-generated fluorescein collected on electron microscope grids revealed a distribution of particle diameters ranging from 0.1 to 18 μ . This distribution leads to a median $a^2\rho$ value of about 35 μ^2 g/cm³ where a and ρ are the particle radius and density.

The observed values of washout coefficient are shown in Figure 2

TABLE 1. Uncorrected Washout Coefficients and Calculated Deposition Velocities

Test	Arc	Silver Iodide		Fluorescein	
		Washout Coeff, sec ⁻¹	Dep. Velocity, cm-sec ⁻¹	Washout Coeff, sec ⁻¹	Dep. Velocity, cm-sec ⁻¹
4	A	2.6×10^{-6}		1.8×10^{-4}	
	B	4.1×10^{-6}	0.011	7.4×10^{-4}	
5	A	1.2×10^{-5}			3.9
	B	1.3×10^{-5}	0.0030		
	C	1.7×10^{-5}	0.017		
6	A			3.1×10^{-4}	
	B			5.0×10^{-4}	0.73
	C			9.5×10^{-4}	1.9

- Notes: 1. Comparisons of silver iodide results for test UIL 5 and fluorescein results for test UIL 6 are presented since these tests were conducted less than an hour apart.
2. Deposition velocities were calculated with the assumption that Arc A computed washout coefficients were unaffected by dry deposition.

together with theoretical values which were calculated from raindrop size spectra measured during the tests and collection efficiencies appropriate to those drop sizes, for monodisperse water droplets ($a^2\rho = 42 \mu^2 \text{ g/cm}^3$), which were measured by Kinzer and Cobb.⁽⁵⁾ The calculation of washout coefficient, Λ , utilized the equation

$$\Lambda = \int_0^{\infty} FEA \, dD \quad (1)$$

where F is the raindrop flux density, E is the collection efficiency and A is the cross-sectional area for drops of diameter D . These results are consistent with the results of

FIGURE 2. Comparison of Experimental Washout Coefficients for Water Soluble Fluorescein Particles with Theoretical Values Calculated from Measured Raindrop Spectra on the Olympic Peninsula

Engelmann,⁽⁴⁾ shown by the solid line of Figure 2, which used Kinzer and Cobb efficiencies and raindrop spectra from Washington State and India. It should be noted that the fluorescein data, corrected for dry deposition, were constrained to the linear relationship of washout coefficient and rainfall rate which was apparent in the uncorrected data. The assumption of complete retention of the particles intercepted by the raindrops, which is inherent in Equation (1), is reasonable for the water soluble fluorescein.

The general agreement of theoretical and experimental precipitation scavenging results using soluble dye offers a potential for examination of several factors which may influence the scavenging process. Additional investigations are necessary, for example, into the effects of electrical forces due to charges on particles and raindrops and the effects of modified raindrop trajectories and raindrop-particle interactions due to wind shear and turbulence. The need for control of the soluble dye particle size in these investigations and for detailed study of the effect of particle size itself has required effort toward development of a suitable generation technique.

Initially, consideration was given to the physical separation of commercially available dry fluorescein into several narrow size groups having distinct mass median diameters. No economical method is available for separation of the moderate quantities which are required. The

technique employed for particle size control in the winter 1968-1969 precipitation scavenging experiments is similar in principle to that used by Schulz, et al.⁽⁶⁾ A dye solution that is sprayed into the air subsequently dries into spherical dye particles. The principal factor in determining the particle size is solute concentration, and it is not difficult to produce a predominant mass of a given particle size. Since the width of the particle size distribution is dependent on the width of the droplet size distribution, monodispersity can be approached only through careful design of the system. The particle diameter, D , produced from droplet diameter, d , is given by the expression

$$D = d \left(\frac{C}{\rho} \right)^{1/3} \quad (2)$$

where C is the solution concentration of the solute whose density is ρ . It is assumed that each droplet completely evaporates to form one solid spherical particle.

The portable agricultural chemical sprayer which was available served as a convenient disseminator for the prototype system to test this concept of particle size control. The unit is powered by a small gasoline engine which drives a centrifugal blower. The blower supplies an air flow of nearly 300 cfm past the atomizer nozzle at about 200 mph. While the liquid flow rate can be varied from about 50 to 1500 cm^3/min through the choice of appropriate flow-restricting orifice and nozzle, suitable droplet size distribution

can be achieved only at the lower flow rates. With the 0.25 in. nozzle, with which the atomizer was initially equipped, a flow rate of 300 cm^3/min produced an apparently satisfactory particle size distribution from a solution of fluorescent rhodamine dye in methanol.

This solute-solvent combination was selected for the following reasons: rapid drying of aerosol to spherical particles; large range of mass median diameters due to high solubility; ease of assay; relative low toxicity; and tracer stability. An early test of a methanol solution of fluorescein (35 g/liter) under high humidity conditions showed stains rather than particles on downwind filters, while a methanol solution of rhodamine (66 g/liter) showed the desired particle formation and only few stains. Subsequent tests of the methanol solution of rhodamine were made to establish the relationship of particle size distribution to the rhodamine concentration.

Had the droplet distribution been known, particle size could have been determined from Equation (2). Because of the rapid evaporation of methanol, it was feasible to establish the relationship by sizing particles from several tests rather than sizing droplets from a single test. Concentrations between 0.126 and 66 g/liter were used to define the size-concentration relationship. The results are shown in Figure 3, where mass median diameters are plotted against rhodamine concentration. A fair amount of scatter is noted for which there is no positive

FIGURE 3. Experimental Relationship of Rhodamine Particle Size to Methyl Alcohol Solution Concentration

explanation. The droplet sizes, which are inferred from these mass median particle diameters, range from 32 to 52 μ . The solid line is appropriate to a mass median droplet diameter of 40 μ .

Figure 4 shows the mass distribution of particles for concentrations of 0.125 and 19.5 g/liter. For the low concentrations the spread is quite narrow, but the higher concentrations yield a fairly broad distribution. However, the distribution is sufficiently limited so that the washout coefficient dependence on particle size can be examined.

Experimental studies were conducted in December 1968 at the field test site on the Olympic Peninsula using the rhodamine particle system. Four pairs of tests were run with solution concentrations selected to yield mass median particle sizes of 0.9, 1.8, 3.6 and 6.3 μ , as determined from the calibration curve of Figure 3. These tests were disappointing since washout coefficients were considerably larger than anticipated and their correlation with particle size was not apparent.

Subsequent microscopic examinations of filters exposed for dry deposition determination during the tests

FIGURE 4. Mass Distribution of Rhodamine Particles for Solution Concentrations of 0.125 and 19.5 g/liter

showed colored splotches suggesting the existence of rhodamine as droplets rather than as particles. This is not clearly the case since particles on the filters might pick up sufficient moisture to cause this appearance when the humidity is near saturation value. It would be expected that the rhodamine droplets would be scavenged more effectively and result in the excessive washout coefficients which were observed.

Examination of the disseminator following the test series showed

several deficiencies which support the rhodamine droplet hypothesis and suggest, furthermore, that the droplets contained water. The unsheltered impeller inlet could permit precipitation to be carried with the air past the disseminator nozzle and allow mixing of water into the methanol droplets as they form. This would retard or prevent the formation of particles and seriously compromise the experiment by modifying the aerosol size and properties. Another deficiency was observed in

the nozzle configuration which permitted a portion of the aerosol to impact on the edge of the disseminator wall. Subsequent reentrainment would alter the droplet size distribution and the droplet composition, as well, through inclusion of water.

Modifications to the rhodamine disseminator were made, therefore, to eliminate these potential sources of malfunction. The impeller intake was fitted with a long inlet which was oriented downward to alleviate the problem of introducing precipitation into the air flow. To prevent impaction of the ejected aerosol on the disseminator wall, the nozzle configuration was altered, solution flow rate was reduced to $170 \text{ cm}^3/\text{min}$ and the airstream velocity increased through a reduction in length and elimination of internal obstructions. Additional tests of the modified disseminator are scheduled for early 1969.

Raindrop Electric Charge Studies

Continuous records of raindrop electric charge were made using the raindrop charge spectrometer during

the December 1968 experiments (UIL-7 through UIL-15), as well as at other times of precipitation. Table 2 presents data collected during the times of the experiments. Listed are numbers of positively and negatively charged raindrops and their average charges, the net average electric charge on a raindrop, the current of measurably charged raindrops, and the average rainfall intensity. The data for each run are summed from several individual samples selected from the total record and do not include measurements over the entire time period shown. However, the samples were chosen to represent the period, taking into account variations in rainfall intensity and magnitude, frequency and polarity of the recorded pulses.

As can be seen from the table, the net charge was always positive during the experiments, with 65% of the drops being positive. Furthermore, the positive raindrops were more highly charged than the negative drops -- approximately 80% of the total charge magnitude was positive.

Inasmuch as the instrument has a

TABLE 2. *Quillayute Raindrop Charge Data*

Experiment	Date	Time PST	N+	N-	Charge, 10^{-15} C			Current, 10^{-11} am^{-2}	$R^* \text{ mm hr}^{-1}$
					q+	q-	q		
UIL-7	12-7-68	0731-0757	474	281	+41	-22	+18	+1.0	2.1
UIL-8	12-7-68	1049-1114	977	332	+194	-135	+110	+8.9	3.8
UIL-9	12-7-68	1238-1303	502	200	+61	-25	+36	+1.1	1.6
UIL-10	12-10-68	1210-1225	211	148	+222	-94	+97	+2.7	2.6
UIL-11	12-13-68	0949-1012	379	271	+73	-25	+32	+1.0	0.7
UIL-12	12-13-68	1119-1144	360	132	+133	-41	+86	+1.6	0.6
UIL-14	12-13-68	1423-1442	407	138	+200	-112	+122	+5.2	1.4
UIL-15	12-13-68	1551-1615	716	411	+298	-144	+138	+7.2	4.4

lower limit to its ability to detect electric charges, and consistently indicates a smaller flux of charged raindrops than the flux⁽⁷⁾ (as recorded by the ozalid paper rain spot samples), it is noted that the average net charge may possibly be too high in most sampling periods. Experiments which involved sequentially varying the angle of the inducing ring -- i.e., alternating between a vertical orientation and an orientation angled into the wind -- resulted in data which indicated that, when angled to the wind, the inducing ring saw a greater percentage of weakly negative drops. Presumably these are smaller raindrops since these would be more nearly aligned with the wind. In general, the particular orientation in which the inducing ring is positioned during an experiment may thus lead to a higher net charge than the true one, but the flux of charged raindrops is lower than true as well. Therefore, it is held that the area electric current (charge flux) reported is quite representative of the true situation since it is the product of the flux through the instrument and the net average charge on a drop.

REFERENCES

1. M. T. Dana and M. A. Wolf. "Experimental Studies in Precipitation Scavenging," Pacific Northwest Laboratory Annual Report for 1967. Volume II: Physical Sciences, Part 3. Atmospheric Sciences, BNWL-715-3, pp. 128-140. Battelle-Northwest, Richland, Washington, October 1968.
2. A. C. Chamberlain. Aspects of Travel and Deposition of Aerosol and Vapour Clouds, AERE-HP/R-1261. Atomic Energy Research Establishment, Harwell, Berks, England, 1953.
3. B. J. Mason. The Physics of Clouds. Oxford University Press, London, p. 424. 1957.
4. R. J. Engelmann. "The Calculation of Precipitation Scavenging," Meteorology and Atomic Energy 1968, David H. Slade, Editor, TID-24190, pp. 208-221. AEC Division of Technical Informal Extension, Oak Ridge, Tennessee, 1968.
5. G. D. Kinzer and W. E. Cobb. "Laboratory Measurements of the Growth and Collection Efficiency of Raindrops," J. Meteorology, vol. 13, no. 3, pp. 295-301. 1956.
6. E. J. Schulz, R. A. Duffee, R. I. Mitchell, and E. W. Ungar. "A Tracer Technique to Measure Deposition of Stack Emissions," Am. Ind. Hyg. Assoc. J., vol. 21, pp. 343-349. 1960.
7. M. Terry Dana. "Studies of Precipitation Electrical Charge," Pacific Northwest Laboratory Annual Report for 1967, Volume II: Physical Sciences, Part 3. Atmospheric Sciences, BNWL-715-3, pp. 140-149. Battelle-Northwest, Richland, Washington, October 1968.

PRECIPITATION CHARACTERISTICS:
SHIPBOARD MEASUREMENTS IN
THE CARIBBEAN SEA
M. T. Dana

Measurements of raindrop electric charge and size and rainfall intensity were made aboard USCGSS Discoverer in the southeast Caribbean Sea. The shipboard electric charge detection unit proved adequate for the highly charged convective rainfall experienced. It was found that the raindrop collections have relatively low net charge averages, while individual raindrops were highly charged. Raindrop size distributions were found to be similar to Pacific Northwest rain, but with greater number of large raindrops. Three methods of measuring precipitation intensity produced comparable results, though all were potentially limited in accuracy.

Precipitation electric charge, size and intensity data were collected aboard USCGSS Discoverer during the 1968 Barbados Experiment On Station Period II, August 10-September 1, 1968. The ship operated about 100 km east of Barbados, West Indies.

Although rain fell at the ship's location during about a dozen of the days of this period, significant amounts were experienced on only two days--August 18, and August 30. Raindrop charge, size and intensity data from August 18 have been analyzed and are represented in Table 1. Raindrop charges were recorded using the raindrop charge spectrometer^(1,2) continuously from 0840 to about 1200. Electrical storm activity was evident throughout the morning, though the rainfall intensity decreased noticeably at about 1000. After this time, the rain was

steady from a solid overcast. The evening period of rain was an isolated thundershower.

The minimum charge detection limit in effect during the cruise was about 16×10^{-3} picocoulomb, some ten times larger than that experienced in operation in the Pacific Northwest⁽¹⁾. This came about as a result of several conditions: 1) a background noise level from electrical equipment aboard ship, and from charged particles (presumably salt) in the atmosphere; 2) a bias voltage from the transducer, which varied between 40 and 200 millivolts (corresponding to a charge range of 65 to 320×10^{-3} picocoulomb); and 3) wandering of the "zero" output level on occasions of intense rain. These limitations on sensitivity did not, however, present a problem, as few charges of magnitude near this lower limit were observed. In fact,

TABLE 1. *Precipitation Characteristics Data, August 18, 1968*

Sample	Time (a)	Number of Drops		Mean Charge ^(b) (Coulomb $\times 10^{12}$)		Median Diameter, mm	Rainfall ^(c) Intensity, mm/hr	
		+	-	+	-		d	e
4A	0852	143	70	0.86	0.61	(f)	(f)	(f)
4B	0854	215	136	2.20	1.99	0.6	10.6	(f)
5F	0932	163	110	1.79	1.66	(f)	(f)	43
5D	0941	145	232	1.76	2.88	1.0	9.4	12
5E	0952	195	189	1.98	1.95	1.0	8.0	64
5B	1012	187	17	0.45	0.42	1.0	3.6	6.5
5C	1018	108	150	1.20	0.73	(f)	(f)	(f)
6A	1129	45	89	1.32	0.99	(f)	(f)	(f)
7A	1138	67	104	0.87	1.08	(f)	(f)	(f)
8A	2133	131	70	0.38	0.58	(f)	(f)	(f)
8B	2139	215	136	3.44	5.83	1.0	9.5	13

(a) Barbados Time (Z - 4 hr).

(b) Using raindrop charge spectrometer calibration determined prior to trip. A post-trip check on the calibration awaits the return of the instrument from Barbados.

(c) Average rainfall rate from shipboard gauge for both the periods (8:30 AM - 12:00 noon) and (9:31 PM - 9:46 PM) was 10 mm/hr.

(d) Calculated from Ozalid paper spectra.

(e) Calculated from water samples collected by J. M. Prospero, University of Miami.

(f) No measurement available.

several periods of hard rain with charge pulses of high magnitude and frequency forced the use of a still lower sensitivity, in order to reduce the tendency for the recorder trace to be off scale most of the time.

Table 1 presents median diameters of raindrops sampled with ozalid

paper⁽³⁾. The size distributions were of the log-normal type as has been observed in Pacific Northwest rain^(4,5). The modes were nearly the same as in Quillayute (Olympic Peninsula) rain-drop spectra, at about 0.4 mm diameter. However, the Discoverer spectra are broader, with a greater

number of large raindrops. Thus, the median is larger--in the vicinity of 1mm. Two samples were bimodal in character; samples 5D and 5B have modes of 0.85 and 0.2 mm, and secondary peaks of 0.4 and 1.2 mm, respectively.

The raindrop sampler box, which features a motor driven paper roll and variable door opening widths, sampled at exposure times from 2 to 15 sec. The more intense rains (greater than about 10 mm/hr) apparently require shorter exposure times, as many taken at 2 sec were too dense to be sizeable.

Plans for using the laboratory-developed weighing gauge rainfall rate recorder⁽⁵⁾ were discarded; the instrument proved too sensitive to the ship's motion. Rainfall intensities were available, however, from three other sources aboard the Discoverer. In addition to being computed from ozalid paper flux spectra (as is routinely done), rainfall rates were determined from water sample amounts collected by J. M. Prospero, of the University of Miami. These samples, of known volume, were collected from a 100 ft² collector over periods of several minutes. In addition, significant rainfall amounts were measured by shipboard rain gauges. The rainfall intensities shown in the table are computed from the first two sources. From the rain gauges, it was found that the average rainfall rates for the periods 0830 to 1200 and 2131 to 2146 were both about 10 millimeters per hour. In

general, the three independent means gave comparable results. It must be noted, however, that the numbers from the water collections are probably minimums: The 100 ft² area was a hard sheet of roofing fiberglass, from which a good deal of water splashed; also, the rain gauges were placed such that the flow of air over the ship probably reduced the amount collected. The ozalid rates, while accurate for short times, may be low for description of rainfall rate over a several-minute period since they were calculated from the less dense (sizeable) samples. Samples taken nearby in time often were too densely covered for sizing.

The hitherto analyzed Caribbean raindrop charge records indicate generally more highly charged raindrops, for all rainfall intensities, than those of Northwest United States precipitation⁽¹⁾. The periods of rain identified as thunderstorms certainly produced raindrop charges of considerably higher magnitude than those found in the exclusively nonthunderstorm United States records. Furthermore, it is apparent that the more intense Caribbean rains, while having charge magnitudes of both signs, do have relatively low net charge averages. This phenomenon is probably due to the increased number of collisions between raindrops and breakup of large drops; these occurrences separate large magnitudes of charge of opposite sign in significant atmospheric electric fields⁽⁶⁾.

REFERENCES

1. M. Terry Dana. "Studies of Precipitation Electrical Charge," Pacific Northwest Laboratory Annual Report for 1967, to the USAEC Division of Biology and Medicine, Volume II: Physical Sciences, Part 3. Atmospheric Sciences, BNWL-715-3, p. 140. Battelle-Northwest, Richland, Washington, October 1968.
2. C. A. Ratcliffe and N. C. Hoitink. "Improvements in Raindrop Charge Measuring System," Pacific Northwest Laboratory Annual Report for 1967 to the USAEC Division of Biology and Medicine, Volume II: Physical Sciences, Part 3. Atmospheric Sciences, BNWL-715-3, p. 150. Battelle-Northwest, Richland, Washington, October 1968.
3. R. J. Engelmann. The Hanford Raindrop Sampler and Selected Spectra, HW-73119. Available from Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia, 1962.
4. D. I. Hagen. "Precipitation Scavenging of Submicron Particles: A Comparison of Theory with Field Results," Pacific Northwest Laboratory Annual Report for 1967 to the USAEC Division of Biology and Medicine, Volume II. Physical Sciences, Part 3: Atmospheric Sciences, BNWL-715-3, p. 165. Battelle-Northwest, Richland, Washington, October 1968.
5. M. Terry Dana and M. A. Wolf. "Experimental Studies in Precipitation Scavenging," Pacific Northwest Laboratory Report for 1967 to the USAEC Division of Biology and Medicine, Volume II: Physical Sciences, Part 3. Atmospheric Sciences, BNWL-715-3, p. 128. Battelle-Northwest, Richland, Washington, October 1968.
6. R. Gunn. "The Electrification of Precipitation and Thunderstorms," Proc. I.R.E., vol. 45, p. 1331. 1957.

THE TRANSFER OF AIRBORNE RADIONUCLIDES
ACROSS THE SEA SURFACE AT 13°N, 58°W

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Air filter samples were collected twice a day at 7, 25, and 76 ft above mean sea surface aboard the USCGSS Discoverer stationed east of Barbados, British West Indies, at 13°N during August, 1968. Beryllium-7 (53 days), ⁹⁵Zr-Nb (65 days), ¹⁰³Ru (40 days), ¹⁰⁶Ru (1.0 yr), ¹³⁷Cs (30 yr), and ¹⁴⁰Ba (12.8 days), concentrations were determined in these samples. The radionuclide concentrations increased significantly from the 7- to the 25-foot sample, but averaged the same in the 25- and 76-foot samples. The concentration increase was greater for samples collected during the day than for those collected during the night. Rain samples and seawater samples down to 210 m were also collected aboard the Discoverer.

Beryllium-7 is produced at a relatively constant rate in the atmosphere by spallation reactions of cosmic rays on atmospheric oxygen and nitrogen; therefore, atmospheric and oceanic concentrations of ⁷Be should remain relatively constant. As a result, the measured concentrations of ⁷Be in air and water samples can be used to calculate values for the vertical eddy diffusion coefficient K_z in the atmosphere and the ocean.

Air filter samples were collected twice a day at three elevations on the research vessel the USCGSS Discoverer operated by ESSA and stationed east of Barbados, British West Indies, at 13°N, 58°W. One of the samplers was located 7 ft above the mean sea surface on a platform directly behind the stern of the vessel. A second sampler was placed at deck level toward the bow at an elevation of 25 ft. The third sampler

was secured to a mast at an elevation of 76 ft. One set of three samples was collected from about 8 p.m. to 8 a.m. each night and another set from 8 a.m. to 8 p.m. each day.

Unfortunately, air passing a ship is deflected upward to a considerable extent, especially if the ship is perpendicular to the wind. During about 65% of the sampling time, the Discoverer was drifting nearly perpendicular to the wind while the rest of the time, it was steaming directly into the wind. Therefore, it is difficult to estimate the average altitude of the origin of the air passing through each of the three samplers. When the Discoverer was drifting perpendicular to the wind, the air sampled by the stern (7 ft) and mast (76 ft) samplers was not seriously deflected upward. However,

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it is difficult to estimate the path of the air passing through the stern sampler when the ship was steaming into the wind. The air could have passed either over or around the vessel. The air sampled by the deck sampler would have been deflected upward to a greater extent when the ship was perpendicular to the wind than when the ship was steaming into the wind.

The radionuclides measured were ^7Be (53 days), $^{95}\text{Zr-Nb}$ (65 days), ^{103}Ru (40 days), ^{106}Ru (1.0 yr), ^{137}Cs (30 yr), and ^{140}Ba (12.8 days). Beryllium-7 is produced by spallation reactions of cosmic rays on atmospheric nitrogen and oxygen while the other radionuclides are fission products. The shortlived radionuclides ^{140}Ba and ^{103}Ru originated from a French nuclear test series that began on July 6, 1968, at 23°S in the Pacific Ocean.⁽¹⁾ Barium-140 did not appear in measurable quantities in the air filter samples until August 14, 1968, while ^{106}Ru concentrations did not become measurable until August 17, 1968. Zirconium-niobium-95 concentrations also increased significantly after August 17, 1968, because of the debris from the French tests. The ^{106}Ru and ^{137}Cs concentrations did not significantly change.

The air concentrations of ^7Be , $^{95}\text{Zr-Nb}$, ^{106}Ru , ^{137}Cs , and ^{140}Ba usually increased with increasing altitude from the 7- to the 25-foot sample; however, the concentrations averaged about the same for the 25- and 76-foot samples. The concentration increase between the 7- and 25-

foot sample fluctuated considerably between successive sets of samples. The increase varying from 0 to almost 80% for ^7Be . The concentration increases for the five radionuclides were generally similar, but not identical, for a given set of samples. The average concentration increase between the 7- and 25-ft samples was significantly greater for the daytime samples than the nighttime samples. For example, the ^7Be concentration averaged 40% higher in the 25-ft samples than in the 7-ft samples for 4 sets of samples collected during the day, but it averaged only 10% higher in the 25-ft samples than in the 7-ft samples for four nighttime sets of samples. The larger concentration gradient during the day was due to the lower concentrations in the 7-ft samples during the day. There was no significant difference in the 25 or 76-ft level concentrations between the night and day.

ATMOSPHERIC VERTICAL EDDY DIFFUSION COEFFICIENTS

The radionuclides ^7Be , $^{95}\text{Zr-Nb}$, ^{106}Ru , ^{137}Cs , and ^{140}Ba were extracted from seawater at depths of 0, 15, 30, 35, 40, 70, 100, 140, and 210 m aboard the Discoverer during the period from August 8, 1968, through August 16, 1968.⁽²⁾ In addition, the concentrations of these radionuclides have been determined in selected rainwater samples.

If one assumes that the horizontal radionuclide concentration variations in the sea are small, thus providing negligible horizontal radionuclide transport, then:

$$\frac{dn}{dt} = f_o + w - \lambda n \quad (1)$$

where n = the radionuclide content in a vertical profile of the sea, expressed in atoms/cm² of the sea surface

f_o = flux of radionuclides across the sea surface due to turbulent transport (atoms/cm²-sec)

w = wet deposition by rainfall (atoms/cm²-sec)

λ = decay constant (sec⁻¹)

t = time (sec)

If the concentration of a given radionuclide equals zero at the bottom of the measured profile, then n can be calculated from the profile. The W can be estimated from the measured radionuclide concentrations in rainwater and the distribution of rainfall in the area. λ , of course, is known for any of the measured radionuclides. If it is assumed that the radionuclide concentrations in the sea are at a steady state, so that $\frac{dn}{dt} = 0$, then Equation (1) can be solved for f_o . However, this assumption certainly is not true for the bomb-produced radionuclides. Their atmospheric concentrations are always changing in a manner determined by the recent history of nuclear testing. Moreover, the concentrations of the longer-lived bomb-produced radionuclides should be increasing in the sea, and their

concentrations do not equal zero at the bottom of the measured profile.⁽²⁾ Beryllium-7, which has a 53 day half-life, is produced by cosmic rays at a relatively constant rate. This process provides a constant average atmospheric concentration and maintains a steady state oceanic concentration. Its measured concentration was essentially zero at the bottom of the profile.⁽²⁾ Therefore, if the seasonal variations in the ⁷Be atmospheric concentrations are small at 13°N and if the amount of ⁷Be in the sea is not changed too drastically by rainfall rate variations, then $\frac{dn}{dt} \approx 0$ for ⁷Be, which provides a solution for f_o for ⁷Be. During the water sampling period, there were no measurable variations in the radionuclide concentrations in the sea, which supports the assumption that $\frac{dn}{dt} \approx 0$.

An air sampler placed on Barbados, British West Indies, is collecting air samples on a weekly basis to define the atmospheric radionuclide concentrations for BOMEX. During the BOMEX experimental period in the spring and summer of 1969, several seawater profiles will be collected and analyzed for all possible radionuclides. From these profiles, the average value of $\frac{dn}{dt}$ for the period between the collection of samples in 1968 and the collection of samples in 1969 can be calculated. It is hoped that variations in the oceanic concentrations will be detected during the 1969 sampling period so that $\frac{dn}{dt}$ may be evaluated for shorter periods of time.

The vertical flux, f , due to turbulent transport is given by

$$f = -K_z \left(\frac{\partial C}{\partial z} \right) \quad (2)$$

where K_z = vertical eddy diffusion coefficient (cm^2/sec)

C = radionuclide concentration (atoms/standard cm^3 of air)

If horizontal transport is neglected and the radionuclide concentration is assumed to be constant, then $\frac{\partial f}{\partial z} = 0$ between sea level and the levels of the concentration measurements. Equation (2) can then be rewritten as:

$$f = f_0 = -K_z \left(\frac{C_2 - C_1}{\Delta z} \right) \quad (3)$$

where C_2 and C_1 are the concentrations at two different altitudes and K_z is the average diffusion coefficient between these two altitudes. K_z can then be calculated from the measured ^7Be concentrations at 7 and 25 ft and the value of f_0 for ^7Be calculated previously. The fluxes across the sea surface of the other measured radionuclides can then be calculated using these values of K_z in Equation (3).

VERTICAL EDDY DIFFUSION COEFFICIENTS IN THE SEA

If it is assumed that horizontal transport in the sea is negligible, the vertical flux f_z at some depth is given by:

$$f_z = \frac{dn_z}{dt} + \lambda n_z \quad (4)$$

where n_z = radionuclide content in the sea below depth z (atoms/ cm^2)

f_z = flux at depth z (atoms/ $\text{cm}^2 \cdot \text{sec}$)

λ = decay constant (sec^{-1})

If the radionuclide concentration is constant below depth z , then $\frac{dn_z}{dt} = 0$ and f_z at any depth can be calculated from the measured radionuclide concentrations in the sea. Moreover,

$$f_z = -K_z \left(\frac{\partial C_z}{\partial z} \right)$$

where C_z = concentration at depth z (atoms/ cm^3). Therefore, K_z can be calculated from the measured concentration.

The pre-BOMEX data have shown that measurable vertical concentration gradients of radionuclides exist in the first few meters above and below the sea surface and that in the ocean at 13°N and 58°W detectable amounts of ^7Be are confined to a rather shallow layer near the ocean surface. These conditions make it possible to use the above equations to calculate values for the vertical eddy diffusion coefficient in the atmosphere and ocean near the sea surface. During the BOMEX sampling period in 1969, we plan to obtain

more accurate and extensive measurements of the concentration gradients so that more accurate values of K_z may be calculated.

REFERENCES

1. "H-bomb--A New Club Member,"
edited by Gordon H. Bixler,
Chemical and Engineering News,
vol. 46, no. 38, pp. 11. 1968.
the Atlantic Ocean near Barbados,"
this report, (BNWL-1051, Part 2),
Battelle-Northwest, Richland,
Washington, 1969.
2. W. B. Silker and H. G. Rieck.
"Radionuclide Concentrations in

DIABATIC TRAJECTORIES AND A TRAJECTORY CASE STUDY
OF THE EFFLUENT FROM PHOEBUS 1B EP-IV FEBRUARY 23, 1967

W. E. Davis and B. C. Scott

Procedures for estimating diabatic effects and techniques for the inclusion of these effects in a trajectory calculation have been presented.

A trajectory case study of the effluent from Phoebus 1B EP-IV, February 23, 1967, has been utilized to demonstrate the application of some of the procedures for estimating and including the diabatic effects into a trajectory calculation.

INTRODUCTION

The path taken by air parcels in the atmosphere has been of concern to scientist and layman alike. This path has been estimated by assuming isobaric or constant level flow. However, when air motions are quasi-adiabatic, the assumption of constant level or isobaric flow can often result in seriously erroneous trajectory calculations. Danielsen⁽¹⁾ demonstrated that the adiabatic trajectories should be used rather than isobaric trajectories when the air flow characteristics of the atmosphere are quasi-adiabatic. An analogous argument can be used when diabatic conditions exist; when the adiabatic trajectory is no longer valid, diabatic flow should be estimated.

Presently, diabatic effects are being evaluated, and techniques are being developed for including these effects in trajectory determinations.

Research has been directed toward the following objectives:

- Development of techniques to identify diabatic conditions and

to estimate diabatic effects and

- Study of the diabatic effects on the trajectory of the effluent from the Phoebus 1B EP-IV reactor test of February 23, 1967.

DIABATIC EFFECTS

Three causes of diabatic effects were studied:

- Convective mixing in the surface layer
- Radiational cooling
- Release of latent heat

The results of these studies were then utilized, when possible, to calculate a trajectory end point through the use of the diabatic energy equation.

Convective Mixing in the Surface Layer

When air parcels moving adiabatically enter turbulent zones such as regions of convective mixing in the surface layer, the adiabatic assumption

is invalid. In addition, the assumption that adiabatic trajectories are describing the motion of individual air parcels is no longer valid due to mixing. However, convective mixing in the surface layer and the trajectories in the affected layer can be estimated with the aid of surface potential temperature analysis.

The upper limit of mixing can be estimated from the surface potential temperature (θ). The surface θ is assumed to equal the θ at the top of the mixing layer when air parcels are mixing upward dry-adiabatically. Thus the mixing layer depth will increase as the surface θ increases. When the surface θ falls, air parcels with potential temperatures greater than that at the surface will emerge from the mixing layer as it stabilizes and move down stream on the newly formed potential temperature surfaces. Isentropic trajectory analysis is initiated over the range of potential temperature surfaces re-formed when the surface potential temperature decreases. These trajectories will describe the transport of the material redistributed during the convective mixing process in the surface layer. A detailed surface θ analysis can serve two purposes: first, to identify the region where surface heating will affect the trajectory; and second, to identify when isentropic trajectories enter or leave the mixing layer.

Radiative Cooling

In the lower atmosphere, radiative heating and cooling often produce large temperature changes. Air parcels

will cross isentropic surfaces in regions where radiative heating or cooling is a major diabatic effect. Consequently, the accuracy of adiabatic trajectories will deteriorate in these regions. Therefore, to locate regions where the atmosphere is emitting or absorbing significant amounts of radiant energy, radiative flux is calculated and the cooling rate is used in a diabatic trajectory calculation.

The radiative flux through various levels in the atmosphere can be evaluated in several ways. However, a discussion of the application and accuracy of the various techniques for calculating radiative flux is not essential to the discussion developed in the report. A detailed discussion of some of the formulations used to compute radiative flux can be found in Smagorinsky, et al.⁽²⁾, Manabe, et al.⁽³⁾, Mintz⁽⁴⁾, Rodgers and Wolshaw⁽⁵⁾, and Sasamori⁽⁶⁾.

Regardless of the procedure used to calculate atmospheric radiation, the technique for including flux divergence in trajectory calculations remains the same. The technique for including flux divergence is as follows.

The first approximation of a diabatic trajectory is obtained by moving an air parcel on an isentropic surface for a 12-hour period. The change in potential temperature ($\Delta\theta$) along the trajectory path is calculated by assuming the averaged value of the radiative flux divergence calculated at the trajectory end points ($t = 0$ hr, $t = 12$ hr) is equivalent to $\Delta\theta$. The air parcel is then returned to the mid-point (in time) of

the original adiabatic trajectory and stepped vertically down (up) by the amount $\Delta\theta$. The air parcel is then moved parallel to the streamlines on the new θ surface for the remaining six hours. At the end of the 12 hr movement, the new trajectory end point is adjusted in order to satisfy the diabatic energy equation.

Release of Latent Heat

Areas of precipitation are identified from either available surface maps or from the hourly Weather Bureau station reports. Once the areas of precipitation are delineated, the diabatic effects accompanying precipitation are estimated. The problem of estimating diabatic effects was approached from the aspect of stability of the atmosphere during precipitation processes. Techniques had to be developed for precipitation occurring both during convective instability and in a stable atmosphere. In the first case, mixing will accompany latent heat releases while in the second, no mixing is assumed to take place.

When precipitation occurs, coupled with convective instability, the problem of estimating diabatic effects is treated in a manner analogous to the application of Engelmann and Davis.⁽⁷⁾ Specifically, the boundaries of the diabatic zone in regions of convective instability can be estimated by lifting the air mass dry adiabatically on a thermodynamic chart until the lifting condensation level (LCL) is reached. The potential temperature at the LCL is assumed to be the lower boundary of the diabatic

zone. The air parcel is then lifted wet-adiabatically until it is in equilibrium with the surrounding atmosphere, and the θ at the equilibrium level is taken to be the upper boundary. The same approach can be used in determining whether cells in a region of convective precipitation can penetrate and "tap" an air parcel moving adiabatically over the region, see Davis, et al.⁽⁸⁾, and Reiter and

Mahlman⁽⁹⁾. Again, once the boundaries are established, isentropic trajectories are taken throughout the layer delineated by these boundaries. These trajectories then describe the transport of the material redistributed during the convective mixing process.

Stable precipitation is handled by first computing the change in potential temperature resulting from the release of latent heat and then incorporating this effect into the energy equation for the end point calculation. The first estimate of the end point is accomplished by moving the air parcel adiabatically. Then, under the assumption that equivalent potential temperature (θ_e) is conserved, the sounding at the end point is used to find a θ surface where θ_e (initial) = θ_e (final). The change in potential temperature is then found by taking θ (initial) - θ (final) at the trajectory end point. The air parcel is moved along the initial θ surface until reaching the point where precipitation occurs. The air parcel is placed on the final θ surface and moved adiabatically. Using the potential temperature change, the diabatic effect can be incorporated in a diabatic energy

equation for end point calculation of the trajectory.

DIABATIC ENERGY EQUATION

In the case of diabatic conditions existing without mixing, it is possible to compute an energy conserving diabatic trajectory. The frictionless-flow energy equation used was computed in Cartesian coordinates (see Haltiner and Martin⁽¹⁰⁾).

$$\frac{d}{dt} \left(\frac{V^2}{2} + c_p T + gz \right) = \alpha \frac{\partial p}{\partial t} + \frac{dQ}{dt}, \quad (1)$$

where $\frac{dQ}{dt} = c_p \frac{T}{\theta} \frac{d\theta}{dt}$.

The kinetic energy term is $\frac{V^2}{2}$, $c_p T$ is enthalpy, and gz is potential energy. The $\alpha \frac{\partial p}{\partial t}$ term is the work performed by the atmosphere on the parcel, and $\frac{dQ}{dt}$ is the diabatic term indicating heating of the system.

Previously, Danielsen's⁽¹⁾ energy equation development in θ coordinates has been used. However, significant errors discovered in that approach are discussed in the following.

The corrected integrated energy equation should read

$$\int_{t_1}^{t_2} \alpha \frac{\partial p}{\partial t} \bigg|_z dt + \int_{t_1}^{t_2} c_p \frac{T}{\theta} \frac{d\theta}{dt} dt = \psi_2(\theta_2, t_2) - \psi_1(\theta_1, t_1) + \frac{V_2^2}{2}(\theta_2, t_2) - \frac{V_1^2}{2}(\theta_1, t_1) \quad (2)$$

with $\psi = c_p T + gz$ (ψ is Montgomery Stream Function) where the following corrections have been made.

A significant error was found in the original integration of the term involving kinetic energy (KE) where

$$\int_{\theta_1}^{\theta_2} \frac{\partial KE}{\partial \theta} \bigg|_{t_2} d\theta \text{ was set equal to}$$

$$\frac{\partial KE}{\partial \theta} (\theta_2 - \theta_1); \frac{\partial KE}{\partial \theta} \text{ indicates time}$$

averaging along the path of the trajectory, which is an inappropriate estimate of the change in kinetic energy required.

This integral should be:

$$\int_{\theta_1}^{\theta_2} \frac{\partial KE}{\partial \theta} \bigg|_{t_2} d\theta = KE(t_2, \theta_2) - KE(t_2, \theta_1) \quad (3)$$

Another problem was found in the original development.⁽¹⁾ It was demonstrated that $\frac{\partial \psi}{\partial \theta x, y, t_0}$

$$= c_p \frac{T(t_0)}{\theta(t_0)}, \text{ but } c_p \frac{T(t)}{\theta(t)} \text{ was}$$

inappropriately set equal to $\frac{c_p T(t)}{\theta(t)}$, which resulted in two of the terms in the energy equation canceling. Since, in general, this approximation is usually not true, a certain error will be produced. In one case that was experienced, the error was found to be insignificant because the ratio of $\frac{T}{\theta}$ remained essentially constant and the approximation that $c_p \frac{T(t)}{\theta(t)}$

$$= c_p \frac{T(t_0)}{\theta(t_0)} \text{ was within the error of}$$

the calculation. Further work will be necessary to delineate the error in the approximation. In the meantime, the energy equation in Cartesian coordinates, where these errors do not occur, is being used.

ILLUSTRATION OF THE TECHNIQUES

The following case study of the effluent from Phoebus 1B EP-IV, February 23, 1967, presented a unique opportunity for testing diabatic trajectory calculations. Confirmation of the trajectory could be checked by the real time aircraft sampling, which provided detailed information about the position of the cloud.

The Phoebus test was conducted at the Nuclear Rocket Development Station (NRDS), 90 miles northwest of Las Vegas, Nevada, on February 23, 1967. At 2154Z, effluent was emitted from the reactor for 41 min ⁽¹¹⁾. However, for convenience, H-hour has been taken to be 2200Z.

The 2200Z rawinsonde (Figure 1) at NRDS indicated that the effluent would be distributed over a deep mixing layer. Thus, to describe adequately the motions of the effluent downwind, several initial θ values were chosen. Those selected include

- $\theta = 301$ at 2405 m MSL
- $\theta = 301.5$ at 2375 m MSL
- $\theta = 302$ at 2655 m MSL
- $\theta = 303$ at 2815 m MSL, and
- $\theta = 305$ at 3210 m MSL

For reference, the elevation of NRDS is 1245 m MSL.

Surface θ analyses from H+0 to H+2 (Figure 2) indicated that all but the 305 θ trajectory would be moving in the surface mixing layer. Therefore,

FIGURE 1. Plot of Temperature, Dew Point and Pressure for Radiosonde Report for Jackass Flats, February 23, 1967, 2200Z

the effluent position in the mixing layer was determined by constructing trajectories at constant levels above the surface. By H+3, the ground had cooled sufficiently to allow the re-establishment of all the selected isentropic levels. The constant level trajectory end points were placed on the original isentropic surfaces and the effluent was assumed to move downstream adiabatically using Montgomery Stream functions.

No additional diabatic effects could be identified until H+26. At that time, calculations with the Elsasser radiation diagram indicated a radiative cooling rate of 0.5 °C per 12 hr in the atmospheric layer containing the trajectories (800 to 600 mb). This cooling rate was probably overestimated through the use of the Elsasser diagram ⁽¹²⁾.

FIGURE 2. Surface θ Analysis - February 24, 1967, 0000Z

However, to illustrate the previously described technique, a diabatic trajectory using the computed cooling rate was initiated from the 302 θ trajectory end point.

The only apparent diabatic effect during the remaining 40 hours of the case study was radiational cooling, which continued to average about 0.5 °C every 12 hr.

Table 1 summarizes the height of each trajectory end point at 12-hour intervals. The effluent clearly is not moving on a constant level or constant pressure surface.

Table 2 summarizes the computed diabatic effects along the trajectory

paths. The net cumulative radiational cooling in the atmospheric layer containing the trajectories is 2.0 °C. The maximum surface θ is a measure of the greatest depth of the mixing layer. The surface θ 's of 302 to 303° in the maximum surface θ column indicate trajectories, originally at these isentropic levels, have entered the mixing layer.

RESULTS

The indicated effluent position was confirmed at several locations⁽¹³⁾ downwind from NRDS (Figures 3 and 4). At H+14, the diabatic trajectory

TABLE 1. Heights of the Trajectory End Points

Time	301.0	301.5	302.0	303.0	35.0	Diabatic
Feb 23/2200 Z	2465 ^(a)	2575 ^(a)	2655 ^(a)	2815 ^(a)	3210	- - -
Feb 24/1200 Z	2500	3188	3400	3400	3500	- - -
Feb 25/0000 Z	2500(b)	2700	2700	2800	3400	2700
Feb 25/1200 Z	3200	3300	3300	3500	4000	3200
Feb 26/0000 Z	3900	3200	2700	2900	- - -	2800
Feb 26/1200 Z	5200	4100	3600	3700	- - -	3500

(a) In mixing layer

(b) Surface potential temperature is 300.3

TABLE 2. Computed Diabatic Effects for 301.5 to 303° θ Trajectories

Time, Z (1967)	Cumulative Net Radiational Cooling at 700 mb, °C	Maximum Surface θ
Feb. 23, 2200 to 24, 1200	-0.3	302-303
24, 1200 to 25, 0000	-0.7	<300 at 25, 0000 Z
25, 0000 to 25, 1200	-1.1	<300 at 25, 0000 Z
25, 1200 to 26, 0000	-1.4	289
26, 0000 to 26, 1200	-2.0	289

analysis indicated that the effluent would be found at 3200 m MSL over Ely, Nevada (altitude 1800 m). The NATS* flying at a pressure-altitude of 3200 m intercepted effluent cloud

near Ely at H+14 and followed its movement northward while flying at a pressure-altitude of 3100 m.

The U.S. Public Health Service⁽¹⁵⁾ intercepted the effluent at 3700 m MSL near Wendover (elevation 1520 m), Utah, at H+19, and at 2600 m near Elko, Nevada (elevation 1550 m), at H+20:30. The timing and positioning of the interception near Elko is predicted by the 301.0° θ trajectory. The trajectory analysis places the material over Wendover at H+19 as

* NATS is the Nevada Aerial Tracking System, which is a highly instrumented Martin 404 aircraft. The pressure-altitude and corrected temperature⁽¹⁴⁾ data from NATS were used to calculate potential temperatures.

FIGURE 3. Isentropic and Diabatic Trajectories of the Effluent from Phoebe IB-EP-IV Reactor Test February 23, 1967.

FIGURE 4. Phoebe IB-IV Effluent Trajectory and Diffusion Pattern. Measured from NATS Aircraft Between Altitude Ranges 9500 to 10500 ft MSL, 23-26 February, 1967(13)

observed, but there is no direct explanation for the height discrepancy of 500 m. However, diffusion from lower θ surfaces is a possible explanation for the observation. Further, the U.S. Public Health Service did not report temperatures, so an evaluation of the potential temperature was not available at the points of interception.

All but one of the trajectories indicated that the effluent would enter Southern Idaho between H+23 and H+26 (Figure 3). The heights determined from the analysis of the effluent ranged from 2500 m MSL near Twin Falls to 2800 m MSL near Malad City. NATS

flying at the approximate level of $\theta = 302^\circ$ contacted the effluent near Malad City at H+21:30 and near Twin Falls at H+22:30. At H+27, the Public Health Service detected the effluent cloud between Malad City and Pocatello. Thus, the indicated effluent positions appeared to have only minimal errors after 26 hr of movement.

The NATS intercepted the effluent at 3000 m near Cody, Wyoming at H+32; at 3300 mm near Billings, Montana at H+40; and at 3300 m near Miles City, Montana at H+41. The altitude of all three contacts was given by the diabatic trajectories, but only the time of arrival at Billings was accurate. The Cody contact indicated an arrival error of at least three hours and the Miles City contact indicated an error of at least 6 hr. Thus, by H+40, the accuracy of the indicated effluent position was beginning to deteriorate for trajectories north of the $302^\circ \theta$ trajectory.

Additional effluent contacts were made by NATS in the Dakotas and Minnesota at a constant pressure altitude of 3000 m. However, the aircraft was sampling the effluent with filters⁽¹³⁾ after H+40 so that specific regions of contact were difficult to define. The trajectory analysis did indicate the presence of effluent at 3000 m in the western and central portions of South Dakota.

Theoretically, the diabatic trajectories can be used to describe the altitude of maximum concentration if an initial altitude of maximum concentration is known. An altitude spiral by NATS at H+7 established the level of maximum concentration to be at an

altitude corresponding to a potential temperature of $301.5^\circ \theta$. A $301.5^\circ \theta$ trajectory from the vicinity of the initial spiral indicated that the level of maximum concentration should be at 2700 m MSL near Burley, Idaho. An additional altitude spiral at Burley at H+22:20 shows the actual maximum effluent concentration at 2800 m MSL.

In Figure 3, the diabatic trajectory using radiational cooling is compared with the $302^\circ \theta$ trajectory. In Idaho, a deviation between their paths first appears. By H+50, the diabatic trajectory is approximately 250 km to the NW of the $302^\circ \theta$ trajectory. Thus, the computed diabatic cooling from the Elsasser diagram resulted in a significant change in the path of the trajectories. Applying this diabatic cooling to the rest of the trajectories would have resulted in the shifting of the trajectories further to the north while maintaining the general spread pattern.

DISCUSSION OF RESULTS

The Phoebus 1B EP-IV case study dealt specifically with material released into the surface mixing layer. Trajectory confirmations in Nevada and Idaho demonstrated that the effluent movement could be satisfactorily described out to at least H+40 hr with diabatic conditions of convective mixing and radiation cooling occurring along the path. In addition, the altitude of maximum concentration was correctly indicated up to 700 km from the release point. Altitudes of effluent contact were successfully in-

licated in Montana and the Dakotas at distances ranging up to 1600 km from the effluent release points.

Surface θ analyses for the first 3 hr of the effluent movement indicate that mixing could have distributed material to the $304^\circ \theta$ isentropic level. An examination of Figure 4 reveals that any upward mixing of the effluent would have produced larger easterly components in the first 26 hr of the trajectory paths. However, aircraft were never at the locations necessary for the verification of this indicated upward mixing for $\theta > 303^\circ$. The diabatic trajectory for radiation cooling indicated a movement of air parcels from the 302° to $300^\circ \theta$ surface. However, no confirmation was available of this movement because of the lack of vertical definition of the measured plume.

Trajectories originating from various altitudes at the source point have described the vertical and lateral spread of the plume (Figures 3 and 4). No known existing diffusion model has this capability of predicting the dispersion of material in an atmosphere where the vertical wind shears are of the magnitude encountered in this case study.

The lack of data, and errors in existing data, eventually produce inaccurate displacements in any trajectory scheme. However, it is difficult to estimate the degree of inaccuracy after H+40 in the Phoebus Study. Aircraft flying in support of radiological monitoring and survey programs covering the Phoebus 1B EP-IV reactor test, continued to search for the effluent at a pressure altitude of 3000 m

over regions where the trajectory analyses indicated it would have been located between 3500 and 4100 m. Thus, it is not known if all the trajectories were in error after H+40. The location of effluent at 3000 m may indicate that turbulent diffusion resulted in the downward movement of material.

CONCLUSIONS AND RECOMMENDATIONS

Various assumptions concerning material movement through diabatic zones in the lower atmosphere have been stated and tested. The results indicate that the diabatic techniques incorporated into a trajectory analysis presented in this paper can successfully describe the downwind coordinates of material released into the atmosphere. However, further case studies are needed to evaluate and confirm the movement of air parcels under varying diabatic conditions in the atmosphere.

REFERENCES

1. E. F. Danielsen. "Trajectories: isobaric, isentropic, and actual," *J. Meteorology*, vol. 18, pp. 479-486. 1961.
2. J. Smagorinsky and Staff Members. "Prediction Experiments with a General Circulation Model," *Proc. Intern. Symp. Dynamics of Large-Scale Processes*, Moscow, 70-137. 1965.
3. S. Manabe, J. Smagorinsky and R. F. Strickler. "Simulated Climatology of a General Circulation Model with a Hydrological Cycle," *Monthly Weather Rev.* vol. 93, pp. 769-798. 1965.
4. Y. Mintz. "Very Long-term Global Integration of the Primitive

- Equations of Atmospheric Motions,"
WMO Tech. Note No. 66. 1964.
WMOIUGG Symp. Res. Develop.
Aspects of Long Range Forecasting,
Boulder, Colorado. 1965.
5. C. G. Rodgers and C. D. Walshaw.
"The Computation of Infrared
Cooling Rate in Planetary Atmo-
spheres," Quart. J. Royal
Meteorol. Soc. vol. 92,
pp. 67-92. 1966.
 6. T. Sasamori. "The Radiative
Cooling Calculation for Applica-
tion to General Circulation Ex-
periments," J. Applied Meteorology,
vol. 7, no. 5, pp. 721-729. 1968.
 7. R. J. Engelmann and W. E. Davis.
Low-Level Isentropic Trajectories
and the MIDAS Computer Program
for the Montgomery Stream Func-
tion, BNWL-441. Battelle-
Northwest, Richland, Washington,
April 1968.
 8. W. E. Davis et al. "Additional
Meteorological Analyses of Shot
Smoky, Plumbbob Test Series,"
Pacific Northwest Laboratory
Annual Report for 1967 to the
USAEC, Division of Biology and
Medicine, Volume II: Physical
Sciences, Part 3, BNWL-715-3
pp. 74-87. Battelle-Northwest,
Richland, Washington.
October 1968.
 9. E. R. Reiter and J. D. Mahlman.
"Heavy Iodine-131 Fallout over
the Midwestern United States,
May, 1962," Technical Paper
No. 70. USAEC Progress Report
No. 2, Department of Atmospheric
Science, Colorado State University.
1965.
 10. G. J. Haltiner and F. L. Martin.
Dynamical and Physical
Meteorology. McGraw-Hill Book
Company, Inc., New York, N. Y.,
1957. pp. 176-177.
 11. T. V. Crawford. "The Long Range
Diffusion of the Effluent Cloud
from the Phoebus 1B EP-IV
Reactor Test of February 23,
1967, UCRL-50418. Lawrence
Radiation Laboratory, University
of California, Livermore,
California. April 1968.
 12. W. R. Kuhn. Unpublished Data.
University of Michigan,
Ann Arbor November 6, 1968.
(Personal Conversation at the
"Conference on the Composition
and Dynamics of the Upper
Atmosphere," El Paso, Texas)
 13. J. E. Hand and V. F. Weissman.
Phoebus 1B EP-IV Effluent and
Ground Deposition Surveys,
No. EGG 1183-1321. 1967.
 14. J. C. Pales. Unpublished Data,
1968. (Personal Communication)
 15. Preliminary Report, Monitoring
and Sampling Phoebus 1B,
February 10 and 23, 1967,
U. S. Public Health Service.
Las Vegas, Nevada, 1967.

PARTICLE COLLECTION EFFICIENCIES ON WIRES

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Collection efficiencies of monodispersed 4 to 27 μ uranine particles were determined for 0.020 to 0.064 in. diameter wires for air velocities from 8.6 to 33.1 ft/sec. The wires were coated with a tacky film. The collection efficiencies are a complex function of particle size, wire diameter, Reynolds number, Stokes number, and wire surface area covered by previously impacted particles. For low coverage from 0.1 to 10% an asymptotic correlation is shown as a function of Stokes number. This asymptote is near the upper experimental limit of published collection efficiency data. When greater than about 10% of the available surface is covered with particles, the collection efficiencies are less than those indicated in published correlations. The disagreement in published efficiencies may be caused by failure to account for wire surface area coverage.

Several investigators have studied theoretically⁽¹⁻⁴⁾ and experimentally⁽⁵⁻¹⁶⁾ the impaction efficiency of particles on cylindrical targets. The experimental data show a significant scatter between investigations.

The impaction of particles on fine wires has been studied in this research to determine the feasibility of using wire impactors as particle samplers near surfaces or in other situations demanding small disturbances of the sampled air. Good sensitivity, adequate reproducibility, and accuracy would have to be shown before impaction on wires could qualify as an acceptable sampling method.

Collection efficiencies were experimentally determined for several wire and particle diameters. Three identical wires were supported perpendicular to the axis of a 2.81 in.

ID vertical tube. The wires were held in the same plane 0.5 in. apart. One inch downstream from the wires a filter was supported within a slip joint in the tubing. Monodispersed uranine particles of either 4, 6, 9, 14, or 27 μ diameter were passed vertically upward through the tube at three turbulent air flow rates. Some particles impacted on the wires; particles not stopped on the wires were collected on the filter. After particle collection, the filter was cut into concentric annuli, each of which was washed with water to dissolve the uranine. The central 1 in. length of each wire was cut off and washed to dissolve the impacted uranine particles. The wash solutions were analyzed fluorimetrically for uranine and the results used to calculate a particle mass balance.

The flux (mass/area) of particles approaching the central 1 in. length of each wire was calculated from the mass balance. The flux was determined from the sum of the uranine on the filter annulus above the wire and the uranine on the wire.

The collection efficiency was defined as the ratio of the average amount of uranine collected on the wire per unit projected wire area divided by the particle flux.

The wires, 0.020, 0.035, and 0.064 in. in diameter, were made tacky to avoid re-entrainment with either one of two coatings. The first coating used was a smooth thin layer of petroleum jelly applied from the melted material. The second coating used was formed from a warm solution of 2 g gelatine, 11 ml glycerine, and 12 ml water. The films were of the order of 15 μ thick for the petroleum jelly and 25 to 50 μ thick for the gelatine-glycerine surface. The petroleum jelly coating retained the uranine particles in their original spherical shape. Particle concentration was a maximum along the frontal edge of the wire (0° angle), and decreased to a negligible concentration at 90°, and was zero on the wire beyond 90°. By contrast, the uranine particles striking the gelatine-glycerine coated surface were soon absorbed and diffused throughout the coating. These two different coatings were used to determine whether the nature of the coating would affect the collection efficiency. Difference in collection efficiency under otherwise identical conditions was not discernible when a small fraction of the

frontal surface of the wire was occupied by impacted particles. When the frontal surface area covered by particles reached several percent, in some cases a higher efficiency was indicated for the gelatine-glycerine coating. The difference was not consistently shown and at this time cannot be attributed without qualification to the properties of the two coatings.

The air velocities and turbulence intensity at the central wire locations in front of the filter were measured with a hot wire anemometer. These were:

Flow Rate In 2.81 in. ID Tube, cfm	Air	
	Velocity, ft/sec	Turbulence Intensity, %
19.2	8.6	9.8
38.4	16.2	7.4
75	33.1	6.5

Collection efficiency data have been obtained for most combinations of the three wire diameters (0.020, 0.035, and 0.064 in.), three air velocities (8.6, 16.2, 33.1 ft/sec), five particle sizes (4, 6, 9, 14, 27 μ diam), and coverage⁽¹⁷⁾ from about 0.1 to 70%.

Collection efficiencies are usually correlated as a function of the Stokes number,

$$\text{Stk} = S/D$$

where D is the wire diameter and S is the stopping distance. The stopping distance is calculated from the expression

$$S = \frac{\rho_p d^2 v}{18\mu}$$

where ρ_p = particle density
d = particle diameter

v = air velocity at tube axis
 μ = air viscosity.

The Stokes number is a dimensionless number which is an independent variable in the dimensionless equation of motion describing particle impaction. The analytic solutions of the equations of motion do not attempt to account for the changes in air flow pattern caused by previously impacted particles or by the presence of air turbulence.

The experimentally measured collection efficiencies are shown in Figure 1, as a function of the Stokes

number. Obviously, other variables are also required to correlate the data. These variables have been determined to include the fractional wire surface area on which particles have previously deposited, and possibly the type of surface coating on the wire. The effects of these additional variables are being considered in developing a general correlation of the data.

The problem in developing this correlation can be illustrated by considering the two dotted lines drawn along the upper and lower limits of the collection efficiency

FIGURE 1. Collection Efficiencies for Cylindrical Wire Collectors

data. The curve labeled "asymptote" defines the upper limit of experimental collection efficiencies for any Stokes number. For data represented by this upper limit, the average projected wire surface area which was covered by particles at the end of each run was from 0.1% to 10%. In contrast, for the lower curve, the surface area coverage ranged from a few percent to 70%. From a comparison of the surface area coverage for these two limits, we conclude that for any particular Stokes number, the collection efficiency decreases as the wire surface coverage increases.

This conclusion was previously reported.^[17] The present data confirm the previous observation and show that the coverage effect is significantly greater than that which could be attributed to residual experimental errors.

We hypothesize that lack of agreement among the experimental collection efficiencies reported by others may be attributed in part to a variation in the fraction of the surface covered during the course of the reported experiments. The fraction of the impaction surface occupied by particles for these experiments was not reported; hence, it is not possible to discretely analyze the literature data in terms of this variable. If the available collection efficiency data as a function of Stokes number are composited, as is shown in Figure 2, it can be seen that the data do show efficiencies falling near to or less than the asymptote or upper envelope of

these data from the current experiments. Experimental errors in all of these determinations are also represented by the lack of agreement, yet few of the data show greater values of efficiency than the asymptote values. The effect of the fraction of surface covered judged by the results of the current study would always bias the collection efficiency toward lower values.

This interpretation suggests that the highest values of collection efficiency will be obtained for the initial particle collection, with subsequently lower efficiencies being realized as the duration of collection and, hence, surface occupied by particles, increases.

A purpose of this study was to determine the feasibility and reproducibility of using particle impaction on wires to determine concentration of airborne particles. The results show that particle collection efficiencies are a complex function of several variables even when monodispersed aerosols are used in controlled laboratory experiments. For field applications in which particles are not of the same size, the ability to accurately interpret wire impaction data is questioned. Undoubtedly wire impaction can be used to monitor the relative airborne particle concentration as a function of time. However, if accuracy is required in measured concentration, consideration must be given to the type of wire coating, nature of particles, and the area coverage of particles.

FIGURE 2. Comparison of Theoretical and Experimental Collection Efficiencies for Circular Cylinders

REFERENCES

1. R. J. Brun, W. Lewis, P. J. Perkins, and J. S. Serafini. Impingement of Cloud Droplets on a Cylinder and Procedure for Measuring Liquid-Water Content and Droplet Sizes in Supercooled Clouds by Rotating Multicylinder Method, NACA-1215. Lewis Flight Propulsion Laboratory, Cleveland, Ohio, 1955.
2. C. N. Davies and C. V. Peetz. "Impaction of Particles on a Traverse Cylinder," *Proc. Roy. Soc., Ser. A*, vol. 234, pp. 269-295. 1956.
3. I. Langmuir and K. B. Blodgett. A Mathematical Investigation of Water Droplet Trajectories, RL-225. General Electric Co., Research Laboratory, Schenectady, New York, July 1945.
4. G. Zebel. "Deposition of Aerosol Flowing Past a Cylindrical Fiber

- in a Uniform Electric Field," J. Colloid. Sci. vol. 20, pp. 552-543. 1965.
5. A. G. Amelin and M. I. Belyakov. "To the Problem of Particle Deposition from a Stream," Doklady Akad. Nauk. USSR, vol. 108, no. 1, pp. 31-33. 1956.
6. G. Asset and T. G. Hutchins. "Leeward Deposition of Particles on Cylinders from Moving Aerosols," Am. Ind. Hyg. Assoc. J., vol. 28, pp. 348-353. July-August 1967.
7. A. C. Chamberlain. "Deposition of Particles to Natural Surfaces," Symposia of the Society for Microbiology, Number XVII, Airborne Microbes, pp. 138-164. 1967.
8. M. N. Golovin and A. A. Putnam. "Inertial Impaction on Single Elements," Ind. Eng. Chem. Fundamentals, vol. 1, no. 4, pp. 264-273. 1962.
9. P. H. Gregory. "Deposition of Airborne Lycopodium Spores on Cylinders," Ann. Appl. Biol., vol. 38, pp. 357-377. 1951.
10. H. D. Landahl and R. G. Herrmann. "Sampling of Liquid Aerosols by Wires, Cylinders, and Slides, and the Efficiency of Impaction of the Droplets," J. Colloid. Sci., vol. 4, pp. 103-136. 1949.
11. K. R. May and R. Clifford. "The Impaction of Aerosol Particles on Cylinders, Spheres, Ribbons, and Discs," Ann. Occup. Hyg., vol. 10, pp. 83-95. 1967.
12. W. E. Ranz and J. B. Wong. "Impaction of Dust and Smoke Particles," Ind. Eng. Chem., vol. 44, no. 6, pp. 1371-1381. 1952.
13. J. Rosinski and C. Nagamoto. "Particle Trajectories and Adherence to Cylindrical Sticky Surfaces," Kolloid-Z., vol. 175, no. 1, pp. 349-361. 1967.
14. J. R. Starr. "Inertial Impaction of Particulates Upon Bodies of Simple Geometry," Ann. Occup. Hyg., vol. 10, pp. 349-361. 1967.
15. W. L. Torgeson. Investigation of Impaction Mechanisms of Particles on Collectors in Turbulent Flow, QPR-7-3057. Applied Science Division, Litton Systems, Inc., Minneapolis, Minnesota, 1967.
16. J. B. Wong, W. E. Ranz, and H. F. Johnston. "Inertial Impaction of Aerosol Particles on Cylinders," J. Appl. Phys., vol. 26, no. 2, pp. 244-294. 1955.
17. G. A. Sehmel and L. C. Schwendiman. "Particle Collection Efficiencies on Wires," Pacific Northwest Laboratory Annual Report for 1967, Volume II: Physical Sciences, Part 3: Atmospheric Sciences, BNWL-715-3, pp. 96-100. Battelle-Northwest, Richland, Washington, October 1968.

PARTICLE DEPOSITION FROM TURBULENT FLOW

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A theoretical model was investigated to effectively describe turbulent deposition of particles onto surfaces. Particle transport to the deposition surface is described by particle eddy diffusivities. Two innovations from published deposition models are incorporated into the new model. The first of these is the discarding of the concept that the particle is finally brought to the surface by "free-flight" due to its inertia. The second is that particle eddy diffusivities are not the same as eddy diffusivities for air momentum as is generally assumed. In this study, the particle eddy diffusivities are back calculated from the deposition data. From these calculations, it is concluded that particle turbulent diffusivities are greater than those for air momentum transfer in turbulent flow. The general range of these particle eddy diffusivities has been determined. Continuing study is directed at determining the functional relationship between particle diffusivities and particle properties, air properties, and the distance from the deposition surface. Since the final diffusivity relationship has not been established, the model cannot yet be used to predict deposition. Consequently, all available data on turbulent deposition velocities of particles to the walls of vertical conduits were correlated with an empirical dimensionless equation containing the important variables.

The transport of airborne particles from the bulk carrying stream across boundary layers to a solid surface is a process of considerable theoretical and practical significance. A full understanding of the parameters controlling the deposition of fine particulate material on surfaces would permit calculation of particle losses to the wall of ducts and sampling lines, and would clarify the significance of rebounding and re-entrainment of particles in a variety of situations. Since the particle under many circumstances becomes a tracer for the movement of the carrying air, a confirmation of concepts and theories regarding air turbulence and eddy diffusivity

may accrue from studies of particle deposition.

Particle deposition⁽¹⁾ has been characterized by a deposition velocity, K , defined as the number of particles deposited per unit area per second per unit average concentration in the gas over the surface. Particles carried in an air stream through a conduit are deposited on the walls to a degree depending upon the deposition velocity, tube length, diameter, the average velocity in the stream, the tube surface conditions, and perhaps other variables. The deposition velocity may be calculated from a simplified particle mass balance around a tube from the model,

$$\frac{C}{C_0} = \exp - \frac{4KL}{V_{av}D} \quad (1)$$

in which C is the average concentration of particles in the air at a distance, L , downstream of the initial entering concentration, C_0 ; V_{av} is the average air velocity; and D is the tube inside diameter.

Models have been used to predict the deposition velocities for cases in which a tube surface is a perfect particle sink. In these models, the assumption has always been made that the concentration of particles is maximum in the turbulent core and that the concentration decreases as the tube wall is approached. The transport of particles to the tube wall has been explained in terms of the concentration gradient -- particles go from a high concentration to a low concentration at a rate proportional to the particle diffusivity.

It is the purpose of this study to determine the quantitative relationships among the variables governing particle deposition during turbulent flow of air and to establish deposition models supported by the data. The objectives of recent studies were to fit the data with an empirical correlation to predict deposition velocities in tubes and to develop a new analytical deposition model which is substantiated by the deposition data.

In previous models^(2,7) deposition has been assumed to occur by turbulent diffusion followed by a final free-flight mechanism at the tube wall. In these models the ve-

locities at the start of free-flight have been almost arbitrarily assumed and the particle diffusion coefficients have been assumed equal to the eddy diffusivity of air momentum. For the new model this simplifying assumption is no longer made, since particle diffusion coefficients are back-calculated from the experimental deposition data.

All the experimental data for particle deposition in vertical tubes have been used in the present analysis. These data are those of Friedlander and Johnstone,⁽¹⁾ Schwendiman and Postma,⁽⁸⁾ Stavropolous,⁽⁹⁾ and Sehmel.⁽¹⁰⁾ The data used for Stavropolous and Sehmel are taken from the smooth curves representing their data.

All the deposition data are not comparable from a modeling standpoint. Models would predict that the airborne concentration of particles should decrease as the tube wall is approached. Such concentrations are observed when the tube wall is a perfect particle sink. However, Sehmel^(11,12) has shown that if the tube wall is not a perfect particle sink, the airborne particle concentration may exhibit a maximum concentration in the region near the tube wall. Qualitatively, this anomalous concentration distribution is believed to result from the effects of particle re-entrainment from the tube walls. However, this anomalous concentration distribution has not yet been satisfactorily quantified

in a model. An empirical correlation has been developed to predict particle deposition velocities -- irrespective of the airborne particle concentration profiles above the deposition surface. Of the equations developed to date, the best fit is the following equation,

$$\frac{K}{u_*} = 1.33 \times 10^{-18} \rho^{1.93} R^{3.20} Re^{3.27}, \quad (2)$$

in which K = deposition velocity,
cm/sec,

ρ = particle density, g/cm³,

R = ratio of particle
diameter (μ) divided
by tube diameter (cm),

Re = tube Reynolds number,

u_* = friction velocity
= $V_{av} \sqrt{f/2}$

V_{av} = average velocity
 f = Fanning friction
factor. (13)

All coefficients are statistically significant and the equation has a multiple correlation coefficient of 0.87. This equation is based upon all the deposition data except those for which the deposition decreased as only the air flow rate was increased.

Published models⁽¹⁻⁷⁾ of particle deposition are based upon concepts of particles diffusing toward a deposition surface up to a final "free-flight" distance. Over this distance, particles are assumed to deposit due to particle inertia determined by the particle diffusion velocity at the start of free flight. Various assumptions have been made for this diffusion velocity by Friedlander and

Johnstone,⁽¹⁾ Davies^(2,5) and by Beal.⁽⁷⁾ The validity of their assumptions was tested by using their models to back-calculate the required diffusion velocity from the experimentally observed deposition velocities. The back-calculated diffusion velocities did not substantiate the validity of any of the diffusion velocities assumed in the models.

The assumption that particle deposition is by diffusion followed by free-flight has always been considered suspect by the writer. In models in which this assumption was required, particle turbulent diffusion coefficients were assumed equal to those of the diffusion of air momentum in turbulent flow. This equality may occur in homogeneous turbulence, but as will be shown, does not occur near a deposition surface. To show this inequality, an analytical deposition model is used.

A model is developed which is based upon the experimentally observed turbulent deposition in vertical tubes. The model is based upon particle motion toward a tube wall from a uniform particle concentration in a turbulent core of the tube. Conceptually, diffusion of the particle's center is considered. When the center is a particle radius from the tube wall, the particle will have deposited on the perfect sink wall.

Explicitly, this diffusion model is

$$K^+ = \int_{r^+}^{y^+} \frac{\epsilon}{v} \frac{dC^+}{dy^+} \quad (3)$$

in which C = local airborne particle concentration, (L^{-3})
 C_o = average C across tube radius, (L^{-3})
 C^+ = dimensionless concentration, C/C_o
 f = Fanning friction factor⁽¹³⁾
 K = deposition velocity, N/C_o , (L/t)
 K^+ = K/u_*
 N = deposition flux, ($L^{-2}t^{-1}$)
 r = particle radius, (L)
 r^+ = dimensionless particle radius, (ru_*/v)
 V_{av} = average air velocity, (L/t)
 u_* = friction velocity, (L/t), in tubes $u_* = V_{av}\sqrt{f/2}$
 y = distance from wall, (L)
 y^+ = dimensionless distance, (yu_*/v)
 ϵ = effective particle diffusivity, (L^2/t)
 ν = kinematic viscosity, (L^2/t).

The basic assumptions in using this equation are: (1) a one dimensional model is applicable in the region near the tube wall; (2) the concentration is uniform for y^+ greater than 30; and (3) the effective particle diffusion coefficient, ϵ , describes the total effect of all forces causing particle motion toward the deposition surface. In general, the effective diffusion coefficient, ϵ , is identical to the turbulent particle diffusion coefficient.

The evaluation of the particle diffusion coefficient, ϵ , is the important problem in utilizing the model of Equation (3). These diffusion coefficients were determined from a trial-and-error procedure by using Equation (3) to back calculate ϵ from experimental particle deposition velocities to perfect-sink surfaces. The calculated results are indicated in Figure 1 which shows the variation of ϵ/ν near a surface.

The probable range of turbulent particle diffusion coefficients can be initially estimated from the curves shown in Figure 1. The upper curves of Lin, Moulton and Putnam⁽¹⁴⁾ and Owen⁽²⁾ have been used in published particle deposition models. These curves are for eddy diffusivities of air momentum in turbulent flow and should approximate eddy diffusivities of very small particles. Also shown are particle ϵ/ν calculated from Wakstein's⁽¹⁵⁾ data for 250 μ particles carried in turbulent air flow in vertical pipes. These particle diffusivities are much greater than momentum diffusivities. Since there is this large discrepancy in diffusivities, we conclude that a relationship to represent particle diffusivities of present interest should exist somewhere between the limits suggested by the air momentum diffusivities and the diffusivities of the large particles.

The relative location of any particle diffusivity relationship was further delineated on this figure. The limits of such a relationship were obtained by an iterative procedure which will now be described.

FIGURE 1. Variation of Particle Eddy Diffusion Coefficient ϵ with Distance from the Wall for Turbulent Flow in Tubes

First, all the data for deposition to perfect sinks were considered. These were the cases for which tube surfaces had been made "sticky". Next, values of ϵ/ν as a function of y^+ were assumed in which the assumed relationship tended to approximate the general slopes of the momentum diffusivity curves. In general ϵ/ν was assumed to be proportional to $(y^+)^3$ for $\epsilon/\nu < 1$, and ϵ/ν proportional to y^+ for $\epsilon/\nu > 1$.

The assumed relationships for particle diffusivity were used in Equation (1) to yield a predicted depo-

sition velocity. Next the predicted and experimental deposition velocities were compared. If the predicted deposition were always greater than the experimental, the assumed relationship for ϵ/ν would be greater than the "true" correlation for ϵ/ν . By trial, this upper limit of ϵ/ν as a function of y^+ was determined. Similarly when the predicted deposition was always less than the experimental, the lower limit of ϵ/ν was determined.

These upper and lower limits of ϵ/ν as a function of y^+ are shown as

the limits of the cross-hatch section of Figure 1. From these curves it is concluded that (1), particle diffusion coefficients are greater than that for turbulent momentum transfer adjacent to a tube wall, and (2) the "true" relationships for ϵ/ν as a function of y^+ must lie within the cross-hatched region. These true relationships are being sought for both the one dimensional model as well as a two dimensional model.

The present analysis has shown that particle deposition from turbulent flow cannot be described by equality of eddy diffusivities of momentum and of particles. Particles have greater eddy diffusivities than have been used in published deposition models based upon diffusion followed by free-flight. The new model describes particle deposition caused solely by particle diffusion to a perfect sink.

REFERENCES

1. S. K. Friedlander and H. F. Johnstone. "Deposition of Suspended Particles from Turbulent Gas Streams," Ind. Eng. Chem., vol. 49, pp. 1151-1156. 1957.
2. P. R. Owen. "Dust Deposition from a Turbulent Airstream," Int. J. Air-Water Pollution, vol. 3, pp. 8-25, 50-53. 1960. Also in Aerodynamic Capture of Particles, edited by E. G. Richardson. Pergamon Press, New York, N.Y. 1960. pp. 8-25, 50-53.
3. C. N. Davies. "The Rate of Deposition of Aerosol Particles for Turbulent Flow Through Ducts," Ann. Occup. Hyg., vol. 8, pp. 239-245. 1965.
4. C. N. Davies. "Deposition of Aerosols from Turbulent Flow Through Pipes," Proc. Roy. Soc. London Ser. A, vol. 289, pp. 235-246. 1966.
5. C. N. Davies. Aerosol Sciences. Academic Press, Inc., New York, N. Y. pp. 425-440. 1966.
6. A. C. Wells and A. C. Chamberlain. "Transport of Small Particles to Vertical Surfaces," Brit. J. Applied Phys., vol. 18, pp. 1793-1799. 1967.
7. S. K. Beal. Transport of Particles in Turbulent Flow to Channel or Pipe Walls, WAPD-TM-765. Bettis Atomic Power Laboratory, Pittsburgh, Pennsylvania, April 1968.
8. A. K. Postma and L. C. Schwendiman. Studies in Micromeritics -- Particle Deposition in Conduits as a Source of Error in Aerosol Sampling, HW-65308. Available from AEC Division of Technical Information Extension, Oak Ridge, Tennessee, May 1960.
9. N. Stavropolous. Deposition of Particles from Turbulent Gas Streams, Columbia University, 1957. (M.S. Thesis in Chem. Eng.)
10. G. A. Sehmel. Aerosol Deposition from Turbulent Airstreams in Vertical Conduits, BNWL-578. Battelle-Northwest, Richland, Washington, March 1968.
11. G. A. Sehmel. "Particle Flux Profiles in Turbulent Flow," Pacific Northwest Laboratory Annual Report for 1966 to the USAEC Division of Biology and Medicine, Volume II. Physical Sciences, Part 3. Earth Sciences, BNWL-481-3. Battelle-Northwest, Richland, Washington, 1967.
12. G. A. Sehmel. The Deposition of Aerosols by Turbulent Flow Processes within Vertical Tubes, BNWL-SA-1500. Battelle-Northwest, Richland, Washington, January 1968.
13. Perry's Chemical Engineers Handbook. McGraw-Hill Book Co.,

- Inc., New York, N. Y., 1950.
3rd ed. p. 382.
14. C. S. Lin and R. W. Moulton.
"Mass Transfer Between Solid
Walls and Fluid Streams," Ind.
Eng. Chem., vol. 45, pp. 636-
640. 1953.
15. S. C. Wakstein. The Motion of
Small Particles Suspended in
Turbulent Air Flow in a Vertical
Pipe, Queen Mary College,
University of London, 1966.
(Ph.D. Thesis)

BROWNIAN DIFFUSION IN A NONUNIFORM GAS

W. G. N. Slinn*

The motion of a small Brownian particle in air that is in thermal and translational nonequilibrium has been analyzed. A new force is described which is similar to that used to explain the thermophoresis effect but which depends on the viscous stress in the gas. The solution to the new Fokker-Planck equation in velocity space has been found. In the generalized convective-diffusion equation, the diffusion coefficient appears as a second order tensor and exhibits the influence of the viscous stress tensor on diffusion. The results are limited to the case when the particle's Knudsen number is large compared to unity.

INTRODUCTION

In a previous report⁽¹⁾ it was shown how Markoff's method could be used to obtain a statistical description of the stochastic force on a Brownian particle. There it was assumed that the host gas was in equilibrium and that the particle's Knudsen number was large compared to unity. Here, although the Knudsen number is still assumed to be large, the results for the case when the gas is not in equilibrium will be reviewed. The derivations of these results are given in Reference 2.

With the methods that have been developed it is possible to analyze the motion of a small Brownian particle in an arbitrary environment provided only that the velocity distribution function for the molecules of the gas is known. In the case of

a nonuniform gas, under well-known conditions⁽³⁾, the Chapman-Enskog velocity distribution function can be used. The resulting equations describing the motion of a Brownian particle are applicable to a wide variety of dusty-gas flows; for example, the flow associated with the precipitation scavenging of submicron particles⁽⁴⁾.

THE CONVECTIVE-DIFFUSION EQUATION

Using Markoff's method, the first two moments of the stochastic force on a Brownian particle in a nonequilibrium environment were calculated. These were used to formulate a generalized Fokker-Planck equation⁽⁵⁾. By extending Kramers' method⁽⁶⁾, a new Smoluchowski equation was derived. Finally, introducing a number density N of Brownian particles a generalized convective-diffusion equation was obtained:

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$$\frac{\partial N}{\partial t} = \nabla \cdot \left[\tilde{D} \cdot \nabla N + N (\nabla \cdot \tilde{D} - \vec{V}_d) \right] \quad (1)$$

where

$$\vec{V}_d = \vec{V}_f + \frac{\vec{f}^{(e)}}{\beta^*} + \frac{\vec{q}}{5p} + \tilde{D} \cdot \left[\frac{\Delta \beta^*}{\beta^*} - \frac{\Delta \cdot \tilde{\tau}}{5p} \right] + \frac{\vec{f}^{(e)}}{\beta^*} \cdot \frac{\tilde{\tau}}{5p} \quad (2)$$

in which

$\vec{V}_f$ is the fluid velocity

$\vec{f}^{(e)}$ is any external force per unit mass acting on the particle

β^* is the drag coefficient per unit mass

p is the local pressure in the fluid

$\vec{q}$ is the heat flux

$\tilde{\tau}$ is the viscous stress tensor

and where the diffusion coefficient appears as the second order tensor

$$\tilde{D} = D^* \left[\tilde{\gamma} - \frac{\tilde{\tau}}{5p} \right] \quad (3)$$

in which, for specular reflection of the molecules, D^* is the usual Einstein diffusion coefficient and $\tilde{\gamma}$ is the identity or metric tensor.

The first two terms in the expression for the drift velocity, Equation (2), are well known. The third explains the thermophoresis effect⁽⁷⁾. The next term arises from spatial variations in the drag coefficient and stress tensor. The final term is new

and might be called the stress-phoresis effect. It is hoped that experimentalists could devise methods to observe this new drift velocity.

The tensorial character of the diffusion coefficient, Equation (3), implies that in a flow in which there exist viscous stresses, Brownian particles do not diffuse spherically symmetrically. Surfaces of constant density, instead of spherical, are ellipsoidal about the mean position dictated by the drift velocity, Equation (2). The dependence of $\tilde{D}$ on $\tilde{\tau}$ at least qualitatively explains the observations reviewed by Fuchs⁽⁸⁾ that the diffusion coefficient in a nonequilibrium environment depends on the fluid velocity. Quantitative investigations are planned.

REFERENCES

1. W. G. N. Slinn. "The Convective Diffusion Equation for the Scavenging of Submicron Particles," Pacific Northwest Laboratory Annual Report for 1967, Volume II: Physical Sciences, Part 3. Atmospheric Sciences, BNWL-715-3. Battelle-Northwest, Richland, Washington, October 1968.
2. W. G. N. Slinn. Brownian Diffusion of Submicron Particles in Air Under Nonequilibrium Conditions, BNWL-987. Battelle-Northwest, Richland, Washington, February 1969.
3. W. G. Vincenti and C. H. Kruger. Physical Gas Dynamics. John Wiley and Sons, New York, N. Y., 1965.
4. W. G. N. Slinn. "Theory of the Precipitation Scavenging of Submicron Particles," USAEC Meteorological Information Meeting, Chalk River, Ontario, AECL-2787. September 1967.

5. S. Chandrasekhar. "Stochastic Problems in Physics and Astronomy," Rev. Mod. Phys. vol. 15, no. 1, 1943.
6. H. A. Kramers. "Brownian Motion in a Field of Force and the Diffusion Model of Chemical Reactions," Physica VII, p. 284. 1940.
7. L. Waldmann and K. H. Schmitt. "Thermophoresis and Diffusio-phoresis of Aerosols," Aerosol Science, edited by C. N. Davies. Academic Press, New York, N. Y., 1966.
8. N. A. Fuchs, The Mechanics of Aerosols. Pergamon Press, New York, N. Y., p. 207. 1964.

MICROMETEOROLOGICAL INVESTIGATIONS ON THE ALE RESERVE

W. T. Hinds*

The design of an inexpensive and accurate anemometer using ducted air fans is discussed, and the accuracy and calibration with respect to standard cup-type anemometers is shown. The Self-Orienting Fan Anemometers (SOFA) are shown to agree within $\pm 2\%$ between themselves, and to agree within about $\pm 3\%$ with the cup anemometers over a range of wind speeds from about 0.5 to more than 7 m/sec. Each SOFA costs about \$80 for parts and takes about an hour for assembly.

The interaction of atmosphere and organisms takes place primarily in two transfers: energy and mass (moisture, usually). The simplest tools for estimating these transfers stem from the hypothesis that flux is proportional to gradient, so that measurement of profiles allows estimation of flux. With this starting point, the ALE micrometeorology work has centered on acquiring appropriate tools for profile measurement. In the annual report for 1967, the temperature profile micrometeorology mast was described; in the following sections, the design and development of a wind profile mast is discussed.

The wind profile is basic in this aerodynamic approach to energy and mass transfer since the wind field is the primary mechanism for mixing energy or mass fluxes with the atmospheric reservoir. Although organisms are not usually sensitive to wind profiles as such (except extremes) the wind profile is essential in measuring certain characteristics of the atmosphere-surface interaction that

influence all fluxes; the most important of these characteristics are surface shear stress (drag), surface roughness, and atmospheric stratification (stability).

The simplest approach to estimating sensible heat flux involves both wind and temperature profiles. The wind profile is used to measure shear stress, which allows estimation of the vertical transfer of momentum; the transfer of momentum down the wind profile gradient is then assumed to be the same as the transfer of sensible heat down the temperature gradient. Thus, using the wind profile mast with the temperature profile mast, the transfer of sensible heat to or from plant communities can now be estimated.

Commercial anemometers generally are of two types: continuously recording and totalizing. The recording types are generally expensive because of the costs inherent in recording machinery. The totalizing types are substantially less expensive.

One inexpensive type of anemometer that offered a solution is the ducted

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fan design. This design has the commendable traits of sensitivity, small size and low purchase cost, but has the severe drawback that it must be oriented directly into the wind stream before reliable measurements are possible. A very simple wind-oriented platform for these fans is described in the following paragraphs and performance characteristics of the composite are discussed.

Construction of a Wind-Oriented Platform

The simplest possible design for an orientable platform is a swivel or bearing supported base with a tail that provides the necessary torque. A workable design is shown in Figure 1. The bearing is a half-inch shaft mounted ball bearing set in the lower platform, with the fan base mounted on the shaft. A sheet aluminum tail attached to a rod provides the area for turning moment due to wind flow. The dimensions are of course rather arbitrary, since the only constraint is that the tail assembly must balance the sensor head. However, it seems likely that truly small dimensions would be difficult to achieve, because the fan weighs very nearly a pound, thus fixing a minimum torque required to orient the assembly in light winds which in turn implies a minimum area for the tail assembly.

Performance

Preliminary checks of performance are encouraging. The Self-Orienting Fan Anemometer (SOFA) shown in Figure 1 was exposed simultaneously with

FIGURE 1. Operating Configuration of the Self-Orienting Air Fan (SOFA)

a standard Shepard-type sensitive cup anemometer at the same location (one meter distant) and checked for performance in a variety of wind speed conditions. The SOFA agreed well with the cup anemometer in moderate to strong winds, but indicated lower wind speeds than the cup anemometer in light wind conditions, as shown in

Figure 2. Since the fan must be oriented into the wind, the SOFA will underestimate the wind flow any time it is not properly oriented; thus, the SOFA will underestimate the actual wind speed in winds approaching the threshold of orientation. Tests in light winds (using the cup anemometer to measure the wind speed) indicated that the SOFA construction shown in Figure 1 will provide orientation in wind speeds of about 20 to 30 cm sec^{-1} , speeds that approximate

FIGURE 2. Comparison of Indicated Wind Speed from the SOFA and a Sensitive Cup Anemometer

the threshold for the fan itself. However, in these very light winds the response of the SOFA is slow enough that considerable underestimation of wind speed results. Reduction of the mass of the fan, if possible, will improve the low speed response, but this step has not yet been attempted.

Comparisons of five fan anemometers in a wind tunnel over a speed range of 0.5 to 12 meters per second indicated that the fans are precise and quite comparable between themselves. In general, no more than $\pm 2\%$ variation between anemometers was found, a commendable accuracy for a simple mechanism.

Conclusion

The cup-type anemometer used here for the standard of comparison is calibrated to yield true wind speed (albeit in nongusty conditions) so that the lower mean wind speed indicated by the SOFA in light winds is probably due to misorientation of the fan. However, this systematic error is correctable by calibration and in moderate to strong winds the two types of anemometers agree very well. It is our feeling then that the SOFA will yield useful data for a small expense.

A CLIMATOLOGICAL SURVEY OF TEMPERATURE-PRECIPIRATION-
VEGETATION RELATIONS ON THE ALE RESERVE

W. T. Hinds* and J. M. Thorp

A description of the major vegetation cover types and their distribution on the ALE Reserve follows a description of the elevational transects on the Reserve. The data collected to date (temperature and rainfall from March 1968) are used to show that the mountain-valley inversion in the Hanford region intersects Rattlesnake Mountain at about 1000 ft MSL, and that the inversion is probably more pronounced in equinoctial seasons than in solstice seasons. The microclimatic amelioration due to the inversion is pointed out. It is also shown that rainfall increases with elevation rather uniformly. An estimated precipitation efficiency (the ratio of estimated annual rainfall to estimated evapotranspiration) is calculated and this indicates a marked increase in efficiency above about 800 ft MSL, coincident with a marked alteration in floristics.

Climatological data are among the most fundamental that may be collected in the early phases of ecological investigation, and, because several years are required to provide confidence in any climatological averages of interest, an early start in measurement of climatic variables is usually advisable. These thoughts led to an early establishment of a network of microclimatological study sites on the AEC's Arid Lands Ecology (ALE) Reserve on the Hanford Works Reservation in Eastern Washington. The network was laid out with the aid of scientists from Terrestrial

Ecology such that all major vegetation cover types or variants were included in the network. This paper provides a brief description of the various cover types found on the reserve, and a discussion of preliminary results from the climatological measurements. Clearly, most of the results are preliminary in nature and may be subject to modification as data accumulate.

Description of the Climatological
Network

The network of microclimate study sites lies on five elevational transects in various degrees of completeness. As shown in Figure 1, the Snively Ranch transect is the northernmost, beginning in upper Cold

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Creek Valley and continuing up into Snively Basin to an abandoned field at an elevation of 1700 ft MSL. The Benson Ranch transect begins in an abandoned field of the old Benson Ranch in Cold Creek Valley and continues over the crest to Anderson's wheat fields, currently under cultivation, at an elevation of 3100 ft MSL. The Central transect begins in the center of Cold Creek Valley in an old playa and continues over the crest at a spring near the summit of Rattlesnake Hills, at 3500 ft MSL. The Winterfat transect begins just out of Cold Creek Valley (near an ecotone between Artemisia tridentata and Eurotia lanata) and continues to the shoulder of the Hills at an elevation of 3100 ft. The Blacktop transect begins in lower Cold Creek Valley and follows a blacktop road to the summit. This transect essentially follows the skyline of the southern portion of the Hills above about 2000 ft MSL and intersects the upper end of both the Winterfat and Central transects. The Benson Ranch transect has provided the most coherent data so far. It is well removed from "edge effects" caused by topographic changes, and is reasonably densely instrumented, so most of the analyses to follow rely heavily on data from this transect.

Plant Cover Types

Two major cover types characterize nearly all the region -- "tall grass" shrubland and "short grass" shrubland. Several other cover types appear in the remaining (small) fraction of the landscape. The following sections describe the general composition of the various cover types and some of their important variations. A more detailed description of the biotic and abiotic characteristics of the ALE Reserve is given by Hinds and Thorp (1969).

Artemisia/Poa (A/P)

The prototype of the "short grass shrubland" on the ALE Reserve is the Artemisia tridentata/Poa secunda cover type, which occurs at lower elevations and extends up to about 800 ft above mean sea level (MSL). Very nearly all of the landscape at low elevations is taken up with this cover or one of its variants, which include (among others):

- Artemisia tridentata-Purshia tridentata/Poa secunda
- Artemisia tridentata-Grayia spinosa/Bromus tectorum
- Artemisia tridentata/Bromus tectorum

Neg 0693126.3

FIGURE 1. Cover Types and Transects of the Ale Reserve

- Old (abandoned) agricultural fields

A great deal of the land area below about 650 ft MSL has been disturbed in one way or another -- by fire, over-grazing or cultivation-- and in those regions, Bromus tectorum is more conspicuous than Poa secunda, although Poa occurs throughout the area (sometimes being restricted largely to shrub canopies). In relatively undisturbed regions, mostly

above 650 ft MSL, the Artemisia/Poa cover type is nearly free from Bromus tectorum, as shown in Figure 2. There are six climatological sites established within this cover type and its variants; the rectangular objects in Figure 2 and the following Figures are Styrofoam shelters housing two U-type maximum/minimum thermometers with their sensing elements at 2.5 dm (10 in.) above the surface.

FIGURE 2. *Artemisia/Poa Cover Type*

Artemisia/Agropyron (A/A)

The Artemisia tridentata/Agropyron spicatum cover type is the prototype of the "tall grass shrubland" on the Reserve. This cover type, or one of its variants, is commonly found above about 800 ft MSL. Variants of this cover type include:

- Grassland regions mostly without shrubs (due to a widespread fire in 1957)
- Artemisia tripartita/Agropyron spicatum
- Agropyron spicatum-Festuca idahoensis
- Old (abandoned) agricultural fields

An extensive fire in 1957 burned the shrubs from a substantial area, leaving a temporary grassland, shown in Figure 3. Unburned regions, shown in Figure 4, are smaller than the burned region but still comprise a substantial area of this cover type. Only restricted habitats with more mesic conditions support the A. tripartita/Agropyron or Agropyron-Festuca variants, which typically occur at higher elevations (above about 2500 ft MSL) and on north- or east-facing slopes. The abandoned fields (which support well developed stands of Bromus tectorum mixed with several forbs and some feral wheat) are located in the northern half of the Reserve (the Snively Ranch region) at elevations ranging from 1700 to 1900 ft MSL. There are 16 sites located within this widespread cover type and its variants.

Sarcobatus vermiculatus (S)

This cover type is restricted to a small area near the northern end of the Reserve where there is a perched water table 30 or 40 ft below the ground surface. Variants of this interesting but minor cover type include stands with Artemisia tridentata and Grayia spinosa included. Grasses in this cover type include Bromus tectorum and Distichlis stricta. One site is situated in this cover type.

Grayia spinosa (G)

Pure stands of this shrub occur in what appear to be old playas along the floor of Cold Creek Valley. Grasses associated with the shrub are sparse, with Bromus tectorum the most conspicuous and Poa secunda (where it occurs) restricted to shrub canopies. The large proportion of bare soil found in this cover type contrasts strongly with most of the other cover types. There is one site in this cover type.

Eurotia/Poa (W)

The Eurotia lanata/Poa secunda cover type occurs in a rather narrow elevational band between about 650 and 850 ft MSL along the southern and central regions of the ALE Reserve. It does not appear to overlap into the regions where Agropyron occurs, so the only variant in this cover type is an admixture of

FIGURE 3. *Artemisia/Agropyron (burned) Cover Type*

FIGURE 4. *Artemisia/Agropyron Cover Type*

Artemisia tridentata which occurs in some areas. One site is located in this cover type.

Eriogonum (E)

The Eriogonum spp. cover type occurs on rocky ridge crests, usually at the higher elevations, and may descriptively be called a "lithosolic" type. The vegetation is low, sparse and wind pruned; cushion form species such as Eriogonum thymoides are prominent. The distribution of this interesting cover type is restricted and includes some lightly protected spots which support Poa secunda and Agropyron spicatum. There is one site in this cover type.

Area of the Various Cover Types

The approximate boundaries of the cover types and distribution of the transects were indicated in Figure 1. Note that the Artemisia/Agropyron cover type is the most widespread, and that most of the remaining area is characterized by Artemisia/Poa. Table 1 indicates the approximate area of each cover type and emphasizes the imbalance.

TABLE 1. Approximate Area of Various Cover Types

Cover Type	Sq Miles	Sq Kilometers
<u>Artemisia/Poa</u>	50	130
<u>Artemisia/Agropyron</u>	60	150
<u>Sarcobatus</u>	0.1	0.3
<u>Grayia</u>	1	3
<u>Eurotia</u>	4	10
<u>Eriogonum</u>	0.5	1.5

Temperature Relations on the ALE Reserve

Data have been collected routinely since March 1968 and, climatologically, do not yet form a complete body of data. Nevertheless, patterns are clear, even though details will vary from year to year. The following is a brief discussion of some of the more important indications to be gained from the data, such as: the influence of the mountain-valley temperature inversion in ameliorating local climates, variations in precipitation efficiency (as indicated by calculated potential evapotranspiration), and indications of precipitation gradients over the Reserve.

Air Temperature Patterns Over the ALE Reserve

A definite and repeated air temperature pattern over the Reserve has become increasingly apparent. The pattern of weekly maximum temperatures is fairly straightforward, with essentially a uniform adiabatic (-5.6 °F/1000 ft) lapse rate of temperature with increasing elevation. Local topography modifies this generalization, especially near the crest of the Rattlesnake Hills. Most notable, perhaps, are the relatively cool environments of Sites 10 and 14. Also noticeable is a persistent tendency for the highest temperatures to occur at Sites 1 and 5.

Isotherms of minimum temperature indicate a well defined temperature

inversion perhaps 600 ft thick above the valley floor. The depth of the inversion may be dependent on season, as indicated in Figure 5, but the measurements are too widely separated in elevation to assure that the warmest part of the inversion is always measured. However, the intensity of the inversion seems strongly dependent on season. During the equinoctial months near October and April, air temperatures near the top of the inversion are some 10 to 15 degrees higher than at the valley floor, whereas, during the solstice months near January and July, the top is only some 5 to 10 degrees higher. The physical processes that may lead to seasonal variation of inversion intensity are not known at present.

In any case, the result is that the microclimates at, say, 100 ft MSL are significantly altered by the varying inversion intensity. For example, during autumn and spring, when many plants are actively growing, night temperatures at 1100 ft MSL are substantially warmer than at 600 ft MSL (the valley floor), as shown in Figure 6. Thus, the frost-free season is substantially longer at 1100 ft MSL than at the valley floor. This amelioration of climate may be correlated with the conspicuous ecotone between Artemisia/Poa and Artemisia/Agropyron cover types that occurs somewhat below 1100 ft MSL, although the relationship is as yet unclear (Price, 1965).

It is noteworthy that the inversion layer is larger and more uniform in areal extent during the warmer

months even though the intensity is reduced. During the cooler months, the warmest area is restricted mostly to regions near the middle of the mountain massif.

Precipitation Efficiency

A plausible idea of gradations in precipitation efficiency (that is, the relation between precipitation and evaporative stress) may be deduced from an estimate of potential evapotranspiration and the differences in precipitation observed in the network of sites. Only a few months of precipitation data are available, so the following quantitative discussion is tentative.

A considerable degree of understanding of precipitation efficiency is available from interpretation of the flora surrounding the network sites; there is a substantial alteration in floristics from one site to another and from one elevation to another. In particular, higher elevations show an increase in number of species, and in places, the existence of species known to require more mesic moisture relations than exist at lower elevations -- Festuca idahoensis is an example.

Table 2 shows estimates of potential evapotranspiration calculated by Thornthwaite's (1954) method, (though controversial, this method is still indicative). The requisite temperature data were gathered during 1968. Potential evapotranspiration (PE) increases with elevation between Sites 5 and 7, in conjunction

Neg 0693126-5

Neg 0693126-7

FIGURE 5a. Isotherms of Weekly Minimum Temperatures of the Ale Reserve (October and January)

Neg 0693126-11

Neg 0693126-6

FIGURE 5b. Isotherms of Weekly Minimum Temperatures of the Ale Reserve (April and June)

Neg 0690528-2

FIGURE 6. Maximum and Minimum Temperatures at Benson Ranch (Site 5, 620 ft MSL) and the Alluvial Fan (Site 7, 1140 ft MSL)

with the increase of minimum temperatures due to the inversion mentioned earlier; thus, the increase in PE may not be real. With additional increase in elevation, however, PE

decreases rapidly. Precipitation data for Autumn 1968 are included to give an idea of the measured increase of precipitation with elevation. From this brief table it is apparent that both the amount and the efficiency of precipitation increases with altitude, in conjunction with the change in floristics of the areas, as mentioned above.

Estimates of the ratio of precipitation to potential evapotranspiration are given in Table 2. These estimates are based on the climatological expectation that one-third

TABLE 2. Annual Potential Evapotranspiration at Selected Sites

Site No.	Elevation ft, MSL	PE, cm/yr ¹	Autumn, 1968 Precipitation, cm	$\frac{P}{PE}$ Estimated
5	620	75	6.0	0.2
7	1140	80	7.4	0.3
8	1930	70	9.5	0.4
10	2900	60	10.4	0.5
Hanford Tower	740	75	5.9	0.2

the annual precipitation occurs during autumn, and are therefore only a gross approximation. Nevertheless, there is a striking gradation in the ratio, indicating a substantial margin for variation in cover type and community structure. Future work will: 1) elaborate and define the climatic character and gradations in this region, for use in determining the interaction between community structure and climate; and 2) define micrometeorological phenomena in this region, for use in determining the interrelationship between function in the plant communities and the atmospheric environment.

References

1. Hinds, W. T., and J. M. Thorp. Biotic and Abiotic Characteristics of the Microclimatological Network on the Arid Lands Ecology Reserve, BNWL-SA-2733. Battelle-Northwest, Richland, Washington 99352. 1969.
2. Price, K. R. Uptake of Iodine-131 from the Soil as Related to Root Distribution and Phenology in Sagebrush Vegetation. Ph.D thesis in Botany, Washington State University, Pullman, Washington. 1965.
3. Thornthwaite, C. W. "A Re-Examination of the Concept and Measurement of Potential Evapotranspiration," in The Measurement of Potential Evapotranspiration, edited by John R. Mather. Johns Hopkins University Laboratory of Climatology, Publications in Climatology, Vol VII, No. 1, Seabrook, New Jersey. 1954.

EVAPORATIVE COOLING OF HEATED IRRIGATION WATER BY SPRINKLER APPLICATIONS

J. F. Cline,* M. A. Wolf, and F. P. Hungate**

By passing water through a standard irrigation sprinkler, heated water was cooled to temperatures satisfactory for plant growth. Reducing the droplet size was the most important factor affecting the rate of heat loss. Droplet temperatures approached but did not reach wet bulb temperatures.

This study was undertaken to measure the extent of temperature reduction of warm water that can be attained by the use of a standard sprinkler and to identify the role of specific environmental and operating factors affecting the cooling rate of water droplets passing through air.

Observations

The experimental results in Table 1 show how supply water temperatures and pressures and associated wet and dry bulb atmospheric temperatures affect the impact temperature of water dispersed through

TABLE 1. Temperature Changes in Heated Water Applied with an Irrigation Sprinkler (Sprinkler: One meter above ground level)

Supply Water		Air Temp, °C		Temperature of Water Droplet at Ground Level, °C				
Pressure, psi	Temp, °C	Dry Bulb	Wet Bulb	4(a)	6(a)	8(a)	10(a)	12(a)
48	50	21	10	14.4 ± 0.8	15.6 ± 1.8	17.2 ± 1.4	18.9 ± 1.3	21.1 ± 1.3
45	50	19.5	10	15.6 ± 0.5	15.0 ± 1.7	17.8 ± 1.8	20.0 ± 0.9	23.3 ± 1.0
40	50	21	10	15.6 ± 0.4	15.6 ± 1.7	17.2 ± 1.8	21.1 ± 0.9	23.9 ± 1.0
35	50	20	9	15.6 ± 0.3	16.7 ± 1.4	17.8 ± 1.4	22.2 ± 0.8	23.9 ± 0.9
30	50	21	10	15.6 ± 0.4	15.6 ± 1.3	17.2 ± 0.1	23.3 ± 1.0	25.0 ± 1.3
25	50	20	9	16.1 ± 0.7	21.1 ± 2.1	25.0 ± 1.0	26.1 ± 1.0	----
20	50	20.5	10	15.6 ± 0.6	15.6 ± 0.6	20.0 ± 0.6	32.8 ± 1.3	----
41	33	12	5	10.0 ± 0.7	11.1 ± 0.6	11.1 ± 1.0	12.8 ± 0.8	15.6 ± 0.7
44	32	20	10	13.9 ± 0.6	12.2 ± 0.6	14.4 ± 1.7	16.1 ± 0.7	17.8 ± 0.05
30	32	20	10	13.9 ± 0.7	13.9 ± 1.0	15.6 ± 1.3	18.3 ± 1.3	21.1 ± 0.05
20	32	20	10	14.4 ± 0.6	15.0 ± 0.6	17.8 ± 0.6	23.3 ± 0.6	----
44	14.5	20	10	11.1 ± 0.6	11.1 ± 0.5	11.1 ± 0.06	11.1 ± 0.4	12.2 ± 0.05
48	15	18	11	13.3 ± 0.1	12.8 ± 0.3	12.8 ± 0.1	12.8 ± 0.3	13.9 ± 0.2
40	15	18	11	13.3 ± 0.1	13.3 ± 0.3	12.8 ± 0.2	12.8 ± 0.05	13.9 ± 0.1
30	15	18	11	14.4 ± 0.05	13.9 ± 0.3	13.9 ± 0.3	13.9 ± 0.1	14.4 ± 0.05
20	15	18	11	14.4 ± 0.1	13.9 ± 0.3	13.9 ± 0.3	14.4 ± 0.3	----

a. Horizontal distances in meters from the sprinkler head.

± = 1 SD

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an irrigation sprinkler. The higher impact temperatures at the greater distances were due to the larger water droplet sizes which were cooled less efficiently because of the reduced surface to volume ratio. Table 2 shows the relationship of measured mean droplet diameter with distance from the sprinkler head operating at a water pressure of 45 psi. Cooling rates were very slow at operating pressures of 20 psi due to the very limited break up especially at 10 m from the sprinkler. This was the only condition under which 50 °C water was not cooled to a temperature less than 30 °C in this experiment.

TABLE 2. Characteristics of Sprinkler Water Curtain with Nozzle Pressure of 45 psi

Water Droplet Characteristics	Horizontal Distance from Sprinkler Head to Point of Deposition, m						
	0	2	4	6	8	10	12
Vertical curtain height, m	1	2.2	2.8	3.4	3.6	1.6	0.1
Mean droplet diameter, mm	-	1.3	1.3	1.5	1.6	2.0	1.7
Terminal velocity, cm/sec ¹	-	-	490	540	565	650	587
Vertical distance in meters to reach terminal velocity [Engelmann, 1962]	-	2	2	2.5	2.8	3.6	3.0

The experimental data are particularly well suited for comparison with the theoretical model because the use of a single sprinkler minimized possible modification of the environment. Also, wind conditions were light during the tests. Thus, model

calculations were made to compare with and to extend the experimental results. Theoretical determination of droplet cooling is provided in the equation⁽¹⁾

$$\frac{dT}{dt} = \frac{3G}{a^2 \rho c_p} \left[K(\theta - T) - \frac{LMD}{R\phi} (e_T - f e_\phi) \right]$$

T is the water temperature

θ is the air temperature

e_T, e_θ are the saturation vapor pressures at the temperature of the water and air, respectively

f is the relative humidity

a is the droplet radius

$\phi = (T + \theta) / 2$

R is the gas constant

M is the molecular weight of water

L is the heat of vaporization of water

D is the coefficient of diffusion of water vapor in air

ρ is the density of water

c_p is the specific heat of water

K is the thermal conductivity of air

G is the ventilation coefficient

Comparison was made with only one experimental case - the second listed in Table 1.

Model input values were the supply water temperature and the ambient air temperature and humidity. Initial velocity components were derived from the measured nozzle velocities shown in Table 3, and the initial angle of the water jet was determined to be approximately 40°. Droplet diameter was arbitrarily selected as 1.6 mm shown in Table 2 as the mean diameter for water droplets at eight meters from the nozzle. The theoretical cooling should be comparable to the

TABLE 3. Water Velocity from Sprinkler Nozzle (3.9 mm in diameter)

Water Pressure, psi	Velocity At Nozzle, m/sec
20	18.1
23	19.1
30	20.5
35	21.9
44	23.7
46	25.8

experimental value determined at eight meters. The above case theoretically indicated droplet impact at 7.2 m and cooling the water to 18.3 °C after nearly 1.7 sec of travel time. This cooling curve is shown in Figure 1 as Case A.

Figure 1 also compares the theoretical cooling curve for the selected experimental case with theoretical curves for other environmental

FIGURE 1. Relationship of Droplet Cooling Rate to Atmospheric Temperature and Humidity

conditions. Cases B and C are typical of the arid conditions of Eastern Washington in summer. Case D, which represents an extremely high dew point for an arid climate, is a hypothetical case which is included to demonstrate the effect of a high dew point on the cooling rate. The environmental conditions for each case are given in Figure 1. In all cases, the initial water temperature is 50 °C, and the nozzle velocity is 24.5 m/sec¹.

Except for the hypothetical case, droplet cooling to temperatures below the critical value of 30 °C was accomplished in approximately 0.5 sec which was well before droplet impact with the surface. Comparison of Case D with Case C reveals, since air temperatures for these cases are equal, that the cooling rate is severely impeded when the dew point is high. The lesser influence of the air temperature on cooling also is demonstrated by the clustering of the curves of Cases A-C spanning a temperature range from 19.5 to 38 °C.

Conclusions

As shown by the experimental results, and by extrapolating to other typical atmospheric conditions, it appears that in an arid region, water at 50 °C can be applied by sprinkler without causing any heat damage to plants. The calculated curve shows that, even in a climatic condition of high dew point and suppressed evaporation, a very appreciable cooling can be anticipated. Two factors not considered in this experimental program

were the effects on droplet cooling by wind action and the increased humidity due to upwind irrigation. Generally, wind is present in these areas, and irrigation is sufficiently extensive to modify the immediate environment. These effects can be stated only qualitatively without further investigation.

Locally increased water vapor content of the air could reduce the rate of droplet cooling and result in higher impact temperatures. It is not clear what the net effect would be if a mean wind were blowing across a field irrigated with rotating sprinklers. However, if the droplets were moving with the wind, a reduced cooling rate would be expected. The cooling rate would be increased if the droplets were moving into the wind because the ventilation coefficient is dependent on relative speed between the droplet and the air. The effect of the mean wind would likely be cancelled except at the edges when the standard overlapping sprinkler patterns are used.

Some control of temperature decrement was achieved by modifying nozzle pressure. Special designed sprinkler heads to produce greater differences in droplet sizes would permit the production of water at different temperatures necessary for spring and summer irrigation. Also, cooler water temperatures can be obtained by increasing the height of the sprinkler head and the nozzle angle. Optimum methods of using warm water will be developed as greater experience is gained.

Reference

1. Best, A. C. "*The Evaporation of Rain Drops*", Quart Journal of Royal Meteorological Society, vol. 78(366), pp. 200-225. 1952.

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PUBLICATIONS AND PRESENTATIONSDOCUMENTS

R. J. Engelmann and W. E. Davis. Low Level Trajectories and the MIDAS Computer Program for the Montgomery Stream Function, BNWL-441. April 1968.

T. W. Horst. Particle Transport in a Condensing Steam Environment, BNWL-848. June 1968.

Staff of the Atmospheric Sciences Department. Pacific Northwest Laboratory Annual Report for 1967 to the USAEC Division of Biology and Medicine, Volume II: Physical Sciences, Part 3. Atmospheric Sciences, BNWL-715-3. Battelle-Northwest, Richland, Washington, October 1968.

PUBLICATIONS

R. A. Hasty. "Reaction of Hydrazine and Iodomethane--Removal of Iodomethane from a Gas Phase in Contact with Alkaline Hydrazine Solution," Chem. Eng. Data J., vol. 12, no. 1, p. 134. January 1968.

J. Mishima. "Methyl Iodide Behavior in Systems Containing Airborne Radioiodine," Nucl. Safety, vol. 9, no. 1, p. 35. January-February 1968.

W. T. Hinds and W. H. Rickard. "Soil Temperatures Near a Desert Steppe Shrub," Northwest Science, vol. 40, February 1968.

G. A. Sehmel. "A Particle Size Distribution Function for Data Recorded in Size Ranges," Ann. Occup. Hyg., vol. 11, no. 2, pp. 87-98. April 1968.

J. D. Ludwick, J. J. Lashock, R. E. Connally, and P. W. Nickola. "Automatic Real Time Air Monitoring of ⁸⁵Kr Utilizing the 4096 Memory of a Multi-parameter Analyzer," Rev. Sci. Instr., vol. 39, no. 6, June 1968.

L. C. Schwendiman. "An Outline of Research at Pacific Northwest Laboratory Related to Airborne Particles," J. Air Pollution Control Assoc., vol. 18, no. 10, pp. 678-680. October 1968.

W. G. N. Slinn and S. F. Shen. "Brownian Diffusion of Submicron Particles Imbedded in an Arbitrary Air Flow," Bull. Am. Phys. Soc., vol. 13, p. 1593, 1968.

PRESENTATIONS

G. A. Sehmel. "The Deposition of Aerosols by Turbulent Flow Processes within Vertical Tubes," Pacific Northwest Regional Meeting of the AIChE, Corvallis, Oregon, February 2, 1968.

G. A. Sehmel. "Particle Sampling Bias Introduced by Anisokinetic Sampling and Deposition within the Sampling Line," Annual Conference of the American Industrial Hygiene Association, St. Louis, Missouri, May 13-17, 1968.

R. A. Hasty. "The Rate of Reaction of Methyl Iodide and Hydrazine in Aqueous Solution," 23rd NW Regional Meeting of the American Chemical Society, Portland, Oregon, June 14, 1968.

L. C. Schwendiman. "An Outline of Research at Pacific Northwest Laboratory Related to Airborne Particles," Air Pollution Control Association 61st Annual Meeting, St. Paul, Minnesota, June 23-27, 1968.

W. T. Hinds. "Some Environmental Consequences of Shading in Shrub Communities," Western Section of the AAAS, Logan, Utah, June 24-28, 1968.

A. K. Postma and L. C. Schwendiman. "Absorption by Reactive Sprays with Appreciable Liquid Phase Mass Transfer Resistance--The Washout of Methyl Iodide by Reactive Sprays," Symposium on Operating and Developmental Experience in the Treatment of Airborne Radioactive Wastes, New York City, New York, August 26-30, 1968. (Published in the proceedings of the meeting).

L. C. Schwendiman, J. Mishima, and C. A. Radasch. "Airborne Release of Particles in Overheating Incidents Involving Plutonium Metal and Compounds," Symposium on Operating and Developmental Experience in the Treatment of Airborne Radioactive Wastes, New York City, New York, August 26-30, 1968.

J. M. Hales. "Hybrid Computer Simulation of Particle Transport in a Condensing Steam System," Spray Technology Meeting at Washington, D.C., November 13, 1968.

W. G. N. Slinn. "Brownian Diffusion of Submicron Particles Imbedded in an Arbitrary Air Flow," American Physics Society, Fluid Dynamics Section Meeting, Seattle, Washington, November, 1968.

W. G. N. Slinn. "Brownian Diffusion of Particles with Large Knudsen Numbers in Nonuniform Gases," Society of Industry and Applied Mathematics Regional Meeting, Richland, Washington, November, 1968.

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