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FINAL REPORT No. 543-14

18 February 1963

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U. S. Army Chemical Corps
Research and Development Contract
DA-42-007-CML-543

AEROSOL LABORATORY

METRONICS ASSOCIATES, INC.

STANFORD INDUSTRIAL PARK
PALO ALTO, CALIFORNIA

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FINAL REPORT

543-14

28 February 1963

SUMMARY OF INVESTIGATIONS

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F. X. Webster
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Chemical Corps Research and Development Program
Contract No. DA 42-007-CML-543

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PREFACE

This final report summarizes the work performed in connection with each of the three major tasks under contract DA-42-007-CML-543. In order of discussion the tasks are:

1. Analysis of Trial Results From Elevated Sources
2. Summary of Chemical Corps Research and Development Program Conducted by Stanford Aerosol Laboratory
3. Development in FP Tracer Technology

During the contract period most of the results have been presented in the Monthly Progress Reports numbered 543-1 through 543-13 covering the period 1 December 1961 - 31 December 1962. Upon completion of a task or major phase thereof the results are presented in Technical Reports. Two have been completed and four are in final process of completion.

In this report the major findings under each task are discussed with references to the pertinent Technical Reports.

Contract CML-543 has been extended to 31 January 1963, i.e. one month beyond the period covered by Monthly Progress Report 543-13. During this month major effort has been directed toward preparation of the Technical Reports. In each of the monthly reports administrative activity including visitors and travel has been mentioned. For sake of completeness this information for the month ending 31 January 1963 is given below.

Visitors

3 Jan 63	Mr. F. L. Horning	Chief, Data Processing Div., Deseret Test Center, Salt Lake City, Utah
3 Jan 63	Dr. J. C. Spendlove	Chief Scientist, P&E Director, Deseret Test Center, Salt Lake City, Utah
22 Jan 63	Mr. Harry Swinkels	Small Business Administration, San Francisco

Travel

During 9-11 January 1963 R. W. McMullen, L. M. Vaughan and W. A. Perkins visited Dugway Proving Ground to review the 502 B Trial program with D. L. Shearer, P. E. Carlson, W. A. Brown and others. Results of trials completed to date were discussed and priorities for future trials in this series were established. Certain changes in operational procedures were recommended.

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I. ANALYSIS OF TRIAL RESULTS FROM ELEVATED SOURCES

The primary objective of the investigation of elevated release source trials is to establish the relationship between controlling meteorological, release, and terrain conditions affecting the vertical and surface dosage distribution of airborne particulate material to downwind distances the order of 15 miles. Major effort has been the analysis of data obtained from trials conducted at Dugway Proving Ground including the BW 502 B, B 589 and BW 485 series of field trials. In addition, trial data obtained by other investigations have been examined including Brookhaven, Hanford, Windsoc and UK. Both the open and classified literature have been reviewed to locate any other potential sources of information.

A final integration of all the accumulated trial data has not been completed. Not all of the BW 502 B and B 589 trials have been run and some of the pertinent data from other investigations are as yet unpublished and the unpublished material requested has not been received. On the other hand, from an analysis of available data two atmospheric diffusion models have been developed and applied. These models are applicable to cloud travel over flat terrain. Available data also permit a comparison of particulate diffusion over open flat terrain and irregular terrain.

A. Summary of BW 502 B Trial Analysis

1. Description of trials

To date eleven out of a projected total of 20 FP trials in this series have been completed by Dugway Proving Ground. Meteorological and FP tracer results obtained from the first nine trials have been examined in detail.*

In all trials FP tracer was released from light aircraft (L-23 and/or L-20) along a crosswind line upwind of a sampling array which extended approximately 15 miles downwind from the release line. The first five trials involved a single aerial release of yellow FP; in Trials B-6, B-7 and B-9 two approximately simultaneous aerial releases of yellow FP and green FP were made at different altitudes, thus doubling the amount of data available with a given sampling array. In Trial B-8 an aerial release was made in conjunction with a parallel surface line release. Release altitudes for the various trials ranged from 100 feet to 450 feet and the length of dissemination was approximately 14 miles.

* Meteorological data for Trials 10 and 11 have been reduced and are in process of analysis. FP tracer data for these trials were received 28 January and have not been examined.

As shown in Table 1 on the following page, meteorological conditions for different trials ranged from strong inversion to moderate lapse with wind speeds at 150-300 feet ranging from 5 mph to greater than 20 mph. Cloud cover varied from clear to overcast.

The sampling array consisted of a line of samplers at 1-mile intervals at the 5-ft level extending downwind from the release line to a distance of 15 miles. Tower-mounted samplers were spaced at 5-ft intervals from 5 to 300 feet on a 300-ft tower located approximately 100 yards downwind and at 15-ft intervals from 5 to 95 feet at towers located 1/2, 2, 6 and 10 miles downwind. Balloon-borne samplers were located near the 100-ft towers with samplers at 75-ft intervals from 175 to 775 feet.

Vertical temperature gradients were measured at the towers between levels from 0.5 m to tower height. Temperature at heights from 100 feet to 1100 feet at 200-ft intervals were obtained by planesonde near the tower positions. One-meter air temperatures were also measured at 10 locations.

Vertical profiles of wind speed and direction at levels from 0.5 m to 300 feet were obtained at the 300-ft tower position and winds aloft at levels from 125 to 1200 feet were obtained from pilot balloon measurements at approximately 10 locations within the test area.

Bivane instruments for measurement of vertical and horizontal wind fluctuation and determination of eddy spectrum were not available when these trials were started. As an interim measure, regular Beckman-Whitley type wind vanes were mounted on their side and oriented in the expected wind direction in order to respond to vertical wind fluctuations. While the limitations of this technique were fully recognized it was felt that the vane angle measurements would show differences between trials at least on a relative basis. Such measurements were taken at 10, 100, 200 and 300 feet on the 300-ft tower. In Trials B-7 and B-8 Gill type bivanes were used at 2 m and 16 m.

Vertical temperature gradients and vertical wind profile data in each trial were used to estimate vertical diffusion in terms of a model based on vertical heat flux considerations. Alternatively, estimates of vertical diffusivity were also made in selected trials using a semi-empirical treatment of available vertical wind fluctuation data obtained from the horizontal vane deflections. These two models are discussed briefly below.

2. Vertical diffusion from heat flux considerations

A model for estimating vertical diffusion based on vertical heat flux considerations was developed by Vaughan and applied to the O'Neill data under

Table 1
Summary of Trial Conditions for BW 502 B Series

<u>Trial No.</u>	<u>Date</u>	<u>Time</u> (MST)	<u>Release</u> <u>Altitude</u> (ft)	<u>Release Line</u> <u>Length</u> (ft)	<u>Source</u> <u>Strength</u> (gm/ft)	<u>Wind</u> <u>Speed</u> (mph)	<u>Temperature Gradient*</u> $\frac{1/2 \text{ m-50 ft}}{(\text{°F})}$	<u>Temperature Gradient*</u> $\frac{2 \text{ m-300 ft}}{(\text{°F})}$	<u>Cloud</u> <u>Cover</u> (tenths)
B-1	14 Mar 61	2219	250	76,000	0.23	18.5 Δ	+3.2	+6.0	4
B-2	15 Mar 61	1900	455	75,500	0.26	11.8 Δ	+0.6	-0.6	10
B-3Y	22 Mar 61	2306	115	75,600	0.24	9.0 Δ	+5.6	>10.5	8
BG		2302	200	75,800					
B-4	28 Aug 61	2329	255	75,400	0.28	19.8 Δ	+5.6	+11.2	5
B-5	29 Aug 61	2009	125	75,600	0.25	20.0 Δ			
B-6Y	5 Sep 61	2056	250	76,000	0.26	21.2 Δ	+7.5	+13.1	1
G			400	76,000	0.21				
B-7Y	4 Oct 61	1630	225	77,000	0.25	5.5 $\Delta\Delta$	+1.1	-2.8	0
G			400	78,000	0.22				
B-8Y	19 Oct 61	1629	0	39,000	0.03**	18.8 $\Delta\Delta$	+2.4	+1.0	6
G			400	75,600	0.25				
B-9Y	6 Jun 62	1849	250	74,500	0.29	22.8 $\Delta\Delta$	+0.1	-1.3	2
G			430	76,000	0.26				

Y = Yellow FP tracer. Yellow FP used if not otherwise specified.

G = Green FP tracer.

* Z to Z + 5 min.

** Surface release from moving vehicle

Δ 150-ft wind

$\Delta\Delta$ 300-ft wind

lapse, neutral and inversion conditions.* In essence, the model is predicated on the equivalence between the turbulent diffusion of heat and matter. As applied to the BW 502 B trials this model has been further developed to a) eliminate the assumption originally required that heat flux be independent of height and b) account for air temperature changes resulting from advection. A brief summary of the diffusion model is given in Appendix A; treatment of the BW 502 B results for trials one through nine is given in Metronics Associates Technical Report No. 97 (in process of publication).

For each trial, values of vertical diffusivity, K , were computed as a function of height. A mean value from the surface to 900 feet together with the average wind speed, \bar{u} , source strength per unit length of release line, Q , and release height, H , were used in Eq. (6) to compute dosage per unit source strength, D/Q , at the surface and aloft.

In comparing computed and observed values the following should be noted:

(1) As with any model, D/Q values computed therefrom represent average values expected from repeated instantaneous releases under identical conditions. Results from a single trial may depart from the computed average.

(2) Computed D/Q represent axial values normal to the crosswind release line in the absence of edge effects resulting from lateral diffusion or lateral motion of the cloud as a whole.

(3) In all calculations the release height has been used without attempting to correct for the initial downward displacement of the cloud associated with the aircraft release. In later calculations this correction will be considered together with adjustments for vertical displacements caused by changes in the average height of the isentropic surfaces.

Curves are given in Technical Report No. 97 showing D/Q isopleths for a vertical section along the central sampling line for each trial. Observed isopleths based on sampling results are given together with isopleths computed from the model. A comparison between observed and computed results follows.

Trials B-4, B-5 and B-6 were essentially free of wind shifts and edge effects along the axial sampling line from the source to the maximum sampling distance of 15 miles. As expected these three trials show best agreement between observed and computed D/Q values.

* Vaughan, L. M. "The Prediction of Atmospheric Diffusion by Using Eddy Diffusivity Based on the Vertical Transfer of Heat", Journal of Meteorology, 18, 43-49 (1961).

Trial B-4. Observed and computed isopleths show rapid mixing in the first two miles; from two to ten miles the cloud top was essentially constant at 500 feet but the calculated top increased from 500 to 750 feet based on the average K value used. However, the computed diffusivity decreased aloft in accordance with the observed cloud behavior. Had the smaller K value been used aloft rather than an average value the calculated height of the cloud top would have agreed well with the observed. The cloud reached the surface between 1 and 2 miles as expected from the computed D/Q values. Both observed and computed D/Q were smaller at the surface than aloft and both showed little change with height between 100 and 400 feet.

Trial B-5. Observed and computed isopleths are in good agreement. At ten miles the observed 100 sec/m^2 D/Q is at 500 feet and the computed at 400 feet. The same isopleth reaches the surface at .75 miles (observed) and 1.25 miles (computed). Throughout most of the sampling array, computed and observed D/Q values differ by less than a factor of two.

Trial B-6: Green FP. The cloud was carried aloft between 2 and 10 miles so that its center was above the release height (400 feet). This displacement follows a similar displacement in the isentropic pattern derived from the air temperature measurements and is probably related thereto. However, the calculated isopleths do not take such a vertical displacement into consideration. Consequently the calculated cloud position was below that observed. At 10 miles the cloud was aloft between 350 and 700 feet, the corresponding computed heights were 50-750 feet. The cloud did not reach the surface within the sampling array hence all surface D/Q values were zero. Corresponding computed D/Q values were also zero.

Trial B-6: Yellow FP. The vertical displacement was evident but less pronounced than for the green FP. Computed and observed D/Q isopleths were in close agreement. At ten miles the computed and observed 100 sec/m^2 isopleths were at 500 and 475 feet, respectively. Both observed and computed surface values were much less than those aloft. The observed 100 sec/m^2 D/Q reached the surface at approximately 5 miles, the computed value at 7 miles.

In the remaining trials, edge effects, wind shift or lateral displacements of the cloud affected the axial sampling results. In all cases differences between observed and computed D/Q values could be accounted for from an examination of the wind trajectories and collateral data.

Trial B-1. Agreement between computed and observed isopleths is poor. Shortly after release a part of the cloud was transported laterally and overran the main portion giving two maxima rather than one at the 1/2-mi balloon position.

Trial B-2. Vertical sampling data were available only at the 6-mile position. Very rapid initial vertical mixing from the release height (455 feet) to the surface was observed and expected from the computed diffusivity. Thus the observed and computed 100 sec/m^2 D/Q reached the surface between 1.5 and 2 miles. At six miles the observed D/Q was constant from the surface to 750 feet, again as expected from the computed diffusivity.

Trial B-3. Edge effects reduced the observed D/Q values at six and ten miles. For this reason the observed 100 sec/m^2 D/Q at the cloud top was at 300 feet whereas the computed height was 475 feet. Because of the low release height (100 feet) this isopleth reached the ground at 0.8 miles; the computed distance was 0.6 miles.

Trial B-7. Both the yellow and green tracer showed extremely rapid vertical mixing i.e. from the surface to 750 feet within the first half mile in accord with the computed diffusivity. The green FP released at 500 feet showed 1000 sec/m^2 at the surface at 1.1 miles compared with a computed distance of 1.25 miles. A wind shift was responsible for observed D/Q values at ten miles being approximately one-fifth the computed values.

Trial B-8: Green FP. The cloud showed a downward displacement between two and six miles followed by an upward displacement to ten miles. For this reason the maximum at six miles was observed at 200 feet rather than at 400 feet as expected. However the magnitudes of the observed and computed maxima were within a factor of two at six and ten miles. Computed and observed surface dosages were less at the surface than aloft. The 100 sec/m^2 D/Q reached the surface at 3.25 miles compared with a computed distance of 4.0 miles.

Trial B-8: Yellow FP. This was the first surface release in the B 502 series. Surface D/Q values agreed well with computed values and the observed and computed rates of vertical mixing were also in good agreement. Considering the 100 sec/m^2 D/Q values aloft, observed and computed heights were 260 and 310 feet at 2 miles; 525 and 480 feet at 6 miles, and 740 and 600 feet at 10 miles.

Trial B-9. During this trial the wind direction was approximately 45 degrees to the sampling line hence both the green and yellow FP were carried across the line and no samples were obtained beyond five miles from the source. Out to five miles the lateral movement of the clouds gave higher D/Q values than would have been expected under conditions of axial flow. Vertical mixing was very rapid as shown by the observed and computed D/Q values. For both the green FP (430 feet release height) and the yellow (release height 250 feet) the 100 sec/m^2 D/Q reached the surface at 1.2 miles compared with a computed distance of approximately 0.5 miles. At the half-mile position both clouds were distributed above the 600-ft level as expected from the computed isopleths.

Table 2 summarizes values of mean wind speed and diffusivity applicable to each trial as used in Eq. (8). Table 2 also includes a comparison of the computed and observed 1/10th maximum ground-level dosage as regards magnitude and distance from the source. The computed values follow immediately from Eq. (9) with $S = 3.8$.

Selection of 1/10th maximum dosage as a basis of comparison is arbitrary, but provides an indication of the usefulness of the model to predict the downwind distance from the source at which the given dosage level can be expected at the surface. Obviously the comparison is critically dependent on the single maximum observed surface value. An uncertainty in the maximum value, which may arise from one of several causes, affects not only the value of 1/10th maximum but also the distance from the source associated with it.

Table 2
Comparison of Calculated and Observed Ground-Level Dosages

Trial	Release Altitude (m)	Mean Wind Speed (m/sec)	Q (part/m) $\times 10^9$	K (m^2/sec)	1/10 Maximum Dosage (part. min/l)		Distance to 1/10 of Maximum (miles)	
					Calculated	Observed	Calculated	Observed
B-1	76	8.84	6.25	0.419	7.8	15*	5.0	0.4*
B-2	139	8.66	7.08	6.38	4.9	3.7	1.1	1.0
B-3	35	6.02	6.53	0.441	26	128	0.7	3.0
B-4	78	9.52	7.63	1.84	8.6	17	1.3	2.2
B-5	38	10.53	6.80	0.492	14	72	1.3	0.2
B-6Y $\Delta\Delta$	76	9.43	7.08	0.351	8.2	3.2 Δ	6.3	3.2
G $\Delta\Delta$	122		11.4		8.2	---	16.5	---
B-7Y	68	1.69	6.80	1.75	49	28**	0.2	0.1
G	122		11.9		48	59	0.6	0.6
B-8G	122	5.78	13.6	0.993	16	30	3.6	3.1
B-9Y	76	7.59	7.90	13.0	11	14	0.1	1.1
G	131		14.2		12	23	0.4	1.1

* Enfilading is involved.

** There was a larger maximum at 6 miles which appeared to be caused by enfilading.

Δ Maximum not reached within 15-mile sampling range.

$\Delta\Delta$ Y = yellow FP, G = green FP.

In general the calculated and observed 1/10th maximum dosage agree within a factor of two. Exceptions are Trials B-3 and B-5. In B-3 the large 1/10th maximum dosage results from an exceptionally large and possibly anomalous surface dosage. This trial also had the lowest release height and the initial downward displacement undoubtedly played a significant part in producing large surface dosage values. In any case, the large observed maximum dosage, whether real or anomalous, leads to a large 10th maximum dosage and in turn to a greater observed distance from the source than calculated. Trial B-5 was also at a release height comparable to B-3. The lack of agreement appears to be associated with the initial downward displacement and resulting variability in the surface dosage.

No observed values are included for comparison with Trial B-6 green. The expected distance to 1/10th maximum was beyond the limits on the sampling grid and the results are in accord with this calculation inasmuch as no significant surface dosages were reported.

Calculated and observed distances to 1/10th the maximum are in reasonably good agreement. In addition to the trials discussed above, exceptions are B-1 and B-9 yellow. As pointed out earlier, Trial B-1 was complicated by transverse flow and overrunning. Likewise in Trial B-9 the wind direction was across rather than parallel to the sampling line. As a consequence dosages were higher than calculated and the observed distance to 1/10th maximum was thereby increased relative to that calculated.

Based on the analysis of the first nine trials (total of 12 releases) in the BW 502 B series, the diffusion model based on heat flux considerations gives favorable agreement between computed and observed results. Differences between computed and observed results can be accounted for in each case by recognizable anomalies in trial conditions.

3. Vertical diffusion from horizontal vane data

An alternative procedure for estimating vertical diffusivity was based on a semi-empirical treatment of available data from the horizontal vanes and applied to six of the BW 502 B trials namely B-2, B-3, B-4, B-6, B-7 and B-8. Limitations of the procedure used are fully recognized. However it was felt that an attempt should be made to use the vane results if at all possible. Specific limitations include:

- 1) The horizontal vanes are not designed to measure vertical fluctuations. As used they are subject to errors from imbalance, changes in wind direction, and limited sensitivity.

2) Results are given in terms of average and extreme range in vertical deflections for time periods of 15 seconds and one minute. Hence, an eddy spectrum as such cannot be derived from the reported data.

3) All data were limited to time periods 10 to 15 minutes following release.* Consequently, estimates of diffusivity derived from these data are applicable to the early portion of the cloud travel. In some instances cloud travel time was an hour or more and conditions may have changed during this period.

4) All data were obtained at the 300-ft tower and may not have been representative of conditions over the entire sampling array.

5) Measurements taken at 300 feet and below may not have been characteristic of conditions aloft.

In the absence of appropriate measurements to establish the eddy spectrum a semi-empirical procedure was developed to estimate a K value appropriate to each trial. Since K is equal to the average product of vertical velocity, w , and eddy size, l , it was necessary to estimate the latter two quantities from the reported vane deflections. In brief, the average 15-second range of vane angle was determined from the three minutes of data. Then pairs of consecutive 15-second periods were combined to obtain the 30-second increments of range, i.e. the difference between the 30-second range and the larger of the two 15-second ranges. The additional range over that occurring in either 15-second period was used based on the arbitrary assumption that the increment provides a measure of the contribution to the total 30-second range from vane oscillations of duration greater than 15 seconds. These 30-second increments were averaged for all 30-second periods. In like manner, average additional vane deflection increments were obtained for averaging periods 1 minute, 2 minutes and 4 minutes. The first averaging period (15 seconds) is considered to represent the cumulative contribution from all shorter averaging periods.

These average increments were cumulatively added to the average 15-second range and plotted against the averaging time. In each trial the cumulative curve rapidly approached an asymptotic value of the ordinate after periods of two to four minutes. For further computation each curve was fitted by least

* Average deflection and deflection range were reported for consecutive 15-second periods during the first three minutes following release and for one-minute periods during the next 8 to 13 minutes as well as for five minutes prior to release.

squares with the rectangular hyperbolic function

$$y = \frac{a \cdot t}{b + t}$$

where

y is the cumulative value of the range increments at time t,
t is the averaging time or interval over which y is computed,
a and b are constants, a being the asymptotic value of y.

It is assumed that the slope of the hyperbolic curve taken at any given averaging time represents the rate of increase of vane angle range associated with eddies of duration equal to the particular averaging time. Hence the magnitude of the vertical velocity w can be expressed as a function of the averaging time and is proportional to the product of the slope of the curve and the time itself.

To obtain an estimate of l it is further assumed that the eddy spectrum is continuous, and the mean wind speed \bar{u} remains constant so that an equivalent eddy size can be defined at each averaging time. The equivalent eddy size is used to define l the vertical distance through which the air moves. In terms of the hyperbolic function the product of wl is given by

$$K = wl = 0.5 \bar{u}^2 ab \cdot 10^{-2} \frac{t^2}{(b + t)^2}$$

To obtain K in m^2/sec , \bar{u} is in m/sec and t is in seconds.

Computed values of K were used in Eq. (8) Appendix A to estimate D/Q at the surface and aloft in each of the trials mentioned above. For comparison, average K values are given in Table 3 as derived from the vane deflection and heat flux consideration.

Values for B-2 show poor agreement because of a major change in meteorological conditions approximately 20 minutes after release and after all the vane data had been taken. During the first 20 minutes of travel, vertical diffusivity was substantially greater than during the balance of the cloud travel time following a decrease in wind speed and increase in stability. Hence the smaller K value is representative of average conditions during the entire travel time; the larger value applies to the first few minutes only. The difference in Trial B-7 is due to similar circumstances.

Table 3
Comparison of K Values

<u>BW 502 B Trial No.</u>	<u>Computed K value (m²/sec)</u>	
	<u>From Vane Deflection</u>	<u>From Heat Flux Consideration</u> *
B-2	80	6.38
B-3	0.1	0.44
B-4	1.4	1.84
B-6	0.35	0.35
B-7	10	1.75
B-8	2.0	0.99

* See Table 2

Agreement between the pairs of K values in the remaining four trials is within the known limits of uncertainty in the procedures used. Except for Trial B-2 the K values from the vane data give representative D/Q isopleth patterns and agreement with observed values within a factor of three in most cases. Therefore, although the interim horizontal vanes are much less satisfactory than bivanes the data obtained is usable in providing approximate values of vertical diffusivity and estimates of D/Q to 15 miles.

B. Summary of B 589 Trials

1. Description of trials

All trials in the B 589 series are conducted on the same test array as the BW 502 trials using BG released from elevated crosswind line sources. Four trials have been completed and additional trials are planned. Final analysis of the test results will be made upon completion of all trials.

Downwind surface samples (5 feet above ground) were located at one-mile intervals to a distance of 15 miles along three radial lines. These lines joined at the 300-ft tower located 300-ft downwind from the approximate center of the release line. Vertical samples were taken on the tower at five-ft intervals from 5 feet to 300 feet. Vertical samples were also taken at 15-ft intervals from 5 to 95 feet on 100-ft towers located on the central radial line 1/2, 2, 6 and 10 miles from the release line. Standard all-glass impingers with preimpingers were used at each sampling position operated at a nominal flow rate of 6 l/min.

Meteorological measurements were essentially the same as those taken during the 502 B trials. (See previous section) Pertinent information is summarized in Table 4.

Table 4
Meteorological and Operational Data for Selected BW 589 Trials

	Trial No.			
	<u>A-4</u>	<u>B-9</u>	<u>B-10</u>	<u>B-11</u>
Date (1961)	Oct 10	Jul 17	Jul 31	Aug 1
Time (MST)	2028	2027	2048	2257
Release Height (ft)	120	60	70	125
Length of Release Line (ft)	75,880	27,500	27,900	27,200
Wind Speed, 2 m (mph)	14	16	10	6
Wind Speed, 150 ft (mph)	26	26	22	13
Wind Direction, 150 ft (°)	152	328	150	132
Relative Humidity, 2 m (%)	65	17	43	43
Temperature, 2 m (°F)	51	87	79	74
Temperature Gradient, 2m - 150 ft (°F)	7.0(inv)	0.0	1.1(inv)	2.9(inv)
Sky Cover (tenths)	1	6	2	4

2. Discussion of results

The release height was at or below 125 feet in each trial; hence, in all cases, the cloud was bounded vertically at the 300-ft tower. Tower sampling data and wind speed measurements were used to determine the source strength. Downwind trajectories were computed from the pibal data for comparison with observed surface and vertical sampling results. Trajectory levels used were nearest available to release height, 125 feet in A-4 and 250 feet in the remaining three trials. Estimates of vertical diffusivity have not been completed for each trial. One trial (B-9) was conducted under neutral conditions, the remainder under stable conditions, but in each case the wind speed near release height was strong, i.e. 13 mph or greater.

Trial A-4. This trial was run under the most stable conditions and with the longest release line. The trajectories show that the cloud was carried approximately parallel to the central sampling line (east and west radial lines not used) for the full 15 miles. Because of the long release line used, edge effects were not expected within the maximum distance sampled. In terms of reported plate counts* significant counts (100 to 128) were obtained at the surface between 2 and 6 miles with no change in count with distance. Between 6 and 15 miles

* All sampling data are based on the sum of duplicate plate counts each prepared from 0.2 ml of impinger fluid. The total volume plated (0.40 ml) represents 2.2% of the total impinger fluid hence 2.2% of the total sample collected.

counts were variable, in most cases less than 60, hence below the limit of statistical reliability.

At the 300-ft tower the cloud was approximately 50 feet in vertical extent with the maximum at 90 feet which was 30 feet below release height. This downward displacement is typical for aircraft releases. The cloud top was not bounded at any of the four 100-ft tower positions except possibly at 1/2 mile. At 2, 6 and 10 miles the tower counts varied from 40 to 200 but showed no systematic trend with increasing distance from the source. Counts above 50 feet at each of these positions were somewhat less than those below 50 feet.

Trial B-9. The 250-ft wind trajectories indicate marked variability in direction and speed. According to the trajectory analysis, the cloud shifted laterally and no recoveries were expected beyond 4 miles on the east, approximately 6 miles on the center and 5 miles on the west sampling lines. Surface sampling results are in complete accord with the trajectory.

Surface counts were generally too small to be statistically reliable. Of the 18 values obtained out to six miles, three exceeded 70 (maximum 110) and the balance were 60 or below and hence of questionable significance.

The vertical dimension of the cloud was 40 feet at the 300-ft tower and its center was displaced upward from the nominal release height by 20 feet. This is the only trial in the series showing upward displacement during the first 300 feet of travel. Variability in release height may be partly responsible for this displacement.

Counts on the 2 and 6 mile 100-ft towers were less than 60 hence of doubtful reliability. There was no trend with distance or with height from 5 to 95 feet. At the ten-mile tower all samples were zero as was expected from the trajectory analysis.

Trial B-10. The air flow pattern based on the wind trajectories was virtually the same as in Trial A-4. However the release line was only 27900 feet long compared with 75880 in A-4 hence edge effects were expected particularly along the east radial line. According to the trajectory, no counts were expected on this line beyond 6 miles and all were essentially zero (maximum value 6). The trajectories also indicate that the cloud was carried the full length of the central and west lines with possible edge effects at the ends of each line. Sampling results are in agreement with this pattern.

Largest counts from surface samplers (259, 387) were obtained at 1/4 and 1/2 miles from the release line. Beyond 2 miles the counts were less than 100 and beyond 7 miles less than 60 with three exceptions. Thus counts on the more distant half of the west and central sampling lines were below the limit of accepted reliability.

At the 300-ft tower the cloud was 50 feet in vertical extent and all of it was below the release height. The cloud center was approximately 30 feet above the surface. Further downwind, the cloud top extended above the 100-ft towers. At 1/2 and 2 miles, counts at 5 and 20 feet were approximately three times greater than those at the top of the towers. At 6 and 10 miles, all counts were less than 60 and showed no change with height or distance.

On the basis of the four trials completed thus far, two conclusions are evident. First, the sampling results both from the surface and the towers agree well with the estimated movement of the cloud derived from the wind trajectory analysis. Second, the present BG assessment technique severely limits the reliability of results obtained from trials run with this material. Surface and 100-ft tower recoveries are so small that assessment of the samples may be made without dilution of the impinger fluid. Of the total sample collected in each impinger at these locations, only 2.2% is actually counted and 97.8% is discarded. Thus the reported counts represent only a small fraction of the sample available and unfortunately the reported counts are frequently at or below the desired level of statistical reliability. Subject to limitations imposed by background counts, the BG trial data could be greatly improved by increasing the fraction of impinger fluid plated for counting. Larger petri dishes or plating several cc of fluid on membrane filters are possible approaches. Use of such procedures would increase assessment costs, but such additional costs could be fully justified by the increased yield of more reliable count data.

C. Summary of BW 485 Trials

The objective of the BW 485 trials is to provide information on the diffusion of particulate material from elevated line sources over complex terrain of a specific type on a distance scale the order of 15 miles. In view of the tremendous variety of possible terrain configurations on this scale, classification of terrain types into recognizable categories was a necessary first step in designing these trials. The terrain type selected for the BW 485 series consisted of an isolated single mountain range with an essentially straight main ridge and with lateral canyons normal to and sloping away from each side of the main ridge. To achieve isolation, it was required that terrain on each side of the mountain range be flat for a sufficient distance so that the air flow approaching the main ridge normal to it would be undisturbed by other terrain features. Further, the mountain range must be large enough so that well defined local katabatic circulation develops within the lateral canyons.

The Cedar Mountain range (Dugway, Utah) is representative of the terrain category selected and was used for the BW 485 trials. The main ridge is oriented

north-south and lateral canyons run generally east-west. Crosswind elevated line source trials were planned with the release line parallel to and upwind of the main ridge in some trials and normal to the main ridge in other trials. Under each of these two flow regimes, the BW 485 trials were to provide information on the extent to which particulate material carried in the free air flow aloft entered into the local katabatic circulation under stable conditions.

Four trials have been completed using FP tracer. All trials were conducted at night with the air flow parallel to the main ridge; none have been conducted with the gradient wind normal to the ridge. Results of the trials have already been reported* and are summarized briefly below.

In each trial the crosswind release was made from an L-23 aircraft along a flight line south of the sampling arrays and at elevations ranging from 1000 to 2000 feet above terrain at the flight line. Sampling equipment was located in six lateral canyons, three on each side of the main ridge and also in a 3 x 4 mile grid extending into the flat area downslope from the three lateral canyons on the western slope of the Cedar Mountains. The nearest sampling positions were approximately 7 miles from the release line; the three pairs of lateral canyons were spaced about a mile apart in the downwind direction. At several locations sequential-type samplers were used in order to measure successive half-hourly particulate recoveries.

Meteorological observations included air temperature at several levels up to 750 feet above the two middle lateral canyons, planesondes, two-meter wind speed and direction at positions on both sides of the ridge and pibal runs from which cloud trajectories could be computed.

Following release, the FP cloud moved northward, crossing several lateral canyons before reaching the three pairs of instrumented canyons. Hence, throughout most of its trajectory before reaching the sampling positions, the cloud was carried over extremely irregular terrain. In spite of the terrain complexity, the computed cloud trajectories at release height agreed well with the surface sampling results. Stable conditions with well developed katabatic flow in the lateral canyons were present in three of the four trials. In brief the trial results show:

1. Mechanical turbulence induced by the irregular terrain provided sufficient vertical diffusion to give significant FP recoveries at the surface in all trials both in the lateral canyons and at the open sampling array to the west.

* R. W. McMullen, W. A. Perkins, "Particulate Diffusion over Irregular Terrain", Technical Report No. 96, Metronics Associates, Inc. 25 January 1963.

2. Maximum half-hourly recoveries were obtained during cloud passage aloft and were associated with direct mixing between the surface and upper levels in spite of low-level stability in the lateral canyons.
3. FP tracer was transported in the downslope drainage flow. Within the canyons, this transport accounted for 50% or less of the total recovery. In the open, it contributed less than 15% to the total recovery.
4. Within a canyon, total recoveries varied by less than a factor of three in most cases and showed no systematic variation with respect to sampler location.
5. Median total recoveries within canyons farthest from the release line were 20 to 50 times greater than those in the canyons nearest the release line (7 miles) indicating that the vertical diffusion of the tracer was continuing as the cloud crossed the sampling array.
6. In most cases vertical samples showed little or no gradient between the surface and 750 feet above.
7. It is concluded that vertical mixing is much more rapid than for the equivalent travel over flat terrain. However it is questionable whether similar results would have been obtained if the trials had been conducted with westerly flow carrying the cloud toward the main ridge rather than parallel to it.

D. Collateral Elevated Release Data

In addition to the elevated release trial data described above, a review of other sources of applicable data has been made including both the classified and open literature. The major objective of this review was to determine whether there is existing information which would supplement the field work conducted at Dugway and provide a means for extending the Dugway results to other areas.

Very little quantitative information is available in the published literature for the distance range of interest and all of it is too fragmentary for making detailed comparison with Dugway results. The most applicable information was obtained from reports on specific trials, i.e. Windsoc, Green Glow (Hanford, Washington), and selected Porton field results. Additional information was obtained through discussion with representatives from GRD and Brookhaven National Laboratory. It is evident from this review that the total amount of applicable field trial information is extremely limited. The most useful is that from Porton and Brookhaven.

Porton Large Scale Trials. Ten daytime trials were conducted at Porton using FP tracer released from aircraft 10 to 84 miles upwind of a single sampling station. At this station samples were taken on a balloon cable from the surface to as high as 6000 feet. In addition gustiness data were obtained at three levels on the balloon cable.

Results from these trials have been examined in detail.* The gustiness data were used to compute vertical diffusivity and in turn vertical dosage profiles for each of the trials at the balloon station. In eight of the ten trials the computed dosage variation with height agrees well with the observed dosage profiles. Absolute values of computed and observed dosages agree within a factor of two at nearly all sampling heights. In one of the two trials showing poor agreement, the diffusion model as used was not strictly applicable because of changes in stability conditions during cloud travel. Uncertainties in the trial data may account for the lack of agreement in the second case.

From the results obtained in this analysis it is concluded that the model used gives satisfactory estimates of dosage as a function of height for cloud travel distances of 10 to 84 miles from an extended elevated crosswind line source under daytime conditions.

Brookhaven Data. Data have been obtained by the meteorological group at Brookhaven applicable to the elevated source problem. This information falls into two categories, namely oil fog trial results from the 420-ft tower and climatological records collected over a period of years from the same tower. Unfortunately most of the data required are as yet unpublished. However a request has been made for specific records following conferences with Smith, Singer and others at Brookhaven.

Several elevated source trials have been conducted at Brookhaven using oil fog released from a smoke generator located on the 420-ft tower and operated at a constant and known rate for approximately one hour. In addition to photographic coverage, filter or densitometer-type samplers were located at the surface to distances of 5 km. In some trials the samplers were fixed, in others they were carried on aircraft, but in all cases an attempt was made to obtain total dosage at sampling positions along the downwind axis of the cloud.

Meteorological data were recorded only at the 420-ft tower; little or no supplemental data were obtained at other locations. However, Singer pointed out that from their experience the tower data are representative of conditions

* D. T. Prophet, "An Analysis of Large Scale Vertical Diffusion of Airborne Material From Elevated Line Sources Using Vertical Gustiness Data (U)", Technical Report 94, Metronics Associates, Inc. March 1962. CONFIDENTIAL (MHA).

along the cloud trajectories. This is particularly true when the wind direction is along rather than across Long Island. In all trials both temperature and wind velocity gradients were measured continually, usually at fast chart speeds.

The reported trial results are limited to neutral and unstable conditions; as expected, positive surface dosages were obtained in most of these trials. Meteorological data as reported are not in sufficient detail to permit calculations of the expected dosages using the methods developed for the BW 502 B series. However, these records are available in unpublished form and have been requested from Brookhaven.

A number of inversion trials were also conducted but the results have not been published because in nearly every case surface dosages were zero. However, even though the results were negative, these trials are of particular interest since the gradient records from the tower can be used to determine whether the zero values are in accordance with the computed vertical diffusivity. A request has been made for these data.

For the past several years Brookhaven tower records have been accumulated on a routine basis providing a unique source of microclimatological information including temperature and wind velocity gradients. Using the method developed for the BW 502 trial analysis, these gradient records could be used to estimate diurnal and seasonal changes in vertical diffusivity at the Brookhaven location. The diffusivities could be correlated with synoptic conditions at the site and compared with values obtained at Dugway and other locations. In view of this possibility, the past data were reviewed in detail at Brookhaven and two years of suitable records on IBM cards have been requested and a programming procedure has been developed for computing vertical diffusivity from the gradient data.

II. REVIEW OF STANFORD AEROSOL LABORATORY INVESTIGATIONS

Stanford Aerosol Laboratory, Stanford University, the predecessor of Metronics Associates, Inc., was continuously engaged in the Chemical Corps research and development program from 1946 to 1961. During this period investigations covered a wide range of subjects in the fields of cloud physics, meteorology and operations research under nine contracts. In the course of this work over 115 separate reports were issued but until the present time it has not been possible to prepare a consolidated summary of the investigations made.

The purpose of the review now being completed is to summarize in a single volume results obtained in the various fields of activity during the 15-year period. In preparing this review, the work is discussed chronologically insofar as possible. However, results of related investigations undertaken at different times are treated together to show how these results are related to each other and how they apply to current problems. Thus the review provides a means of information retrieval on a number of subjects investigated some time ago and in which interest has revived.

Chapter headings and major topics included in the review are given below:

- Chapter 1. Early Experiments
- Chapter 2. The Fluorescent Particle Tracer Technique
 - I. The Tracer Material
 - II. Dissemination
 - III. Sampling
 - IV. Assessment
 - V. Validity
- Chapter 3. Meteorological Instruments and Methods
- Chapter 4. The Relative Diffusion of Gases and Aerosols
- Chapter 5. Meteorology and Cloud Travel in Cities
 - I. Objective and scope of the work in cities
 - II. Urban Meteorology
 - III. Urban cloud travel
- Chapter 6. Mountain-Valley Meteorology and Cloud Travel
 - I. Objectives and scope of the work in mountainous terrain
 - II. Cibo Peak
 - III. Hill 5785
 - IV. Little Baldy
 - V. Intersite comparisons
- Chapter 7. Meteorology and Cloud Travel in Complex Terrain

Chapter 8. The Wheat Rust Problem (or The Atmospheric Transport of
Wheat Rust Spores)

Chapter 9. Other Meteorological and Cloud Travel Studies

All of the reports have been reviewed and preparation of the written
material is nearly complete.

III. FP TRACER TECHNOLOGY

A limited amount of effort has been directed toward improving the FP tracer technique in two respects. The collection efficiency of the Rotorod sampler has been investigated using several different lots of FP material to determine how the efficiency varies with particle size. A number of UV illuminator systems for particle assessment have been compared visually and photoelectrically and a procedure for measuring brightness of single fluorescent particles has been developed. In addition to the above investigations, laboratory analyses have been made on lots of FP material submitted for testing by Dugway Proving Ground.

A. Investigation of the Rotorod FP Collection Efficiency

1. Objective and Conclusion

One of the specific tasks enumerated in the memorandum of understanding to Contract CML-543 was to reinvestigate and define with greater confidence the collection efficiency of the FP collector rod for the Rotorod sampler with the coating technique as employed at Dugway Proving Ground. Prior to the work reported herein the only definitive measurements of the collection efficiency of the FP collector rod as presently used were those made in connection with the original development work.* Since this earlier work involved the making of collection efficiency measurements for several different combinations of collector configuration and surface coating, the number of replicate results obtained with any one combination was necessarily limited. In addition most of these earlier measurements were intentionally made using FP material from a single lot for which the particle size characteristics were fairly well known. This latter experimental limitation was obviously necessary in order that the larger effect of lot-to-lot variations in particle size characteristics would not completely obscure the effects on collection efficiency of the various collector rod configurations and impaction surface coatings then being investigated.

As will be shown presently, lot-to-lot variations in FP particle size accounted for the major portion of the variations in collection efficiency found in the present investigation. Within a given trial in which a suitable lot of FP material and an efficient mode of aerosolization are used, the uncertainty in sampling results due directly to variable Rotorod collection efficiency appears to be no greater than the overall uncertainty inherent in any other mode

* CML-448 Memorandum Report No. 9, 11 May 1960.

of aerosol sampling.

This latter statement is in essence the practical conclusion to be drawn from the CML-543 series of Rotorod FP collection efficiency measurements. The detailed experimental data supporting this conclusion, as well as the other subsidiary findings, are presented in CML-543 Technical Report No. 98.

2. Scope and experimental procedures

The CML-543 series of collection efficiency measurements consisted of 7 field experiments of 4 trials each (Metronics FE's 134-140). As the assessment of the collector rods and reference filters from each field experiment was completed the detailed results obtained were then presented in a CML-543 Monthly Progress Report. All 28 trials were conducted under essentially fair weather daytime conditions.

The test procedures used in each trial were essentially as follows:

- 1) a line source release of FP was made from a hi-speed blower-type aerosol generator mounted on the tail gate of a station wagon which was driven slowly along a route approximately 300 to 750 feet upwind of the nearest sampler,
- 2) the resulting airborne FP were collected at two separate stations, each of which consisted of a closely-spaced array of Rotorod samplers (RR's) surrounded by reference membrane filter samplers (MF's), and
- 3) before, during, and following each series of trials the wind speed, direction, temperature, and humidity was continuously recorded at a fixed station at Metronics building--the field test site being located usually not more than a few hundred feet from the building. A typical arrangement of closely-spaced RR's and reference MF comprising each sampling array is shown schematically in Figure 1.

The FP collector rods used were silicone grease-coated for particle retention and were of the current standard design being used at Dugway, namely the H-shaped 60 x 30 x 0.38 mm chromel ribbon collector as shown in SAL Dwg. #A70-3-1061, revision dated 19 May 1961. When rotated at the standard speed of 2400 RPM this collector rod samples air at 41.2 l/m. The MF's consisted of 1-inch diameter aerosol sampling membranes held in magnetic type holders and aspirated at 5 to 8 l/m.

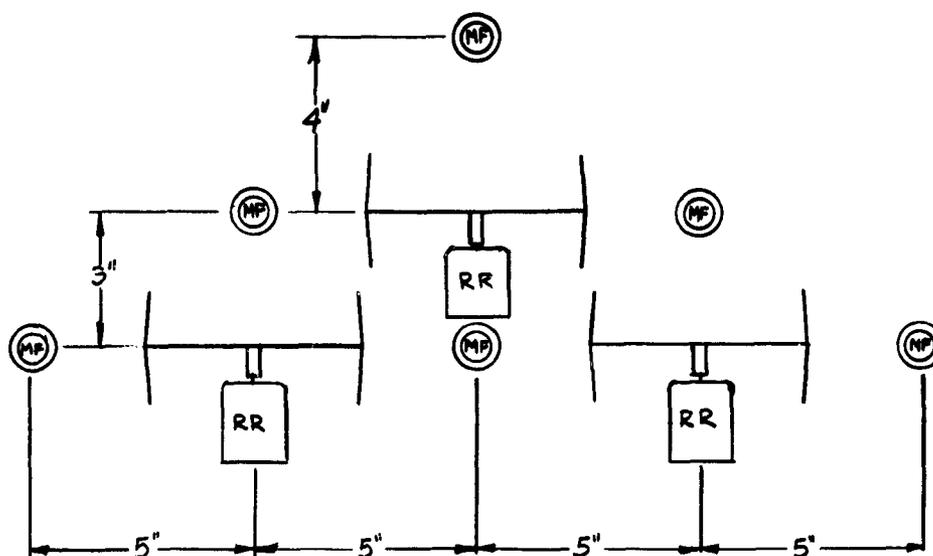


Fig. 1--Typical arrangement of RR's and MF's used in 12 of the CML-543 series of FP collection efficiency trials. Except for fewer samplers per array the same close spacing was used in all other trials of this series.

Although a few trials were conducted under wind speeds as low as 3 mph and a few others under winds as high as 18 mph, the winds experienced during most trials were in the range 8 to 14 mph. Even though too few data were obtained under a range of meteorological conditions sufficient to warrant a conclusion in this regard, it should also be mentioned that there was observed no readily evident variation in collection efficiency that could be attributed to differences in meteorological conditions.

3. Results summary and discussion

Presented in Table 5 is a concise summary of the FP collection efficiencies obtained from the CML-543 series of measurements. In this table the average percent efficiency obtained in all trials using the same lot of material is presented in the order of increasing FP mass mean diameter (MMD). With one exception the collection efficiency increases in step with the increase in MMD, or expressed in terms of the independent variable explicitly measured, the collection efficiency increases as the FP particles-per-gram (PPG) decreases.

Table 5

Rotorod FP Collection Efficiency Summary

<u>MMD</u>	<u>FP Material Used</u>		<u>Collection Efficiency Results</u>			
	<u>Color & Type</u>	<u>PPG</u>	<u>No. Values</u>	<u>Avg % Eff.</u>	<u>Std. Dev.</u>	<u>Coeff. Var.</u>
1.8	Yellow-2266	7.9×10^{10}	14	28.1%	4.4	0.156
2.4	Yellow-2266	3.3×10^{10}	12	52.9	3.1	0.058
2.4	Green-3206	3.3×10^{10}	24	54.1	4.8	0.089
3.1	Yellow-2267	1.6×10^{10}	24	74.7	6.3	0.085
3.4	Yellow-2267	1.2×10^{10}	24	60.7	7.1	0.116
3.8	Yellow-2267	0.9×10^{10}	16	69.2	8.1	0.117

The exception to the trend is, of course, the 74.7% collection efficiency obtained with the 3.1 μ FP material. Although the data per se on which this result is based appear to be as adequate as those for any of the other results shown, there are some other factors which should be mentioned concerning the particular test conditions and material used. Shortly after the start of the first trial of the series from which these data were obtained (FE 140), a shift in wind direction necessitated a change in the route that had to be taken by the FP line source disseminator vehicle. As a consequence a compromise from the original test plan had to be made to the extent that the line source vehicle had to approach within 150 feet of the nearest sampling station instead of the 300 to 750 feet closest upwind approach used in all other tests. This shorter travel distance from line source to samplers may have contributed to the somewhat greater than usual variation among the reference filter samplers.

The FP material with which the 74.7% efficiency was obtained has lower-than-average percentages of particles in both the fine-particle and large-particle ends of the spectrum--thus tending to be collected efficiently while at the same time exhibiting a smaller than typical MMD.

The collection efficiency result of most practical interest is the 60.7% efficiency obtained with the 3.4 μ FP. This FP is from Dugway Lot 12-21 and is typical of the 12-series lots as will be evident by examining the tabulations of PPG and MMD values presented in a following section of this report.

The most encouraging results obtained in this investigation are those for the 2.4 μ yellow and 2.4 μ green FP's. The close agreement obtained in collection efficiency justifies the implicit assumption made at the beginning of the investigation that the primary variables to be considered do not include such chance differences as those of particle color and intensity, time and process of manufacture, and minor differences in chemical composition. The 2.4 μ

yellow is type 2266 FP from SAL Lot 8B which was manufactured several years ago by New Jersey Zinc Co. The 2.4 μ green is type 3206 FP recently developed and manufactured by U.S. Radium Corp. and furnished to Dugway as Lot H324-2 and since used in Dugway trial 502 B-7.

B. Investigation of UV Illumination Systems

For illumination of the FP material in the near ultra-violet under the microscope, a combination of the B-H4 "black light" bulb and the Bausch and Lomb Spherical Illuminator with the aspherical condenser has been used extensively. (See "The Fluorescent Particle Technique", Chemistry Department, Stanford University, June 1955, pp. 45-46, 132-134 and 150-153, published under Chemical Corps Research Contract No. DA-18-064-CML-2564.) From time to time, certain improvements have been made in this basic illumination system and during the past year experiments have been conducted to determine the comparative efficiency of certain alternative illumination systems.

The most recent modification of the original system consists of the following:

- 1) The G. E. H100A3838-4/T mercury lamp has been substituted for the B-H4 mercury bulb; both lamps have the same electrical characteristics, but differ in that the outer envelope of the B-H4 lamp consists of "black" glass which absorbs most of the visible light output while transmitting most of the 3600 A near ultra-violet.
- 2) Since the G.E. H100A lamp has a clear envelope, the proper filter for intercepting nearly all of the visible light is placed in front of the condensing lens. This filter, the Corning No. 5840, color specification, 7-60, polished, 3 1/8 inches square (about 4.5 mm thick) is more efficient than the "black glass" envelope of the B-H4 lamp (which also tends to vary in its transmittance from lamp to lamp) in that the filter has a relatively higher transmittance for UV and a lower transmittance for the visible light.
- 3) The Spherical Illuminator housings have been made light-tight, since otherwise the unfiltered visible light from the H100A lamps, even after reflection from the black-painted surfaces, would interfere with the dark adaptation of the observer's eyes.
- 4) As a necessary consequence of (3) the Spherical Illuminators have been fitted with a forced air exhaust system to prevent the lamps from overheating. Each pair of illuminators is exhausted by a common exhaust fan, the Ripley Model 8472, 115 V, 60 cy, 40 watt, with 3-inch

blower rated at 77 CFM at 3100 RPM. The blower intake is connected to the open top of the Spherical Illuminators by means of a T fitting and elbows made of 3-inch stovepipe, followed by 20-inch sections of 3-inch flexible automobile defroster tubing. The air enters the Spherical Illuminator at the bottom of the housing through a series of baffles necessary to suppress stray light.

The above particle illumination system, with the two modified lamps opposite each on either side of the microscope stage gives a measured amount of effective illumination three times the amount given by the older arrangement using the B-H4 lamps. The brightness of the standard FP material is now so great that a convenient low level of room illumination can be permitted without loss of counting accuracy.

Experiments have been conducted comparing the effectiveness of the above illumination system with (a) the Beck (London) metallurgical vertical illuminator with the No. 2342 (10X) and No. 2343 (20X) objectives with reflectors, and (b) a 3/16-inch quartz rod with polished ends, used as a light pipe without any additional optics. System (a) (using a single lamp with filter) gave only about 1/20th the effective illumination produced by the above two-lamp system, and System (b) (also using a single lamp) gave about 1/4th of the effective illumination. In both cases, substitution of the more powerful 250-watt AH5 mercury lamp gave less good results since, due to the large diameter of the outer glass envelope, there was less efficient optical use of the source brightness, i.e. the inner quartz tube containing the mercury arc.

It is concluded that: 1) the present system of particle illumination has been brought to a point where there will be little further gain in counting accuracy by further increase in the UV particle illumination; 2) the vertical illuminator system cannot be made to compete with the present system on a practical basis; and 3) further improvements in the quartz rod, light-pipe, system may result in certain practical advantages over the present system. In equipment designed for the automatic register of the particles, using a photomultiplier tube, there is good justification for obtaining still more intense illumination, and for this purpose some improvement in the present system, and probably still more improvement in the quartz light-pipe system, could be obtained.

C. Techniques for Comparing Illumination Efficiency and for Estimating Particle Brightness

Development of techniques for measurement of the apparent brightness of the FP material as seen in the microscope and, independently, for measurement of the effectiveness of the UV illumination system were investigated for two reasons. These factors are of importance in increasing the efficiency of the counting procedures and also in determining whether or not there is any tendency for fluorescent properties of the FP material to change as a result of outdoor exposure or of adverse storage conditions.

Quantitative brightness measurements can be made by several methods, as follows:

(1) Measurement of the total UV light flux which illuminates the same approximate area of the filter (or Rotorod) that appears in the microscope field.

(2) Measurement of the total visible light flux passing through the microscope eyepiece that originates from a special FP-covered microscope slide.

(3) Direct photoelectric measurement of the brightness of the individual FP particles by means of a photomultiplier tube together with a subsidiary optical system attached to the microscope so that a particle is first selected visually and identified as to position on the slide.

(4) Comparative visual measurement of particle brightness by matching an artificial particle image, adjustable in brightness, to the same brightness per unit area as the selected real particle.

For method (1), a Weston Photronic barrier type of cell, was employed, which was covered by a thin sheet of brass with a 1 mm center hole. The cell was placed under the microscope so that the center hole was in the same relative position with respect to the objective as an FP slide during assessment. The UV light entered the hole at a considerable slant and, since the Photronic cell has a glass cover, a portion of the UV light was reflected. However, the relative measurements for comparing different systems of illumination are probably not too seriously affected, and the method is simple. The cell current, assumed to be proportional to the UV illumination, was indicated on a microammeter with a range of 30 microamperes, full scale.

Method (2) is more direct than method (1), since the visible light from the particles themselves is measured. The phototube, or phototube plus filter, should be selected to have as nearly as possible the same wavelength sensitivity characteristics as the human eye, and it should be protected from the effect of reflected UV by a filter such as the Wratten G, which has an extremely low transmission for the blue, violet, and ultraviolet light. An RCA 1P22 photomultiplier tube, with 1500 volts total applied potential, produced an

anode current of about 1 microampere when used in the present measurements. To prevent possible contamination from the FP-covered slide, the FP material either should be enclosed under a glass or quartz cover slip, or else mixed with a small quantity of binder such as diluted Canada balsam or Krylon.

Method (3) is similar in effect to method (2), except that far greater sensitivity of the phototube is required. Some of the factors concerning this requirement are discussed in CML-448 Memorandum Report No. 17 (SAL, 23 October 1961), "Comments on the Feasibility of Developing an Automatic FP Particle Scanner for Atmospheric Tracer Studies". Since a photomultiplier tube of the required sensitivity was not available for the experiments, this method was not actually tried in the present series of measurements.

Method (4) requires a microscope eyepiece equipped with a beam-splitting mirror or prism so that the comparison spot may be superimposed on the field showing the FP's. The spot itself is projected from a pin-hole aperture in a piece of aluminum foil placed directly in front of a lamp bulb filament. The intensity of the spot is controlled by the voltage applied to the lamp filament. Since the spot color changes with applied lamp voltage a suitable filter is necessary.

It was found that one of the interference filters, a 2" square Lichtenstein 570-8B-40 (Number 9553-19), when interposed in the pin-hole beam, had such sharp filter characteristics that there was no apparent change in color of light with lamp voltage. The specified peak wavelength, 570 millimicrons, gives a comparison spot that is scarcely distinguishable from a true FP particle except for the round shape and uniform brightness of the spot. Although a trifle greener than the average FP, there is no uncertainty in adjusting the lamp voltage to the point where the average brightness per unit area of the comparison spot and a selected particle appear the same. It does not appear necessary to match the particle in size, at least within a diameter factor of 5X or so. Ideally, the combination of the adjustable brightness feature with the adjustable size feature (as presently used in the particle-sizing procedure) would be desirable and would probably lead to better accuracy for both particle brightness and particle size measurements.

The 6-volt, 2.5-ampere bulb which was used to illuminate the pinhole was calibrated by measuring, for various lamp voltages, the output of a Weston Photronic cell placed three inches in front of it, interposing the same interference filter used in front of the comparison spot. This data could be expressed as smooth curves showing relative brightness, over a total range of 240:1 in brightness, for lamp voltages (easily controllable and measurable to

$\pm .01$ volt) from 4.5 to 1.5 volts. The change per 0.1 volt varied from about 12.5% at 4 volts to about 60% with a mean lamp voltage of 1.5 volts. Thus, the reproducibility of the spot brightness varies from about $\pm 1.25\%$ to $\pm 6\%$, and it is advantageous to arrange the optical system (using neutral density filters as needed) so that a particle of average brightness gives a reading of about 3 volts.

Using the above methods (1), (2), and (4) the ratio of the illumination from the standard two-lamp system with aspherical condensing lenses to the illumination produced from a single quartz rod and lamp was determined. The results are shown below:

	<u>Method (4)</u>			<u>Method (1)</u>	<u>Method (2)</u>	<u>Mean</u>
	Visual Comparison Individual Particle*			Measurement of Effective UV by Photronic Cell	Evaluation of Light through Eyepiece from Special FP-covered Slide	
	A	B	C			
Ratio	1.9	2.5	1.9	3.7	2.8	2.6

* Estimated Diameters: A, 5 microns; B, 2 microns; C, 0.8 microns.
Measured Brightness Ratios: A/B, 2.3; A/C, 4.9 (per unit area).

The above data for particles A, B, and C is based on nine independent voltage adjustments for equal brightness per unit area between the comparison spot and the particle. Obtainable precision, after a little experience on the part of the operator, is estimated to be about $\pm 10\%$. The higher ratio for method (1) is probably real, since the glass condensing lenses have considerable absorption for 360 millimicron UV and still more for the shorter wavelengths. Results from all three methods indicate that the quartz-rod method of illumination can be made competitive with the improved two-lamp method now in use; in addition, the quartz-rod method may be less expensive and more convenient.

Method (1) for evaluating the inherent particle brightness may be applied to the problem of determining the possible decay of inherent fluorescent properties of the particles during prolonged downwind travel under adverse conditions, e.g. high humidity, temperature, air pollution and sunshine intensity. Near and distant samples of the same material may be compared in terms of average brightness for specified particle size groups, as determined by the adjusted comparison lamp voltage and selected pinhole sizes. By measuring relatively large numbers of the selected sizes, any decrease in average brightness should become apparent.

D. Physical Analysis of FP Tracer Materials

Aerosolization tests were made on several lots of Dugway FP material to determine the PPG (particles per gram) value for each lot and to obtain, as required for subsequent particle size analysis and particle color and brightness measurements, standard collections on membrane filters of each such aerosolized specimen. PPG values were determined as required for source strength calculations in connection with the evaluation of the 485 and 502 trial data. PPG values and either approximate or detailed particle size analyses were made as required in support of the Rotorod FP collection efficiency investigation. The same collections and data were also used in support of the UV illumination and particle brightness work summarized in the immediately preceding sections of this report. In addition to the PPG and particle size data from aerosolization tests made on Dugway FP materials the data from similar tests made for other clients were also used in support of the Rotorod FP collection efficiency work.

The theoretical model and experimental technique used in making standard aerosolization tests of FP tracer materials has been described in detail in the FP Manual.* Additional theoretical and experimental considerations together with a review of the reliability and application of data from several such tests have also been presented in Quarterly Report 111-10.**

Except for some recent improvements in equipment and procedures the aerosolization tests and related physical analysis of FP materials performed in connection with CML-543 were made essentially as described in the foregoing referenced reports.

Presented in Table 6 is a summary of the PPG value and the corresponding MMD (mass mean diameter) for each of the 17 lots of Dugway FP materials tested in connection with CML-543. The results from particle size analysis and from the examinations of certain of these materials for color and brightness are presented elsewhere in this report as well as in the technical report on the Rotorod FP collection efficiency.

* "The Stanford Fluorescent-Particle Tracer Technique: An Operational Manual", June 1955, Contract DA-18-064-CML-2564.

** Stanford Aerosol Laboratory Quarterly Report 111-10, July-August-September 1956, Contract DA-42-007-403-CML-111.

Table 6

PPG and MMD Values for Various Lots of Dugway FP Material

<u>Aerosolization Test No.</u>	<u>Material Tested</u>	<u>Used in Dugway Trial</u>	<u>Aerosol Properties</u>	
			<u>PPG</u>	<u>MMD</u>
58	2267 Lot 12-2	485-A1	1.39×10^{10}	3.24 μ
59	2267 Lot 12-5	485-A2	1.37×10^{10}	3.26 μ
60	2267 Lot 12-6	485-A3	1.30×10^{10}	3.32 μ
61	2267 Lot 12-7	485-A4	1.25×10^{10}	3.36 μ
62	2267 Lot 12-20	502-B6-Y	1.11×10^{10}	3.51 μ
63	2267 Lot 12-21	502-B7-Y	1.18×10^{10}	3.43 μ
64	3206 Lot H-324-1	502-B6-G	2.96×10^{10}	2.53 μ
65	3206 Lot H-324-2	502-B7-G	3.32×10^{10}	2.43 μ
68	2267 Lot 12-15	502-B1	1.69×10^{10}	3.05 μ
69	2267 Lot 12-16	502-B2	1.50×10^{10}	3.17 μ
70	2267 Lot 12-22	502-B8-Y	1.44×10^{10}	3.21 μ
71	2267 Lot 12-14	502-B3	1.44×10^{10}	3.21 μ
72	2267 Lot 12-18	502-B4	1.49×10^{10}	3.18 μ
73	2267 Lot 12-19	502-B5	1.44×10^{10}	3.22 μ
74	2267 Lot 12-23	502-B9-Y	1.59×10^{10}	3.10 μ
75	2267 Lot 12-24	---	1.63×10^{10}	3.08 μ
76	2267 Lot 12-AB*	---	1.45×10^{10}	3.21 μ

* Composite blend of FP 2267, Lots 12-1 through 12-33.

APPENDIX A

Application of Heat-Flux Model to an Elevated Line Release

1. Calculation of Vertical Eddy Diffusivity

An estimate of the vertical flux of heat may be made from the mean rate of cooling of the atmosphere in the lower levels. The estimate of cooling is complicated by advective temperature change. This complication may be resolved by assuming that the advective temperature change is constant and independent of height; then, the rate of temperature change may be expressed by

$$\frac{\partial \theta}{\partial t} = - \frac{\partial F(z)}{\partial z} + C \quad (1)$$

where θ = potential temperature at height z .

$F(z)$ = vertical flux of heat divided by the heat capacity per unit volume of air.

C = rate of temperature change due to advection.

Integrating Eq. (1) through a layer of atmosphere from some low level z_1 to height z , and dividing by $(z - z_1)$ the mean rate of cooling through the layer z_1 to z is obtained, i.e.

$$\frac{1}{z - z_1} \int_{z_1}^z \frac{\partial \theta}{\partial t} dz = \frac{F(z_1) - F(z)}{z - z_1} + C \quad (2)$$

If the mean cooling rate is plotted against $1/z$ a limiting value is approached as $z \rightarrow \infty$ (or $1/z \rightarrow 0$). This gives an estimate of the rate of temperature change C due to advection, i.e.

$$C = \lim_{z \rightarrow \infty} \frac{1}{z - z_1} \int_{z_1}^z \frac{\partial \theta}{\partial t} dz \quad (3)$$

If it is further assumed that the vertical turbulent heat flux approaches zero as z becomes large, an estimate of $F(z_1)$ may be obtained from

$$F(z_1) = \lim_{z \rightarrow \infty} \left[\int_{z_1}^z \frac{\partial \theta}{\partial t} dz - C(z - z_1) \right] \quad (4)$$

Substituting the values of C and $F(z_1)$ in Eq. (2) the flux $F(z)$ may be computed. The vertical eddy diffusivity $K(z)$ may then be obtained from

$$F(z) = -K(z) \frac{\partial \theta}{\partial z} \quad (5)$$

When the rate of temperature change is constant with height, $F(z_1)$ cannot be computed from Eq. (4). In this case, however, the heat flux may be assumed to be independent of height and the eddy diffusivity may be estimated from the wind speed at a height z_1 equal to 40 times the roughness parameter, z_0 , as was done for the O'Neill data, i.e.

$$K(z_1) = \frac{u(z_1)z_1}{20} \quad (6)$$

The diffusivities at other levels may then be calculated from

$$K(z) \frac{\partial \theta}{\partial z} = K(z_1) \left(\frac{\partial \theta}{\partial z} \right)_{z_1} \quad (7)$$

2. Calculation of Dosage

Vertical eddy diffusivities and wind speeds may be fitted by power-law functions and used to compute the dosage per unit source strength downwind from an elevated line release. However, it was found that, for intermediate-scale cloud travel, mean values of eddy diffusivity and wind speed gave nearly the same

results as power-law functions of these parameters. Hence, dosages downwind from an infinite crosswind line source may be calculated from the equation

$$\frac{D(x,z)}{Q} = \frac{S^{\frac{1}{2}}}{\sqrt{\pi} \bar{u} H} e^{-(r-1)^2 S} (1 + e^{-4rS}) \quad (8)$$

where $D(x,z)$ = dosage at downwind distance x and height z .

Q = source strength per unit length of release line.

\bar{u} = mean wind speed

H = height of source

$r = z/H$

$S = \frac{uH^2}{4Kx}$

K = mean vertical eddy diffusivity.

For ground-level dosages Eq. (8) reduces to

$$\frac{D(x,0)}{Q} = \frac{2S^{\frac{1}{2}}}{\sqrt{\pi} \bar{u} H} e^{-S} \quad (9)$$