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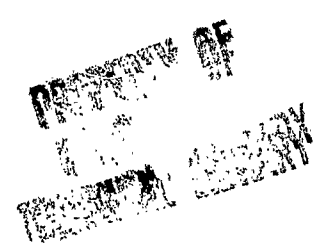
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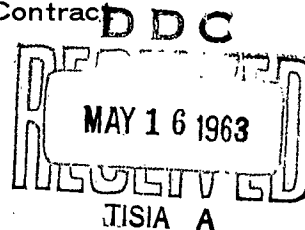
Intermediate-Scale  
Aerosol Cloud Travel And Diffusion  
From Low-Level Aerial Line Releases

L. M. VAUGHAN  
R. W. McMULLEN

**405 940**

30 January 1963

U. S. Army Chemical Corps  
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**AEROSOL LABORATORY**

METRONICS ASSOCIATES, INC.  
STANFORD INDUSTRIAL PARK  
PALO ALTO, CALIFORNIA

METRONICS ASSOCIATES, INC.  
3201 Porter Drive  
Palo Alto, California

13 March 1963

To all holders of copies of Technical Report No. 97: "Intermediate-Scale Aerosol Cloud Travel and Diffusion From Low-Level Aerial Line Releases" by L. M. Vaughan and R. W. McMullen, 30 January 1963.

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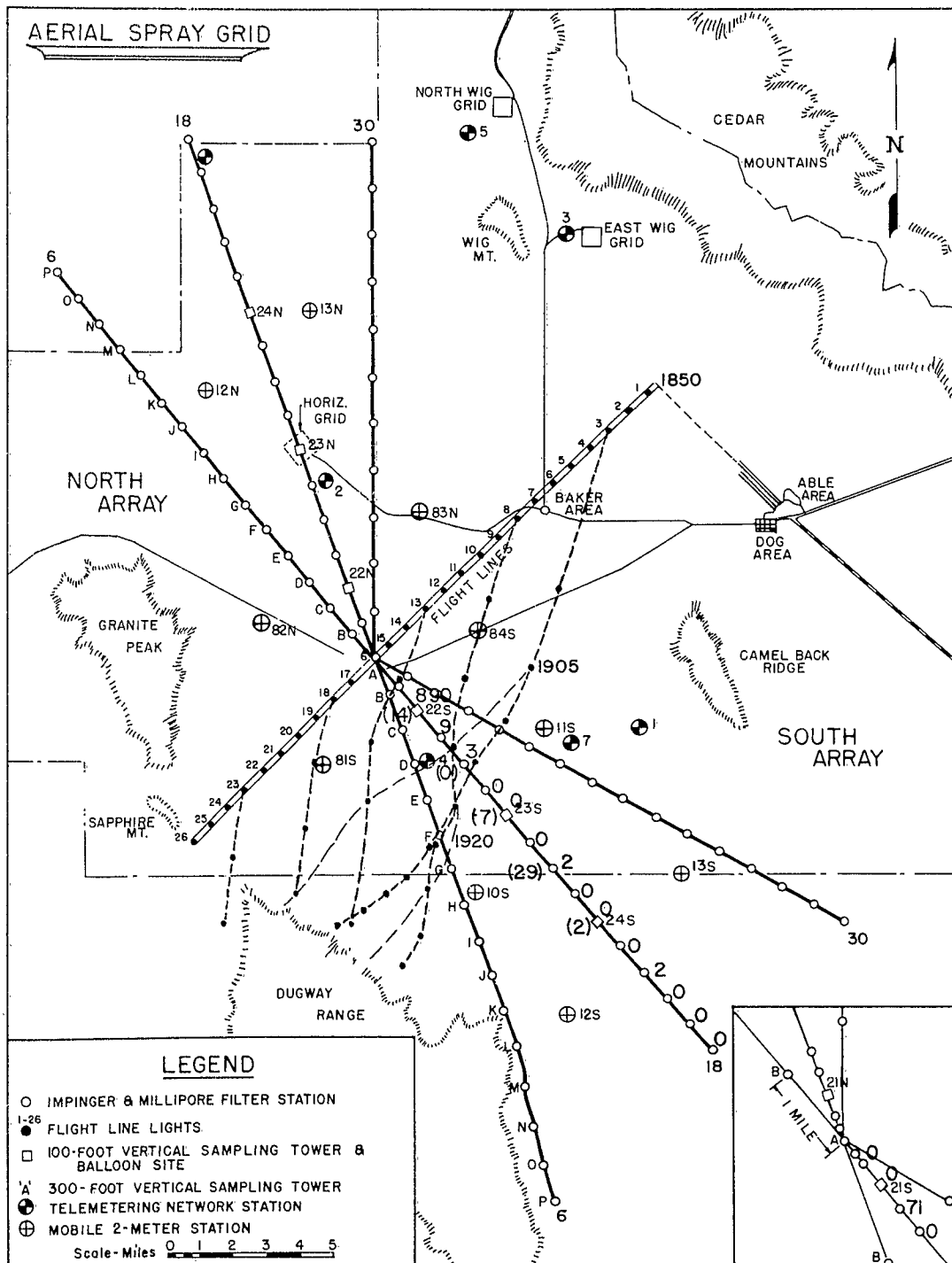


Fig. 21--Trial B-9: Yellow FP recoveries at 5 feet and trajectories calculated from 250-ft winds.

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⑮ INTERMEDIATE-SCALE AEROSOL CLOUD TRAVEL AND DIFFUSION  
FROM LOW-LEVEL AERIAL LINE RELEASES

⑩ by  
L. M. Vaughan and  
R. W. McMullen

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For

Chemical Corps Research and Development Program  
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Aerosol Laboratory  
Metronics Associates, Inc.  
3201 Porter Drive  
Palo Alto, California

## ABSTRACT

A series of low-level aerial line releases of fluorescent particles under a variety of atmospheric stability conditions is being conducted at Dugway Proving Ground, Utah. Aerosol samples are obtained at ground level to 15 miles and aloft to 700 feet from tower and balloon-mounted samplers. The first nine of these trials have been analyzed in terms of a diffusion model based on estimates of the vertical eddy heat flux obtained from mean temperature profiles and their change with time. Satisfactory agreement was obtained between calculated and observed dosages when the winds at release altitude were reasonably uniform and nearly parallel to the downwind sampling line.

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## SUMMARY

A series of low-level aerial line releases of fluorescent particles (FP) is being conducted at Dugway Proving Grounds, Utah. These trials have been designated as the BW 502 B series and the first nine trials have been analyzed and are included in this report.

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 first 5 trials were made with a single aerial release of yellow FP but in Trials 6, 7 and 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 the same sampler array. In Trial B-8 an aerial release was made in conjunction with a parallel line release at ground level. Altitudes for different releases ranged from 100 feet to 450 feet and the length of dissemination was approximately 14 miles.

The sampler 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 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. Temperatures at heights from 100 feet to 1100 feet at 200-ft intervals were obtained by planesonde near the tower positions. One-meter 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 tower positions and winds aloft at levels from 125 to 1200 feet were obtained from pilot balloon measurements at approximately 10 locations within the test area.

Vertical temperature profiles and rates of temperature change with time were used to compute vertical eddy diffusivities and these were used to compute dosages per unit source strength for each trial. Reasonable agreement between calculated and observed dosages was obtained when aerosol cloud trajectories were nearly parallel to the sampling line.

In Trials 4, 5, and 6 the aerosol cloud trajectories were such that the entire sampling array was traversed by the central portion of the cloud so

that samples obtained should represent expected recoveries from an infinite line release. In Trials 2, 3, and 8 trajectories indicated some possibility of edge effects and enfilading due to shifts in wind direction, but recoveries in general appeared to be normal within the sampling range. In Trial 1, trajectories indicated possible over-running of one portion of the aerosol cloud over another giving a bimodal vertical distribution of recoveries to 6 miles downwind and edge effects at greater distances. A wind shift at higher levels in Trial 7 produced edge effects and enfilading. The winds in Trial 9 were at an angle of approximately 45 degrees with the sampling line so that no appreciable recoveries were obtained beyond 4 miles.

In Trials 1, 3, 5, and 6 conditions were stable and vertical diffusion was small. Good agreement was obtained between calculated and observed diffusion except for Trial 1 for reasons noted above. Trials 4 and 8 were conducted under moderately stable conditions giving moderate vertical dispersion. However, a sharp upper boundary to the FP cloud at approximately 450 feet was observed in Trial 4. This sharp boundary was not predicted by the calculations because a mean value of vertical diffusivity was used although the calculated diffusivities showed a marked decrease above 500 feet. In Trial 8, agreement between calculated and observed vertical diffusion was good except at 10 miles downwind where a shift in wind direction produced enfilading.

Trials 2, 7, and 9 were conducted under near-neutral conditions and gave large vertical diffusion in agreement with calculations for the first 3 or 4 miles downwind. However, wind shifts and edge effects in Trials 2 and 7 yielded dosage values lower than those calculated at 10 miles downwind and in Trial 9 both the yellow and green FP clouds missed the sampling line beyond 4 miles.

In all cases the proper order of magnitude of vertical diffusion was predicted from the calculated eddy diffusivities and lack of agreement between calculated and observed dosages in some trials was primarily due to enfilading and edge effects.

The maximum ground level dosage obtainable from an elevated line release was found to be relatively independent of atmospheric stability and approximately equal to one-half the source strength divided by the product of mean wind speed and release altitude. The distance at which the maximum occurs however, is very dependent upon stability.

It appears that for elevated releases the use of a mean diffusivity and a mean wind speed through the first 1000 feet gives almost as good results as fitting the diffusivity and wind profiles by power laws. Since the dosage calculations

for constant diffusivity are simpler and can be made readily from a suitable nomogram, the use of constant diffusivity and wind is recommended for diffusion calculations for cloud travel to distances of 10 to 20 miles.

## I. INTRODUCTION

A considerable amount of experimental data has been obtained for ground-level releases of aerosols and gases for a wide range of atmospheric stability (e.g. "Project Prairie Grass", O'Neill, Nebraska, 1956 [17]). Some data are also available for aerosol travel from elevated point releases at a height of 150 feet for distances to 2 miles under lapse conditions [2] and at 355 feet for distances to 3 miles under lapse and neutral conditions [3]. Data from elevated line releases at heights of 1000 feet to 2500 feet and distances up to 60 miles have been published [4]. Only recently, however, have data become available for intermediate-scale travel from low-level aerial line releases of fluorescent particles at altitudes from 100-500 feet and distances up to 15 miles. One series of six trials designated as the BW 502 A series was run at Dugway Proving Ground, Utah, during October and November 1960 under strong inversion conditions with the exception of Trial A-2 which was made under near-neutral conditions [5]. A second series designated as the BW 502 B series was begun in March 1961 and is still in progress.\* Nine of these latter trials have been analyzed and are included in this report.

Various diffusion models have been used for elevated releases. The most familiar of these were formulated by Sutton [6] and by Bosanquet and Pearson [7]. Sutton's equations require estimates of virtual diffusion coefficients from gustiness measurements and vertical profiles of wind. Bosanquet's equation is valid only for near-neutral conditions. Hay and Smith [4] and Hay and Pasquill [8] have recently developed techniques for estimating dispersion directly from wind fluctuations. Since reliable wind fluctuation measurements were not available for most of these trials, analysis of the data has been made in terms of a "heat-flux" model which was successfully applied to diffusion trials at O'Neill, Nebraska, in 1956 [9].

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\* Dugway Proving Ground Test Plan DPGTP 502, Phase B, Aerosol Diffusion from Line Source Releases Made Under Various Atmospheric Stability Conditions(U), June 1961, CONFIDENTIAL DPG 61-1238.

## II. APPLICATION OF HEAT FLUX MODEL TO AN ELEVATED LINE RELEASE

### A. Notation

$h$  = height of line source above ground

$z_0$  = roughness parameter

$z_1$  = arbitrary reference height

$K(z)$  = vertical eddy diffusivity at height  $z$

$u(z)$  = mean horizontal wind speed at height  $z$

$\theta$  = potential temperature of air. In this analysis it is the temperature the air would have if it were brought adiabatically to ground level.

$A$  = rate of temperature change due to advection

$H_E$  = vertical flux of heat due to turbulent transfer (i.e. the eddy heat flux)

$\rho$  = density of atmosphere

$c_p$  = specific heat of air at constant pressure

$F$  = eddy heat flux divided by the heat capacity per unit volume of air, i.e.  $F = H_E / \rho c_p$

$D$  = dosage, i.e. the time integrated concentration,  $\int_0^{\infty} C dt$ .

Dosage is measured by dividing the amount of material collected by the flow rate of air through the sampler.

$Q$  = source strength, i.e. the amount of tracer released. For line releases it is the amount of tracer per unit distance.

### B. Approach

Heat is transported vertically through the atmosphere by several processes, i.e. radiation, molecular diffusion, advection, convection, and turbulent transfer or eddy diffusion. Only the processes of diffusion and convection may be directly related to the vertical dispersion of aerosols or gases in the atmosphere.

Molecular diffusion of heat is generally so small that it may be neglected except at the earth-air boundary. Vertical transfer of heat by advection implies a net vertical motion of the atmosphere, but these vertical displacements at low levels are generally very small with respect to horizontal movements of the atmosphere. Radiative heat transfer within the lower atmosphere is generally small except very close to the ground, and this transfer may be considered to be independent of height within the first thousand feet of atmosphere considered in this study.

Vertical transport of heat by convection is an important factor under daytime conditions with clear skies and strong insolation. Under inversion and



near-neutral conditions, however, the vertical heat transport is dominated by eddy diffusion, and may be expressed in terms of an eddy diffusivity and the vertical gradient of potential temperature, i.e.,

$$H_E = c_p \rho K(z) \frac{\partial \theta}{\partial z} \quad (1)$$

Although the eddy diffusivity  $K(z)$  is a function of stability and wind speed it is assumed to be independent of time during the period of cloud travel.

### C. Calculation of Vertical Eddy Diffusivity

If the vertical eddy diffusivity for matter is assumed to be equal to that for heat, the diffusion of aerosols or gases within the atmosphere may be computed from measurements or estimates of the vertical eddy heat flux. Since no heat-flux measurements were made during these trials, estimation of the heat flux was obtained from the rates of temperature change within the atmosphere. The estimation of heat flux is complicated by advection of colder or warmer air over the area. However, assuming that the advective temperature change,  $A$ , is constant and independent of height, the rate of temperature change may be expressed by

$$\frac{\partial \theta}{\partial t} = - \frac{\partial F}{\partial z} + A \quad (2)$$

Integrating Eq. (2) through a layer of atmosphere from some low level  $z_1$  to height  $z$

$$\int_{z_1}^z \frac{\partial \theta}{\partial t} dz = F(z_1) - F(z) + A(z - z_1) \quad (3)$$

The mean rate of temperature change through the layer is obtained by dividing Eq. (3) by  $(z - z_1)$ . Plotting this mean value against  $1/z$ , a limiting value is approached as  $z \rightarrow \infty$  (or  $1/z \rightarrow 0$ ). This gives an estimate of the advective temperature change,  $A$ , i.e.

$$A = \lim_{z \rightarrow \infty} \frac{1}{z - z_1} \int_{z_1}^z \frac{\partial \theta}{\partial t} dz \quad (4)$$

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

$$F(z_1) = \lim_{z \rightarrow \infty} \left[ \int_{z_1}^z \frac{\partial \theta}{\partial t} dz - A(z - z_1) \right] \quad (5)$$

Substituting the values of  $A$  and  $F(z_1)$  in Eq. (3), the flux  $F(z)$  may be calculated. The vertical eddy diffusivity  $K(z)$  may then be computed from

$$F(z) = -K(z) \frac{\partial \theta}{\partial z} \quad (6)$$

Under near-neutral conditions the rates of temperature change are nearly equal at all levels and the eddy heat flux may be assumed constant and independent of height. In this case the heat flux cannot be determined from Eq. (5), but under the assumption that the diffusivities for heat and momentum are equal near the ground the eddy diffusivity may be estimated from the wind speed at a height equal to 40 times the roughness parameter as was done for the O'Neill data [10], i.e.

$$K(z_1) = \frac{u(z_1) z_1}{20} \quad (7)$$

The diffusivities at other levels may then be computed from

$$K(z) \frac{\partial \theta}{\partial z} = K(z_1) \left( \frac{\partial \theta}{\partial z} \right)_{z_1} \quad (8)$$

Eddy diffusivities and wind speeds may be fitted by power-law functions, i.e.

$$K(z) = K(z_1) \left( \frac{z}{z_1} \right)^m \quad (9)$$

and

$$u(z) = u(z_1) \left(\frac{z}{z_1}\right)^n \quad (10)$$

#### D. Calculation of Dosage

Dosages downwind from an elevated line release may be calculated from the equation

$$\frac{D(x,z)}{Q} = \frac{\alpha}{u(h)h} r^{1-\beta} S e^{-(r^2+1)S} I_{\beta-1}(2rS) \quad (11)$$

$$\begin{aligned} \text{where } r &= \left(\frac{z}{h}\right)^{\frac{\alpha}{2}} \\ S &= \frac{u(h)h^2}{\alpha^2 K(h)x} \\ \alpha &= 2 - m + n \\ \beta &= (1 + n) / \alpha \end{aligned}$$

$I_{\beta-1}$  = modified Bessel function.

It was found that the use of mean values for eddy diffusivity and wind speed gave almost as good results as the use of power laws. Hence the dosages were recalculated using constant  $u$  and  $K$  values. In this case Eq. (11) reduces to

$$\frac{D(x,z)}{Q} = \frac{S^{\frac{1}{2}}}{\sqrt{\pi}uh} e^{-(r-1)^2 S} (1 + e^{-4rS}) \quad (12)$$

$$\begin{aligned} \text{where } r &= \frac{z}{h} \\ S &= \frac{uh^2}{4Kx} \end{aligned}$$

### III. DESCRIPTION OF TEST AREA

#### A. Terrain and Vegetation

The test area, designated as the Aerial Spray Grid (ASG) lies within the Dugway Valley and is centered approximately between Granite Peak on the west and Camel Back Mountain on the east. The Cedar Mountains lie to the northeast and the Dugway Mountains to the south. This area is relatively flat with a mean elevation approximately 4300 feet above sea level.

Vegetation\* on the main portions of the north and south grids consists of three plants: Greasewood (*Sarcobatus vermiculatus*), Shadscale (*Atriplex confertifolia*) and Grey Molly (*Kochia vestita*). Scattered among these plants are Salt Sage (*Atriplex nutalli*) and in areas where water stands periodically, some Seepweed (*Dondia* sp) occurs. Greasewood is the tallest vegetation and is about 2 to 3 feet tall. Portions of the terrain and vegetation are shown in Figs. 2 and 4.

#### B. Sampler Array

Aerial releases were made along a line oriented northeast-southwest with lights at approximately 4000-ft intervals for a distance of 19 miles (Fig. 1). Near the center of this line was a 300-ft tower with samplers spaced at 5-ft intervals to the top of the tower (Figs. 2 and 3). Samplers at the 5-ft level were located at 1/4-mile intervals to 1 mile downwind from the release and at 1-mile intervals to a distance of 15 miles from the release. Only the center line of the north or south array shown in Fig. 1 was used during these trials. Vertical sampling was also obtained from samplers at 15-ft intervals from 5 to 95 feet on four 100-ft towers (Stations 21, 22, 23 and 24) located 1/2, 2, 6 and 10 miles downwind from the release line. Sampling at 75-ft intervals from 125 to 775 feet was obtained by means of balloon-supported samplers near the 100-ft towers (Fig. 4).

#### C. Meteorological Array

Temperature gradients from 50 feet to 100, 150, 200 and 300 feet were obtained at the 300-ft ASG tower and from 0.5 m to 1, 2, 4, 8 and 16 m on a profile mast located due east of the tower. Wind speeds were also obtained at the same heights and wind directions at 2 m, 16 m, 150 feet and 300 feet. Temperature gradients were also obtained from 0.5 m to 2 m, 4 m, 8 m, 16 m, and 100 feet on the four 100-ft towers located 1/2, 2, 6, and 10 miles downwind from the release line. Wind speeds were also measured at 0.5 m, 2 m, 8 m, 16 m and 100

---

\* Letter from C. D. Neff, Director of Test Operations at Dugway Proving Ground, June 22, 1962.

feet at these towers. Two-meter and 8-m winds were measured at stations indicated in Fig. 1. One-meter temperatures and pilot balloon winds were also measured at all stations. Surface observations and 2-m and ground temperatures were obtained at the "met" van (Fig. 5) located 2000 feet southeast of the ASG tower.

Vertical components of wind were measured at four levels on the ASG tower. During the first four trials, measurements were made at 10 feet, 100 feet, 200 feet and 300 feet. For later trials measurements were made at 2 m, 16 m, 200 feet and 300 feet.

Temperatures at 200-ft intervals from 100 to 1100 feet were obtained from aircraft soundings over the control point and at Stations 22, 23 and 24.

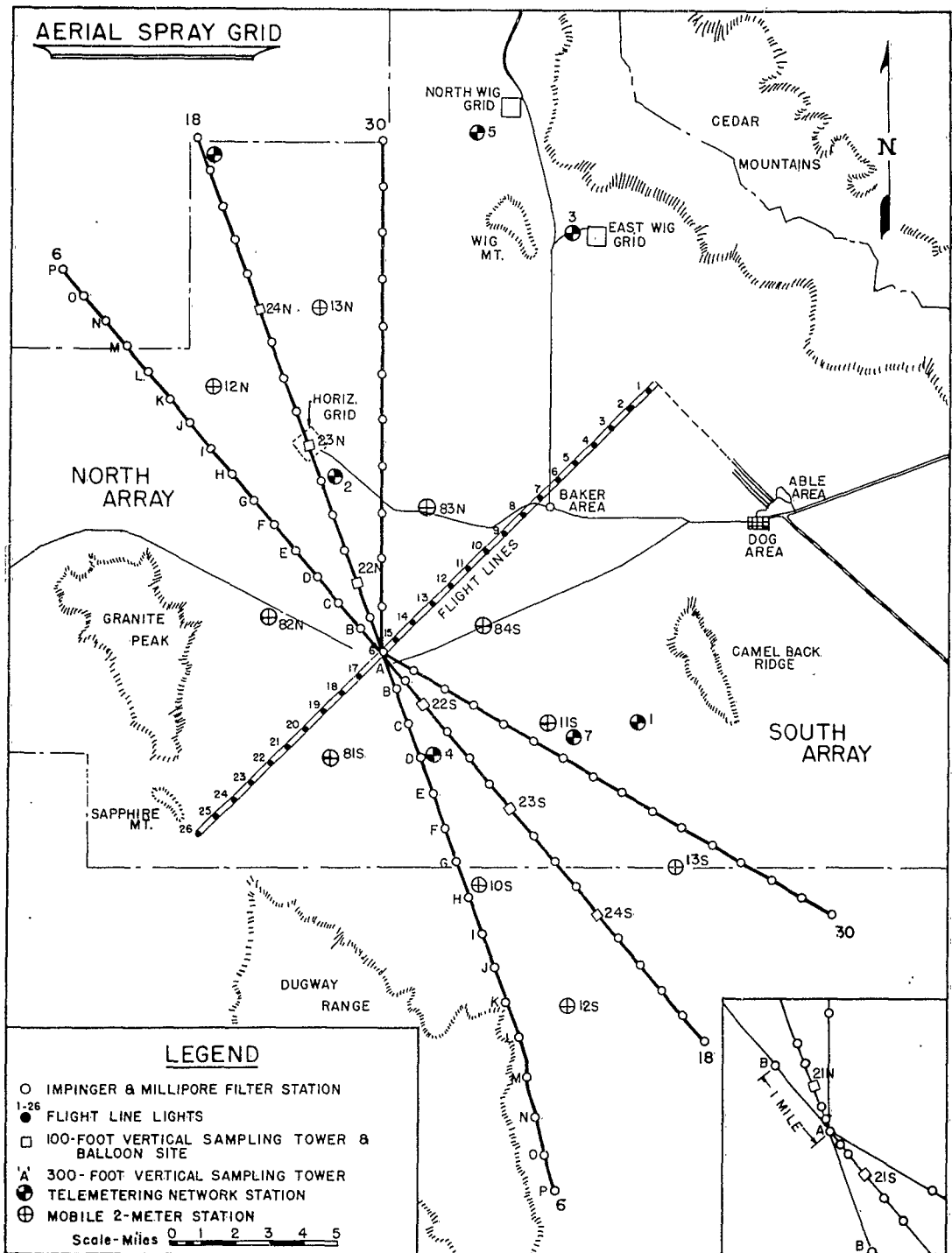


Fig. 1--Aerial Spray Grid Test Area.

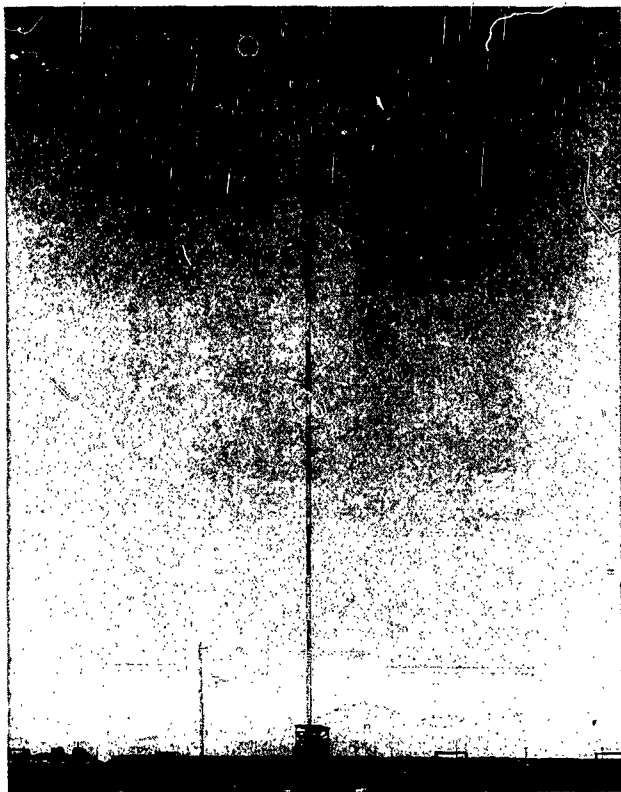


Fig. 2--ASG meteorological and sampling tower, 300 feet and 16 m meteorological tower. (U.S. Army Photograph)

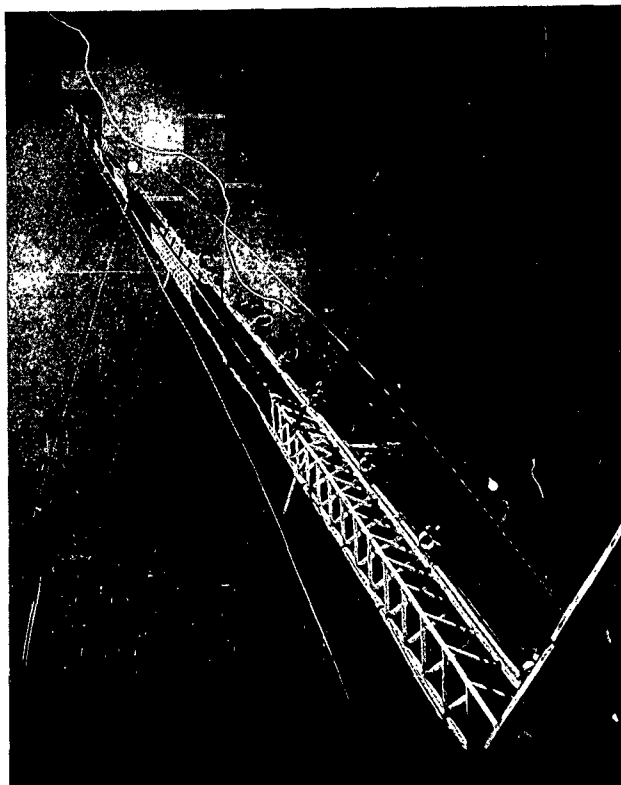


Fig. 3--ASG tower with membrane filters spaced at 5-ft intervals. (U.S. Army Photograph)

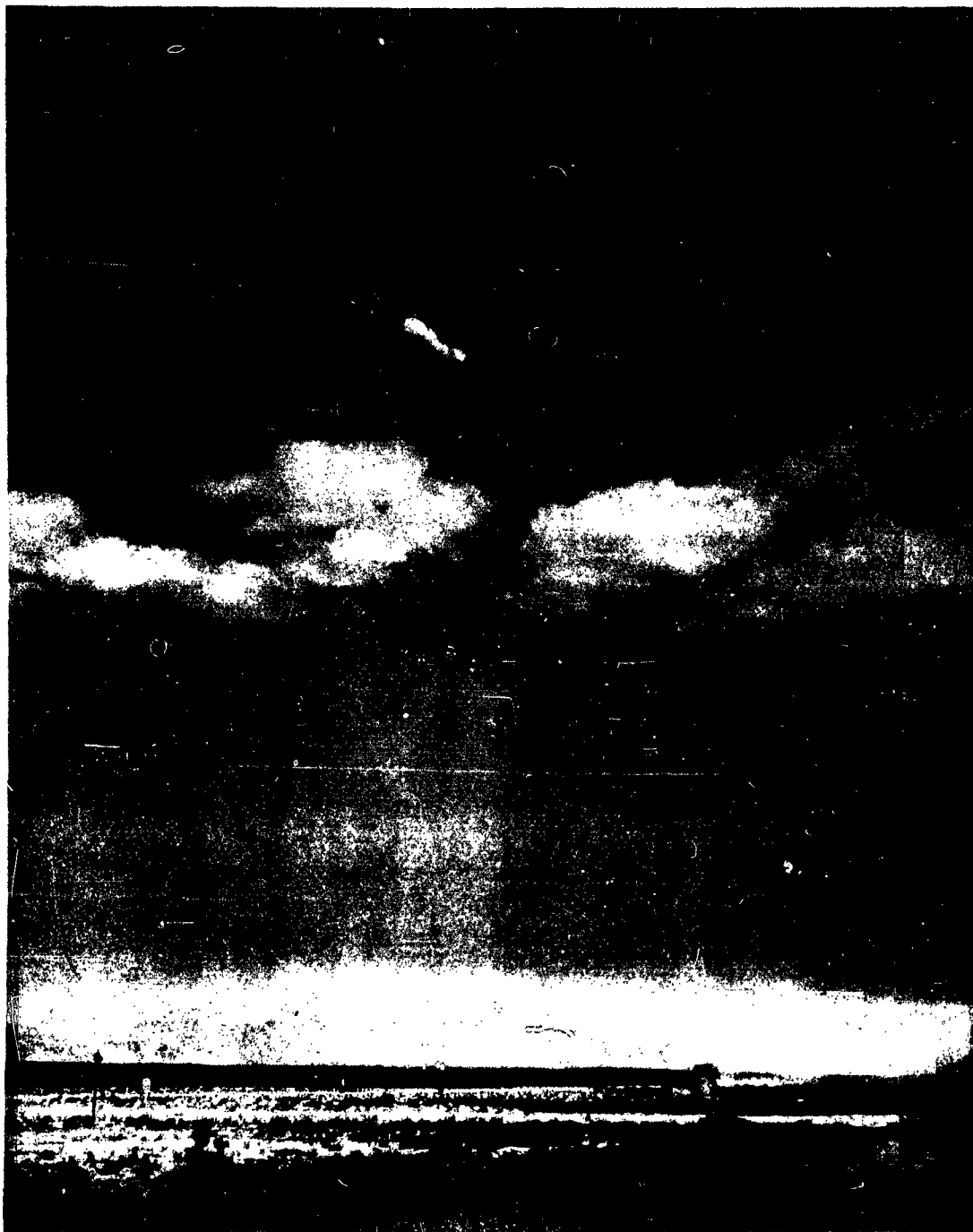


Fig. 4--Sefang balloon used to support Rotorod samplers at 75-ft intervals from 175 to 775 feet. (U. S. Army Photograph)



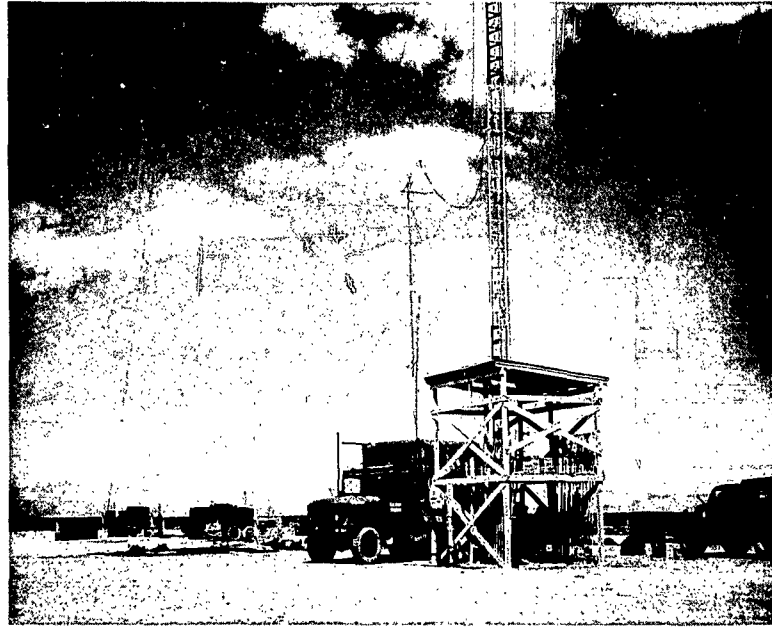


Fig. 5--Meteorological van with mast. (U.S. Army Photograph)

#### IV. TRIAL CONDITIONS, METEOROLOGICAL MEASUREMENTS AND ANALYSIS

##### A. Trial Conditions

Times, release altitudes, source strengths and general meteorological conditions prevailing during the first nine trials of the BW 502 B series are summarized in Table 1 below. More detailed meteorological data are given in Section VI.

Table 1  
Summary of Trial Conditions for BW 502 B Series

Trial No.	Date	Release		Source Strength (gm/ft)	Wind Speed		Temperature Gradient*		Cloud Cover (tenths)
		Time (MST)	Altitude (ft)		2m	150ft	1/2 m-50 ft (°F)	2m-300 ft (°F)	
1	14 Mar 61	2219	250	0.23	6.3	18.5	+3.2	+6.0	4
2	15 Mar 61	1900	455	0.26	13.6	20.4	+0.6	-0.6	10
3FP	22 Mar 61	2306	115	0.24	2.6	10.3	+5.6	>10.5	8
BG		2302	200						
4	28 Aug 61	2329	255	0.28	7.0	20.8	+5.6	+11.2	5
5	29 Aug 61	2009	125	0.25	11.8	20.6	+0.2	0	
6Y	5 Sep 61	2056	250	0.26	4.8	21.2	+7.5	+13.1	1
G			400	0.21					
7Y	4 Oct 61	1630	225	0.25	3.6	4.2 <sup>Δ</sup>	+1.1	-2.8	0
G			400	0.22					
8Y	19 Oct 61	1629	0	0.03**	5.6	18.8 <sup>Δ</sup>	+2.4	+1.0	6
G			400	0.25					
9Y	6 Jun 62	1849	250	0.29	11.8	23.9 <sup>Δ</sup>	+0.1	-1.3	2
G			430	0.26					

\* Z to Z + 5 min.

\*\* West vehicle release

Δ 300-ft wind

##### B. Instrumentation

Temperature gradients were measured with copper-constantan thermocouples (No. 18 wire) shielded from direct solar radiation. Gradients were recorded on 6-point Brown Recorders using a color code to differentiate between various levels.

Chart speed was 8 inches per hour. Response of recorders was 90% of 5 degrees change in 0.5 seconds. Gradients between 2 m and each level on the 16-m masts were measured each 30 seconds. On the ASG tower gradients were measured with reference to the 50-ft level.

Surface observations of air temperature, relative humidity and ground temperature were taken with standard mercury thermometers and electrically driven aspirated psychrometers in thermoscreens. When aspirated psychrometers were not available, sling psychrometers were used.

Aircraft temperature soundings were made with a thermistor probe and a Beckman-Whitley temperature bridge Model 196 or 197. Model 196 has a range from -70 to +60°F and Model 197 has a range from 10 to 140°F. The response time is of the order of 80 seconds.

Wind directions and speeds were measured with Beckman-Whitley wind vanes and 3-cup anemometers and were recorded on Esterline-Angus Recorders at chart speeds of 3 inches-per-hour or 3 inches-per-minute. Accuracy of wind direction was  $\pm 3$  degrees and wind speed  $\pm 0.5$  mph. Vertical components of wind direction were measured at 10, 100, 200, and 300 feet by mounting standard Beckman-Whitley vanes in a horizontal position with fixed azimuth perpendicular to the release line. In trials conducted since April, 1962, bivanes were used at 2 m and 16 m.

Pilot balloon wind measurements were made by the single theodolite method using 30-gm balloons weighed off to give the same free lift as 10-gm balloons. Observations were taken every 30 seconds over a 3-minute or 6-minute period.

#### C. Data Reduction

Data reduction was performed by personnel at Dugway Proving Ground. Vertical temperature gradients were reduced to averages over 5-minute intervals using the 0.5 m level as the reference value. Points on the recorder chart were joined with straight lines and the equal area method was used to determine average values.

Wind speed and direction data were reduced to averages and ranges over specified time intervals. Recorders were run at fast chart speed (3 inches-per-minute) for 15 or 20 minutes at the beginning of the test period and these data were averaged over 15-second periods for 3 minutes near release time and 1-minute intervals for the remainder of the fast chart run. Averages and ranges for slow chart speed (3 inches-per-hour) were obtained for 5 or 10-minute intervals.

#### D. Analysis of Meteorological Data

Temperature gradients from the ASG tower and the 100-ft towers were averaged over periods ranging from 1 hour to 2 1/2 hours depending upon the duration of the trial. These averaging periods were subdivided into two equal time intervals in order to compute the change of temperature with time. Temperature gradients were converted to temperatures by means of 1 or 2-m temperatures taken at the "met" van and at the 100-ft towers used in averaging the gradients. These temperatures were then converted to potential temperatures by adding 1.8°F per 100 meters (0.55°F per 100 feet) to each temperature.

Planesonde temperatures over the control point and over Stations 22, 23 and 24 were averaged at each height. Two series of runs were used to obtain the change of temperature with time. One series was generally taken before the release and two after. The latter two series were used when available in order to have data comparable to that obtained from the towers. These temperatures were also converted to potential temperature by adding 0.55°F per 100 feet.

Potential temperature gradients for each level were obtained from the difference in potential temperature between the level above and the level below the specified height.

Eddy diffusivities for each level were computed by the method described in Section II and these values of  $K(z)$  were fitted to power-law functions from regressions of  $\log K(z)$  on  $\log z$ . Mean values of  $K(z)$  were obtained by weighting each value by the height interval it represented.

Mean wind speeds were obtained from all available anemometer and pilot balloon data over the same time interval as the temperature data. These values were also fitted to power-law functions from the regression of  $\log u(z)$  on  $\log z$ , and mean wind speeds were obtained by weighting each speed by the height interval represented.

Calculations of aerosol cloud trajectories were also made from the available wind data. Pilot balloon winds nearest the release height were used with the exception of the ground vehicle release in Trial B-8 in which the 2 and 8-meter winds were used. The details of these calculations are given in Section VI.

## V. DISPERSAL AND SAMPLING OF FLUORESCENT PARTICLES

### A. Dispersal

Aerial line releases of yellow FP were made from an L-23 aircraft flying at an indicated air speed of 150 knots. Dissemination along the flight line was generally begun near lights 3 or 4 (Fig. 1) and continued for a distance of approximately 14 miles. The tracer was dispersed by means of a high-capacity aerosol generator designed at Stanford University [10]. Average dissemination rates ranged from 0.2 to 0.3 gm per ft.

In Trials 6, 7 and 9 a simultaneous aerial line release was made from an L-20 aircraft flying at a higher altitude above the L-23 at a speed of approximately 100 knots. Green fluorescent particles were used in order to distinguish from the yellow FP. In Trial 8 two ground vehicles were used to disseminate yellow FP. The two vehicles started approximately 3300 feet west of the ASG tower and traveled in opposite directions. Green FP were disseminated by the L-20 aircraft.

Aircraft altitudes and positions were determined with photo-theodolites. These instruments have an overall accuracy of approximately 1 mil. Three photo-theodolites were used in most of the trials to date and they were located 8000 to 15000 feet from the flight line. Each plane was tracked by the photographers. All flight line lights have been surveyed and are used as baseline checks. Tower lights have also been surveyed so that altitudes above terrain are correct. A still camera was also used near the ASG tower and aircraft altitudes below tower height may be checked against the tower lights. Accuracy of altitude measurements was considered to be  $\pm 10$  to 20 feet depending upon distance of theodolite from the flight line and the azimuth at time of observation.

Timing of FP dissemination was by means of stop-watches on the aircraft.

### B. Source-Strength Factors

The source-strength factor is defined as the effective number of particles dispersed from each gram of tracer released. The yellow FP used on these trials was from Lot No. 12, USRC 2267 manufactured by U. S. Radium Company. The source-strength factor for this material was approximately  $8.3 \times 10^9$  particles per gram. This value was obtained from calibration trials of the L-23 disseminator on the Aerial Spray Grid in 1961 [11]. Additional efficiency calculations from the BW 502 B trials are given in Appendix A. Efficiencies of the vehicle disseminators used in Trial B-8 have not been determined. Hence, the same source-strength factor was used as for the L-23 aircraft disseminator.

The green FP used in these trials, also manufactured by U. S. Radium Company, was from Lot No. H-324. Calibration trials for the L-20 aerosol generator

with green FP have not yet been run but from comparative recoveries by Rotorod samplers on the balloon cables the source-strength factor appeared to be nearly twice that for the yellow FP, i.e.  $1.66 \times 10^{10}$  particles per gram. Hence this value was used to convert FP recoveries to dosages per unit source strength.

The source-strength factors for these materials include the efficiencies of dispersal and are not the maximum number of particles obtainable from a gram of material. In the case of the green FP, the value may also be affected by differences in Rotorod collection efficiency for different materials.

### C. Sampling

Samples at the 5-ft level were collected on membrane filters (Fig. 6) at 1/4-mile intervals to 1 mile and at 1-mile intervals to 15 miles. These filters were oriented face downward and aspirated at a flow rate of 6 liters per minute. Turn-on and turn-off were accomplished manually at the tower positions and radio control was used at all other positions. In addition to the total dosage samplers, sequential samplers (Fig. 7) were located at 2, 4, 6, 8 and 10 miles. Ten membrane filters were aspirated sequentially at 15-minute intervals. A control sample was taken before the release.

Samples at 5-ft intervals to 300 feet were also taken with membrane filters on the ASG tower (Fig. 3) and at 15-ft intervals from 5 to 95 feet on the 100-ft towers. In addition, Rotorod samplers [12] were mounted at 65, 80 and 95 feet near the membrane filters on the 2, 6, 8 and 10-mile towers (Fig. 8) in order to check the efficiency of the Rotorod samplers for the FP used in these trials. A discussion of Rotorod efficiency is given in Appendix B. The Rotorod samplers were operated at 2400 RPM with a maximum flow rate of 41.3 liters per minute. The efficiency of collection for the yellow FP was about 60%. Therefore an effective flow rate of 24 liters per minute was assumed for these trials or 4 times the flow rate of the membrane filters.

Rotorod samplers were also mounted on cables (Fig. 9) supported by Sefang balloons (Fig. 3). The samplers were spaced along the cables at 75-ft intervals from 175 to 775 feet. Actual heights above terrain were determined from measurements of the "blow-down" angles of the balloons at 15-minute intervals. Balloons were flown at positions 1/2, 2, 6 and 10 miles downwind from the release.

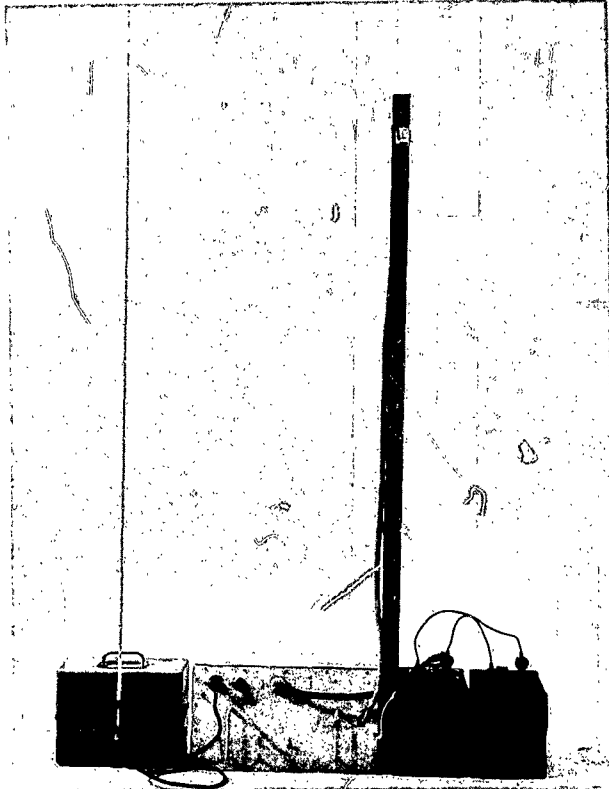


Fig. 6--Total dosage sampler, membrane filter, radio controlled. (U.S. Army Photograph)

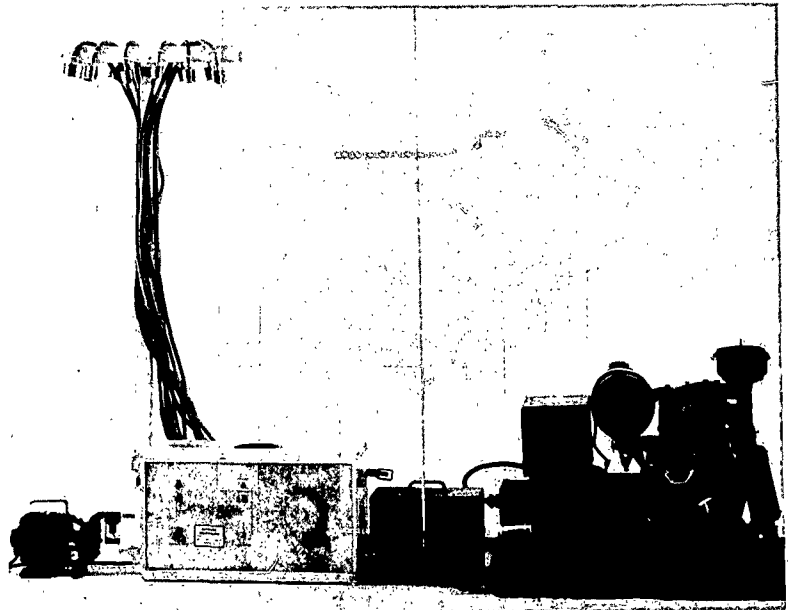


Fig. 7--Sequential sampler, membrane filter, radio controlled. (U. S. Army Photograph)

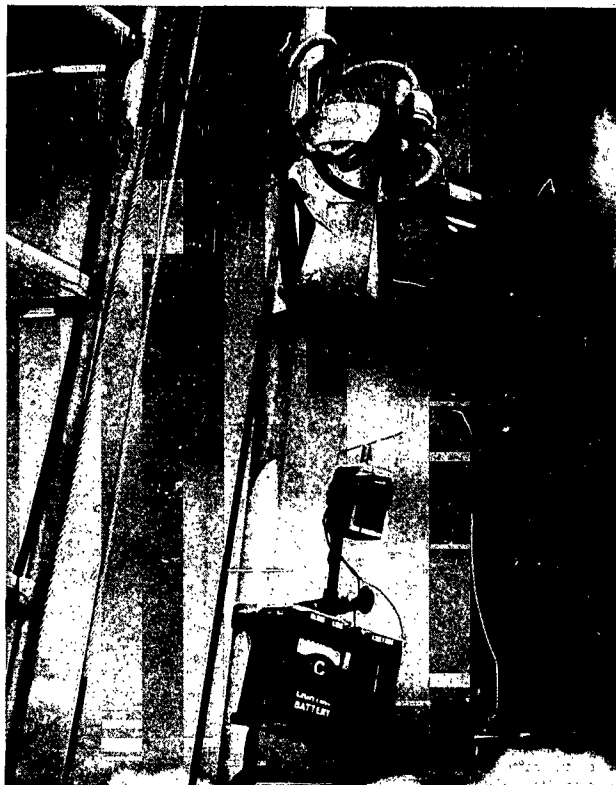


Fig. 8--Rotorod and membrane filter samplers used for calibration of Rotorods. (U. S. Army Photograph)

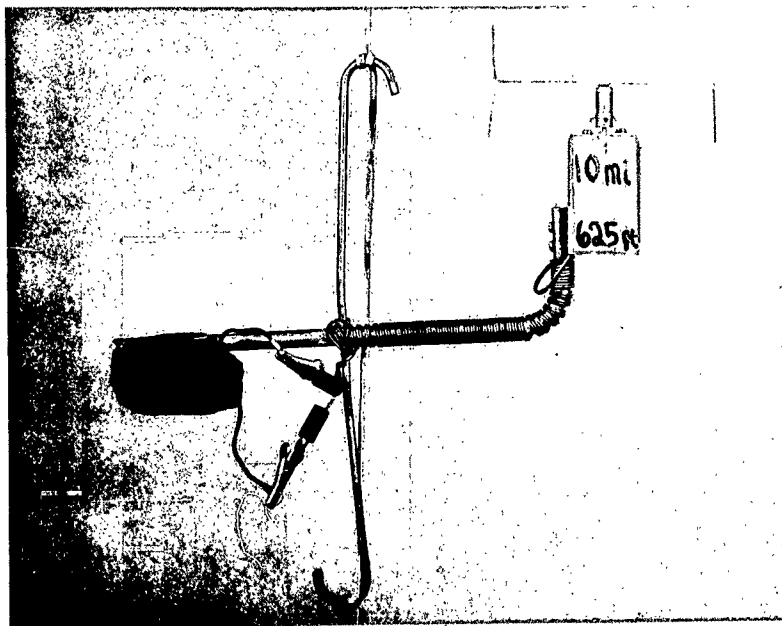


Fig. 9--Rotorod sampler mounted on balloon cable. (U.S. Army Photograph)



## VI. AEROSOL CLOUD TRAVEL AND DIFFUSION

### A. Comparison of Recovery Patterns and Calculated Trajectories

Trajectories were calculated for each trial at the pibal level nearest the release altitude. The calculation involved projection of the movement of each of five points on the release line. This projected movement was made on the basis that the motion of the point could be estimated by a weighted mean of the various pibal winds in the vicinity of the point. Each wind was weighted by the inverse of the square of the distance from the point to the pibal position with weights less than half the maximum weight being disregarded. With the point in continuous motion there is a continuous change in weights and hence in the motion. However, from a practical standpoint, the point was considered to have a constant motion over a short time period and then new weights were applied at the end of the period to determine the motion during the ensuing short time period. The time period used was 5 minutes for each trial except B-7 for which a 15-minute period was used because of low wind speeds.

The two end points over Lights 3 and 28 are close to but generally do not coincide with the beginning and end of the dissemination line. The trajectories of these two points might be inferred to be the cloud boundary. Such an inference is incorrect since lateral diffusion will cause material to lie outside the limits of these two trajectories, particularly after long travel. A corresponding diminution of the cloud must occur within the nominal cloud boundaries represented by the two outside trajectories. Thus, recoveries should be expected outside but close to the apparent cloud boundaries and recoveries within but close to these boundaries should be less than recoveries made near the center of the cloud's path.

#### Trial B-1

The calculated trajectories shown in Fig. 10 along with ground-level recoveries indicate that the sampling turn-on and turn-off schedule was adequate for complete sampling of the cloud with the possible exception of the most distant positions. The recoveries reported are consistent with the calculated trajectories. The maximum recoveries were obtained at positions 4 to 7 miles from the release line, an area shown by the trajectories to be an area in which enfilading occurred. The nominal western edge of the cloud missed the sampling line beyond 7 miles and the smaller recoveries beyond this point were probably obtained because of lateral diffusion from the enfilading portion of the cloud which traveled essentially parallel to and to the east of the sampling line.

Recoveries aloft substantiate the calculated trajectories since the values obtained at the 6-mi balloon position were from 5 to 15 times greater than those at corresponding levels at the 10-mi position.

Trial B-2

The small recoveries on this trial make it difficult to assess the validity of the calculated trajectories (Fig. 11). The sampling schedule appears to have been adequate to sample the entire cloud passage at most positions.

Balloon-supported samplers at 6 and 10 miles obtained recoveries which were small and of essentially the same magnitude which is not inconsistent with the trajectories.

Trial B-3

The sampling schedule was ample to cover the cloud passage at all positions. The recovery pattern is not consistent with the calculated trajectories (Fig. 12), particularly the value of 4112 at the 13-mi position. The values at the two most distant positions while appreciably smaller than the average value at nearer positions still appear too large to be attributed to lateral diffusion from the main body of the cloud.

The trajectories indicate that the cloud should have been intercepted by all four balloon sampler arrays and the sampling results confirm this although, oddly, the largest single recovery on a balloon was at the 10-mi position.

Trial B-4

The trajectories (Fig. 13) indicate a good hit of the sampling array and the sampling results including those from the balloon-supported samplers are consistent with this indication. The sampling schedule was more than ample to ensure sampling of the entire cloud passage at all positions.

Trial B-5

The trajectories (Fig. 14) show passage of the cloud over the sampling array but with such speed as to raise the question as to whether a large fraction of the samplers were turned on soon enough to sample the entire cloud. In no case was the calculated arrival time over the position earlier than the beginning of operation of the samplers but in many cases, allowing for uncertainties in turn-on times and in the trajectories themselves, it appears that the turn-on times were marginal and hence the entire cloud may not have been sampled. Beyond the 2-mi position, the margin of safety between turn-on time and calculated arrival was 10 minutes or less at all but two of the positions.

Trial B-6

The calculated trajectories (Figs. 15 and 16) for both colors of FP are consistent with the recovery pattern both at ground level and aloft and calculated arrival times indicate the sampling schedule to have been completely adequate.

Trial B-7

The trajectories (Fig. 17) at the 250-ft level (yellow FP cloud) indicate that the samplers at the three most distant positions may have been turned off prematurely. The low recoveries obtained at these three positions tend to confirm the trajectories as calculated.

At the 480-ft level (green FP cloud), the trajectories (Fig. 18) indicate that the cloud did not reach the more distant positions at any time during which the samplers were operating. The sampling results do not confirm the trajectories in this respect. However, the material recovered at ground level must necessarily have passed through air flow layers intermediate between the ground and the release level, hence some recovery might be expected at these positions although probably not as large as those obtained. The largest recovery of green FP at the 10-mi balloon position was made 230 feet below the release level at 170 feet in a layer of air that pushed farther south than air at higher altitudes.

The premise that the major portion of the total recovery at ground level is associated with the passage of the main body of the cloud aloft is strengthened by the large recoveries at the 6 and 7-mi positions beneath a point of stagnation in the cloud's movement at release level.

Trial B-8

The yellow FP cloud was disseminated from two moving vehicles and so the trajectories for this cloud (Fig. 19) were calculated on the basis of the available 2 and 8-meter winds. The amount of data available at these levels was not extensive in a geographical sense. Recoveries were obtained some six miles beyond the indicated distance at which the cloud changed direction due to a wind shift. Actually, the sampling results indicate that the major cloud concentration probably reached the 4 and 5-mi positions where total dosage recoveries obtained were large with respect to those nearer and farther from the release line. The recoveries beyond the turning point of the cloud at ground level must be attributed to material which diffused upward from the release level and then subsequently downward to the sampling positions. Travel to this distance must have occurred principally in the faster-moving air flow at levels above the release level. Support for this argument is found from the vertical sampling data which shows some yellow FP aloft at the 1/2-mi position although recoveries were small compared to the recovery at ground level. Beyond 1/2-mi the increasing height of the 500-particle recovery isopleth is indicative of the diffusion upward of the cloud. At 2 mi, the isopleth was above 150 feet; at 6 mi, it was at about 250 feet; at 10 mi, it was at about 525 feet.

Turn-on times were early enough to sample the cloud at the time of arrival at all positions it reached. All samplers were turned off at 1745 because of the wind shift.

The green FP cloud is shown by the trajectories (Fig. 20) as having reached the end of the sampling array (15 mi) before turn-off time at 1745. However, the sampling results suggest that the main body of the cloud did not travel beyond the 13-mi position before turning.

#### Trial B-9

In general, the sampling results and the calculated trajectories (Figs. 21 and 22) are consistent for both the yellow and green FP clouds. Certain anomalous results were reported, particularly the sums of the green FP sequential recoveries at the 6 and 8-mi positions. However, these results are open to considerable question. The test officer's report for this trial indicates that 5 sequential samples were taken at the 6-mi position ending with Filter No. 5. Of the total recovery reported, 50 particles were collected on the first five filters and counts totaling 197 were reported on the other five filters which officially were not operated. Similarly, at the 8-mi position 120 particles were obtained on the 7 filters that were operated and 266 on the 3 filters that were not operated. These discrepancies tend to invalidate these values as evidence that the sampling results are inconsistent with the calculated trajectories. Moreover, the maximum balloon-sampler recovery at the 6-mi position was 8--as compared to the maximum recovery at 2 mi. of 10,246.

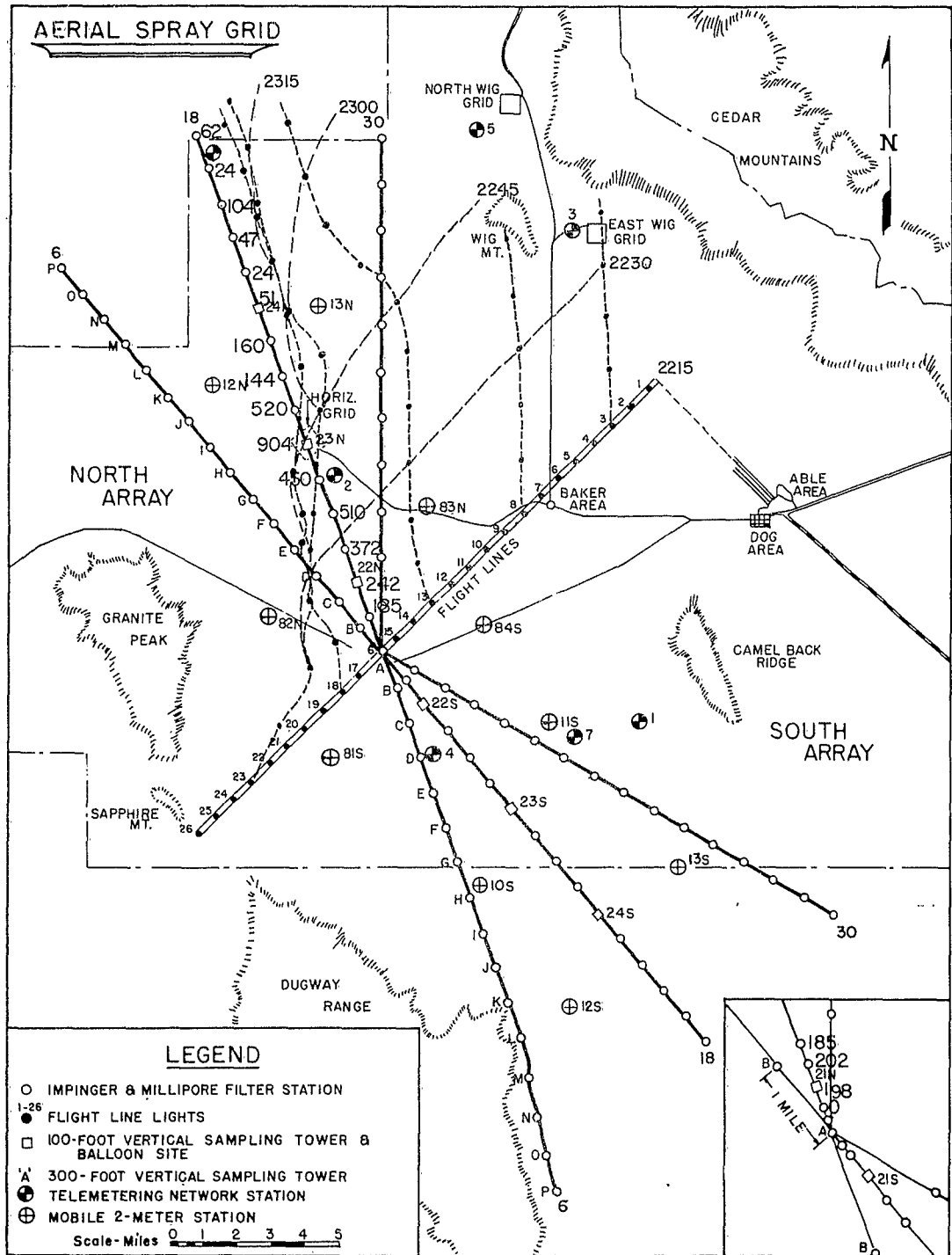


Fig. 10--Trial B-1: FP recoveries at 5 feet and trajectories calculated from 250-ft winds.

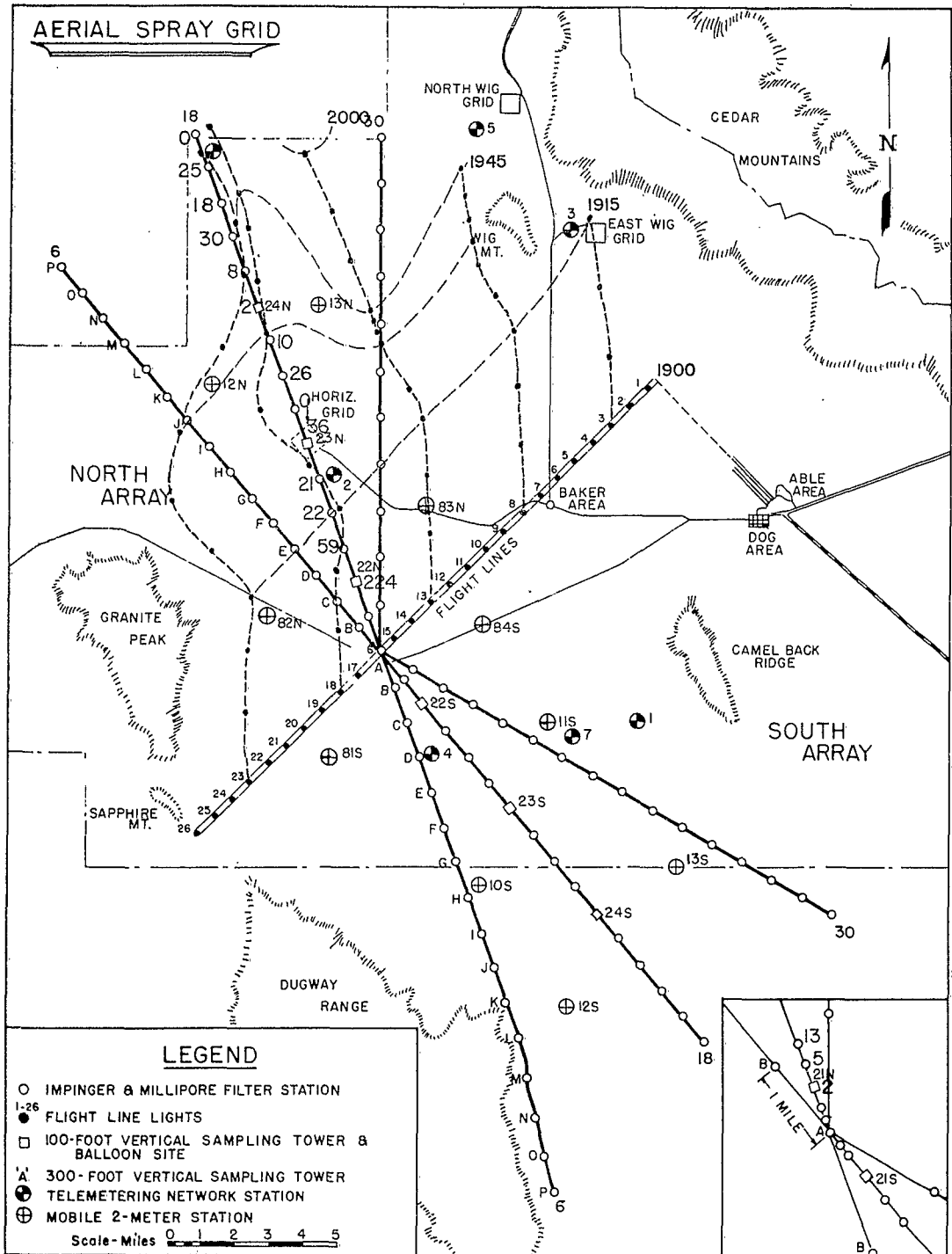


Fig. 11--Trial B-2: FP recoveries at 5 feet and trajectories calculated from 480-ft winds.

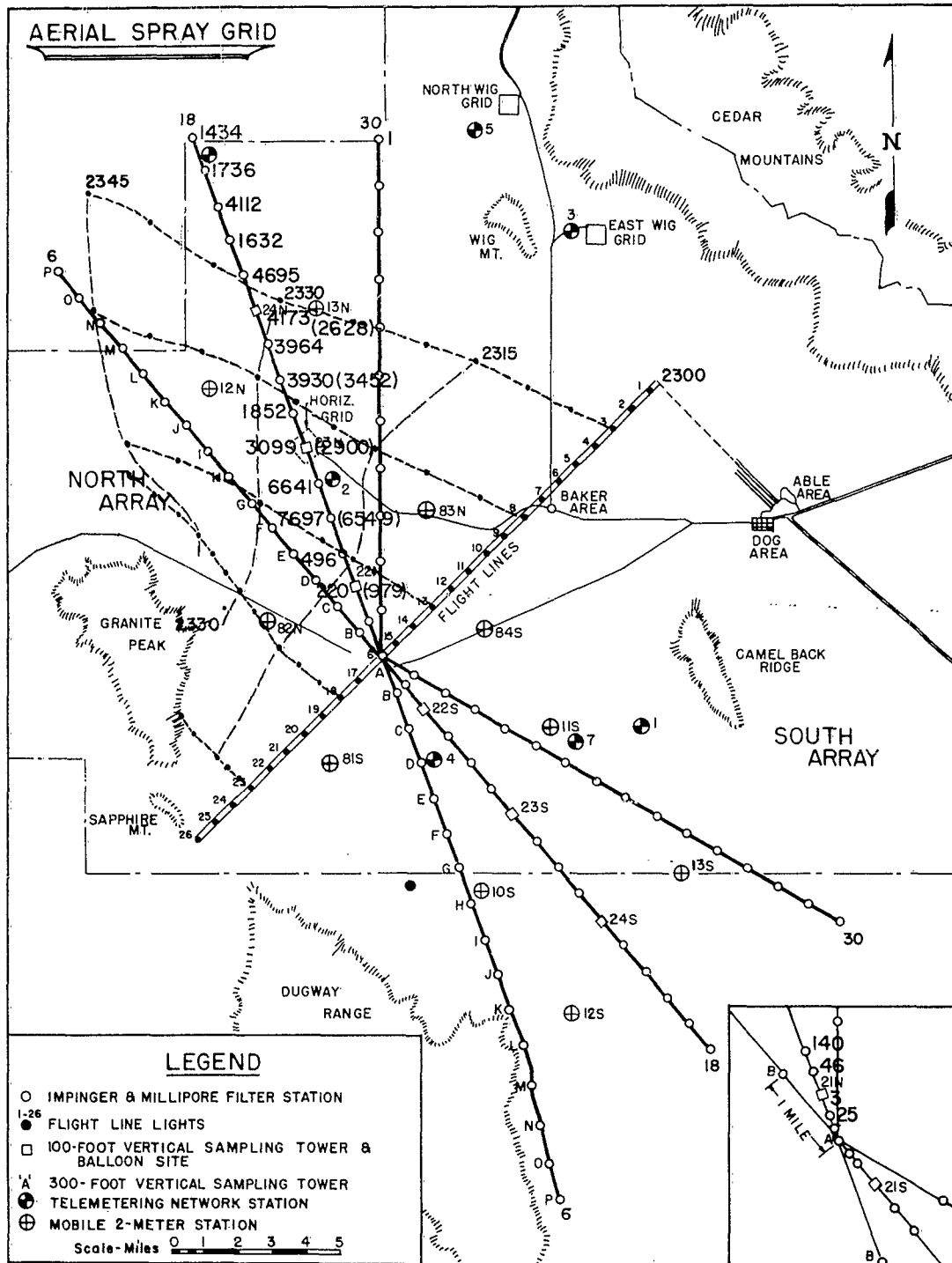


Fig. 12--Trial B-3: FP recoveries at 5 feet and trajectories calculated from 250-ft winds.

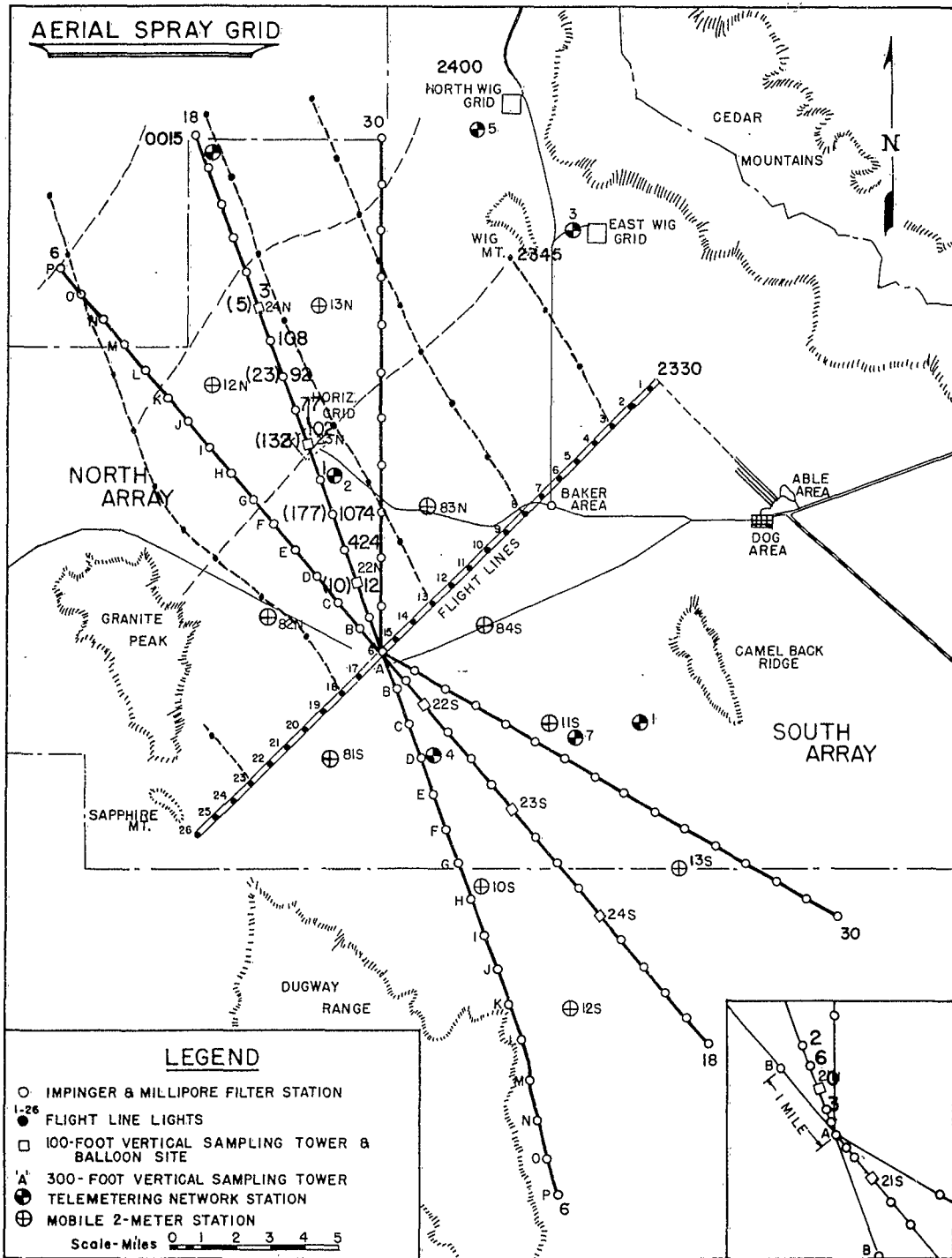


Fig. 13--Trial B-4: FP recoveries at 5 feet and trajectories calculated from 250-ft winds.



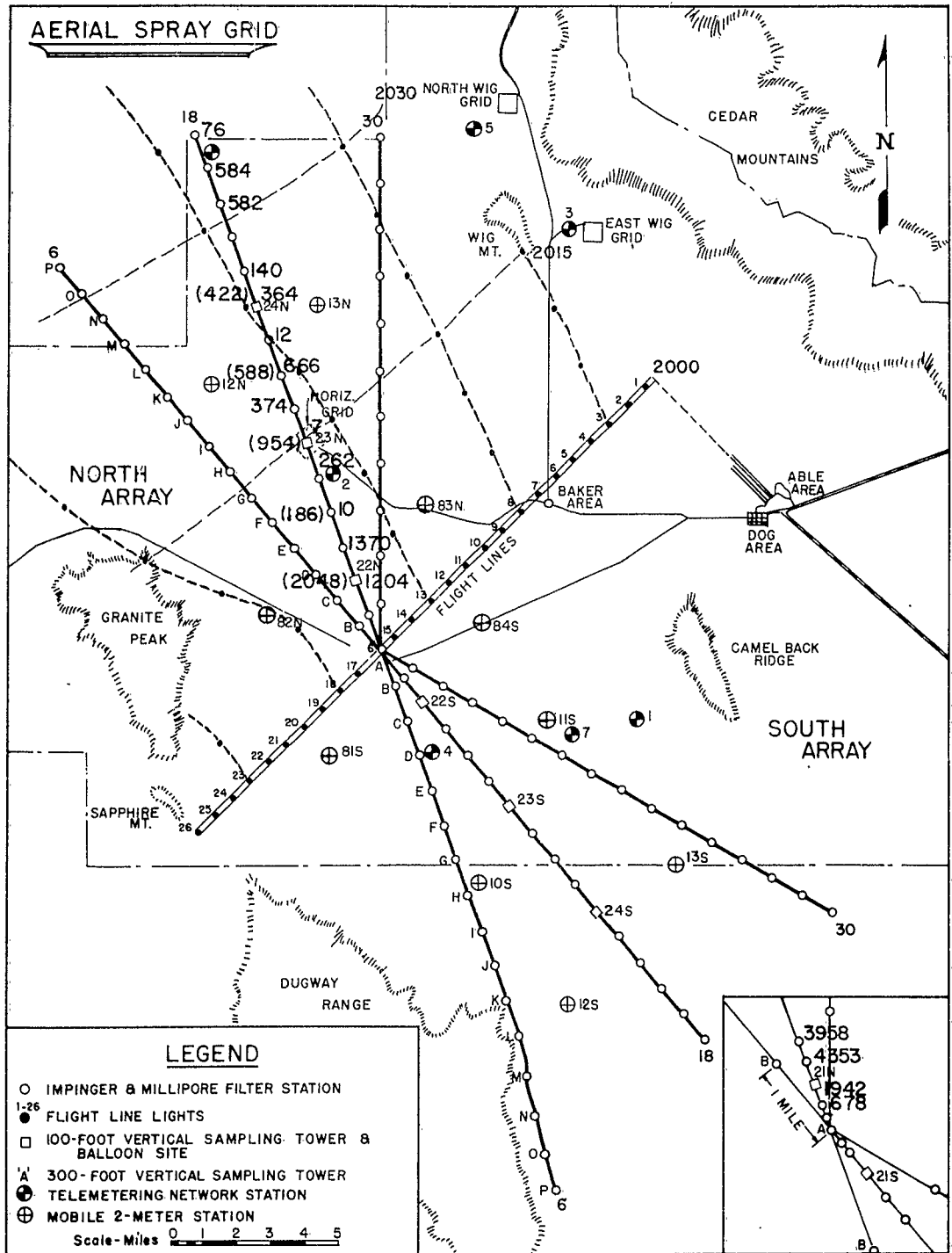


Fig. 14--Trial B-5: FP recoveries at 5 feet and trajectories calculated from 250-ft winds.

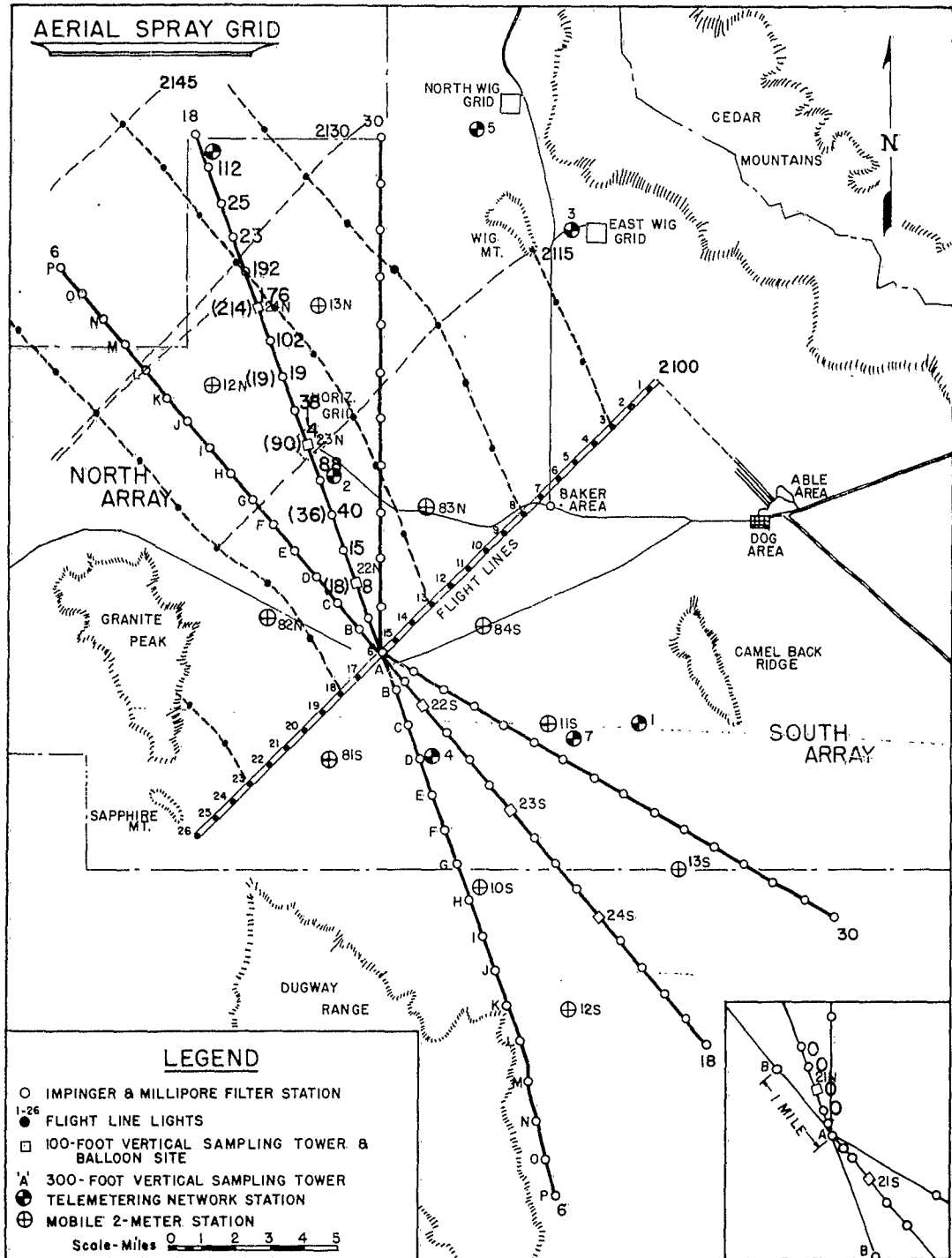


Fig. 15--Trial B-6: Yellow FP recoveries at 5 feet and trajectories calculated from 250-ft winds.

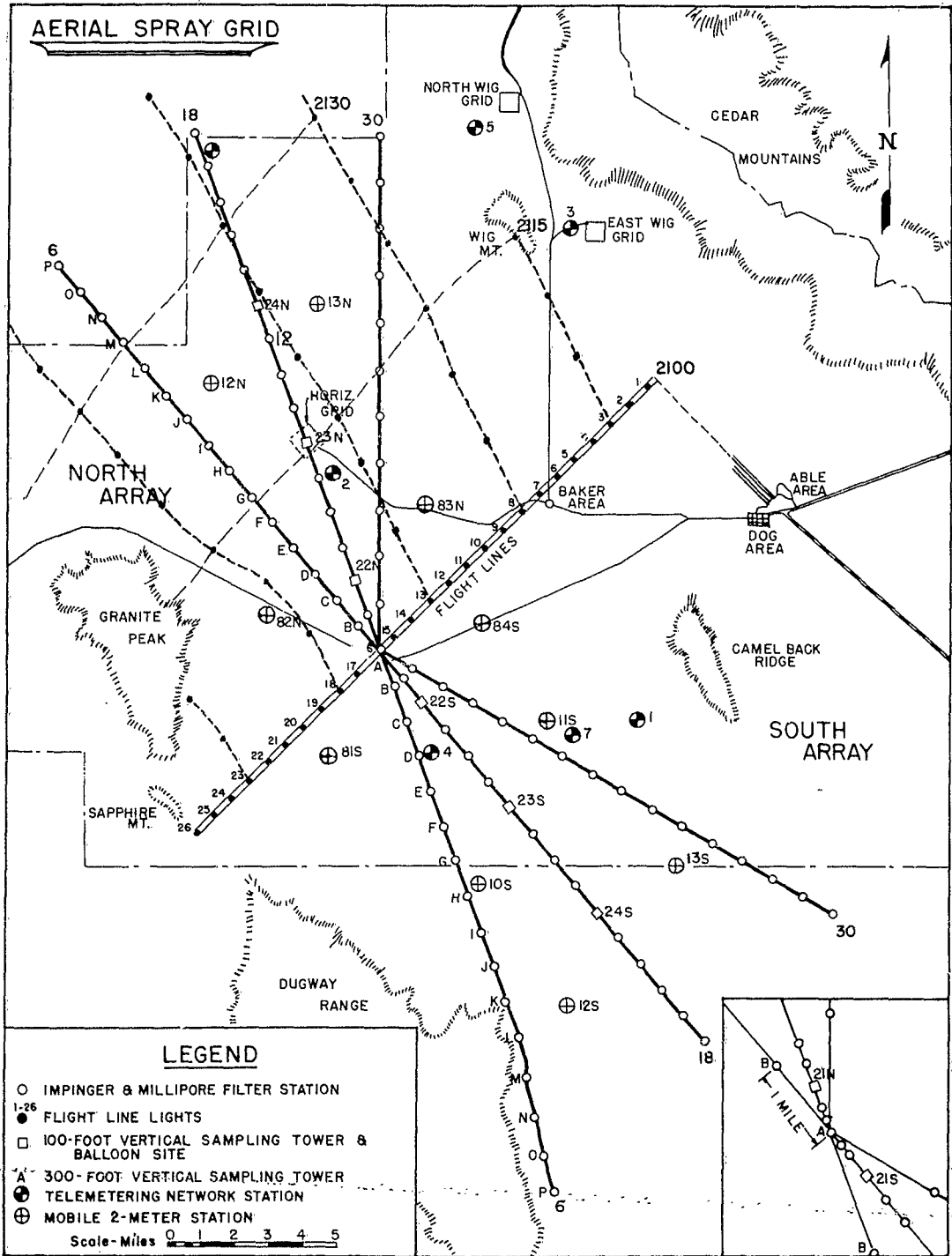


Fig. 16--Trial B-6: Green FP recoveries at 5 feet and trajectories calculated from 480-ft winds.

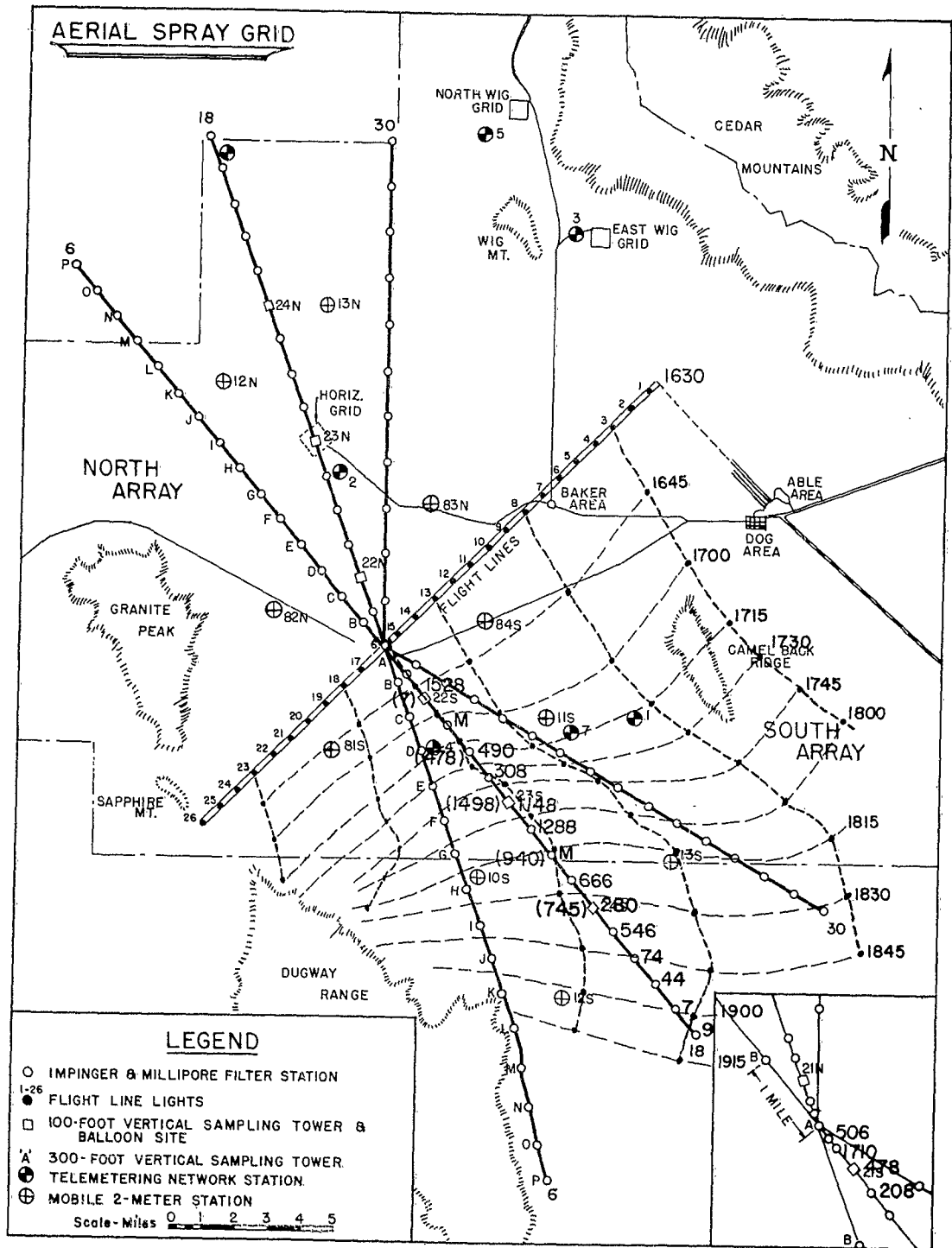


Fig. 17--Trial B-7: Yellow FP recoveries at 5 feet and trajectories calculated from 250-ft winds.

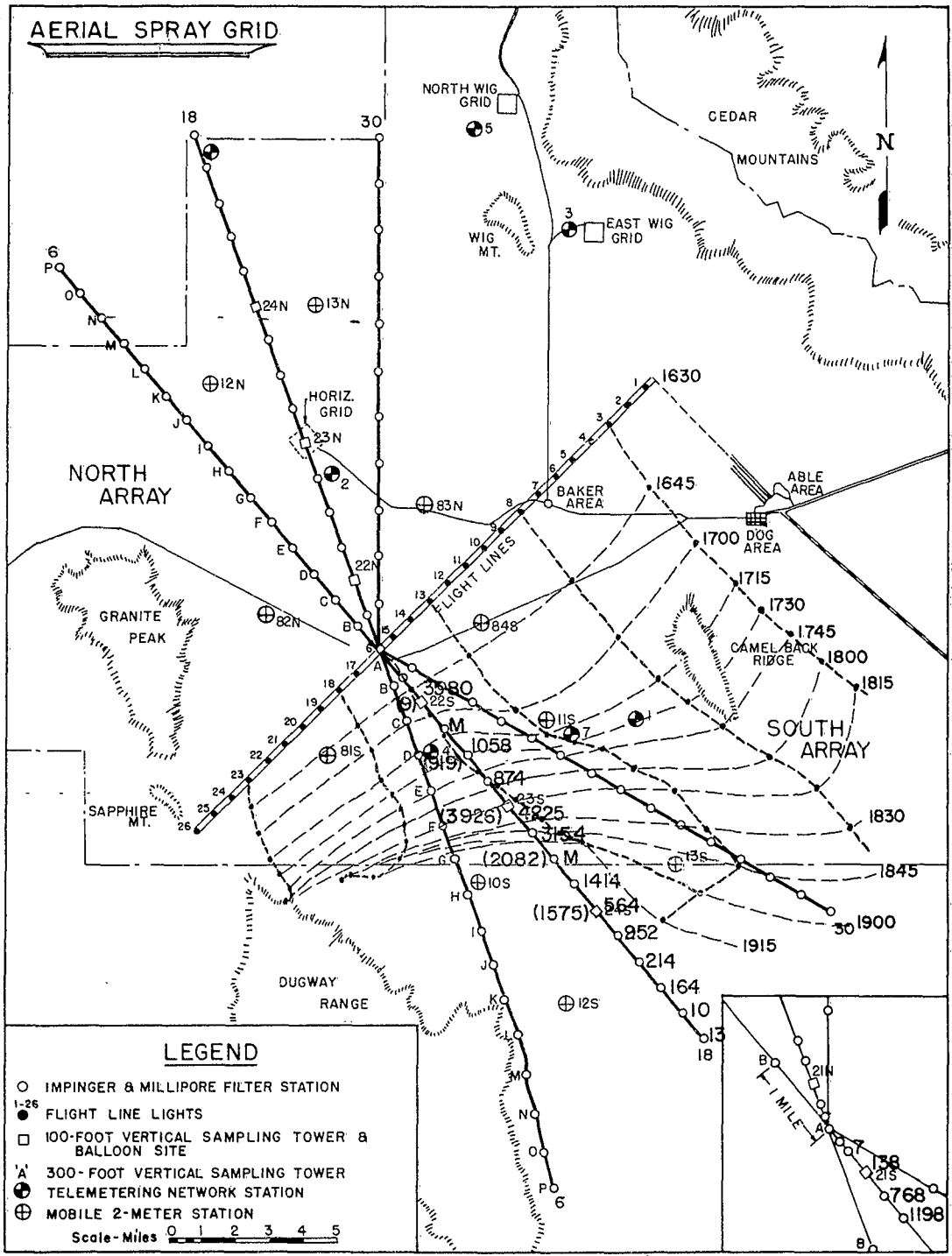


Fig. 18--Trial B-7: Green FP recoveries at 5 feet and trajectories calculated from 480-ft winds.

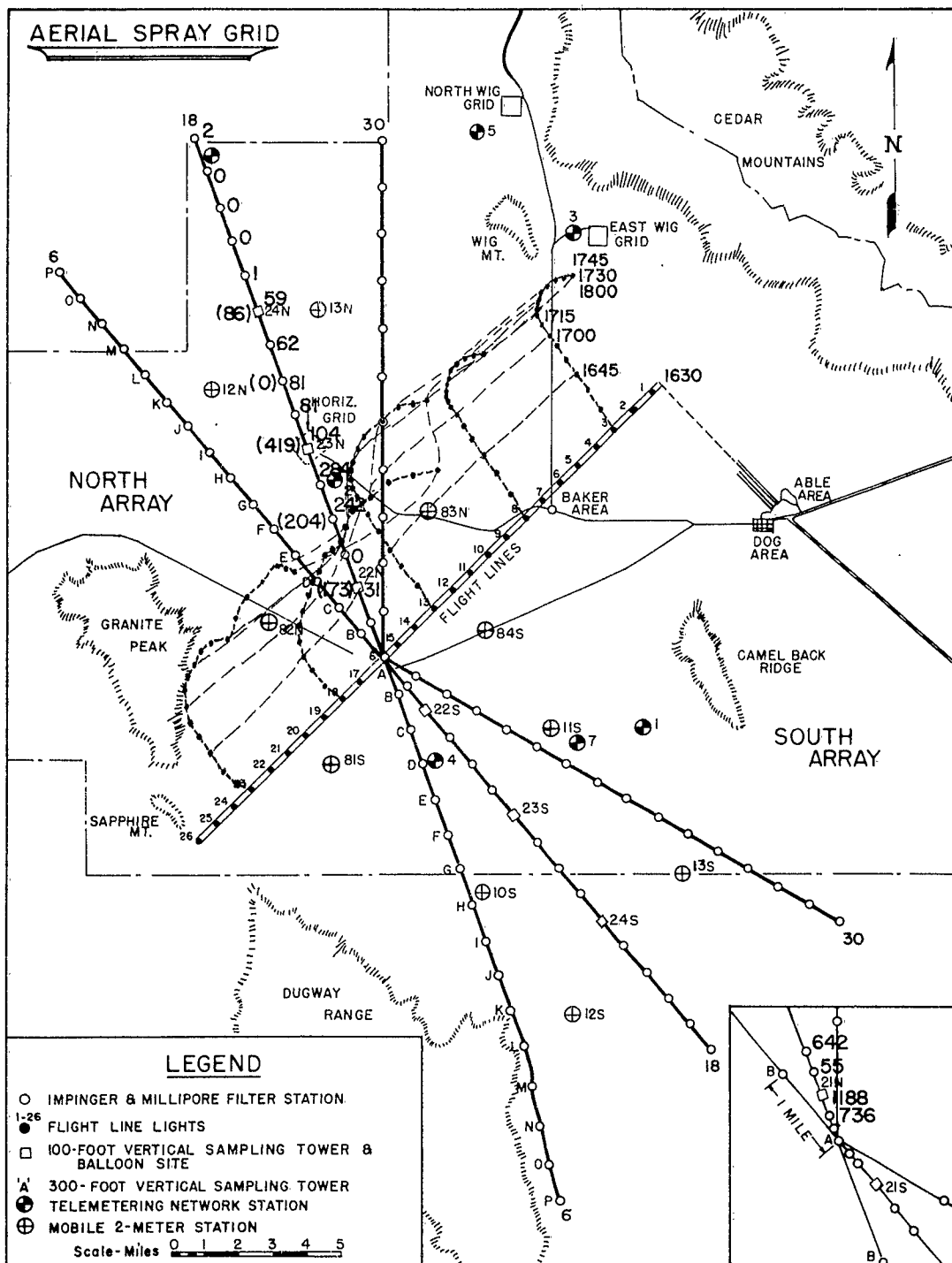


Fig. 19--Trial B-8: Yellow FP recoveries at 5 feet and trajectories calculated from 2m and 8m winds.

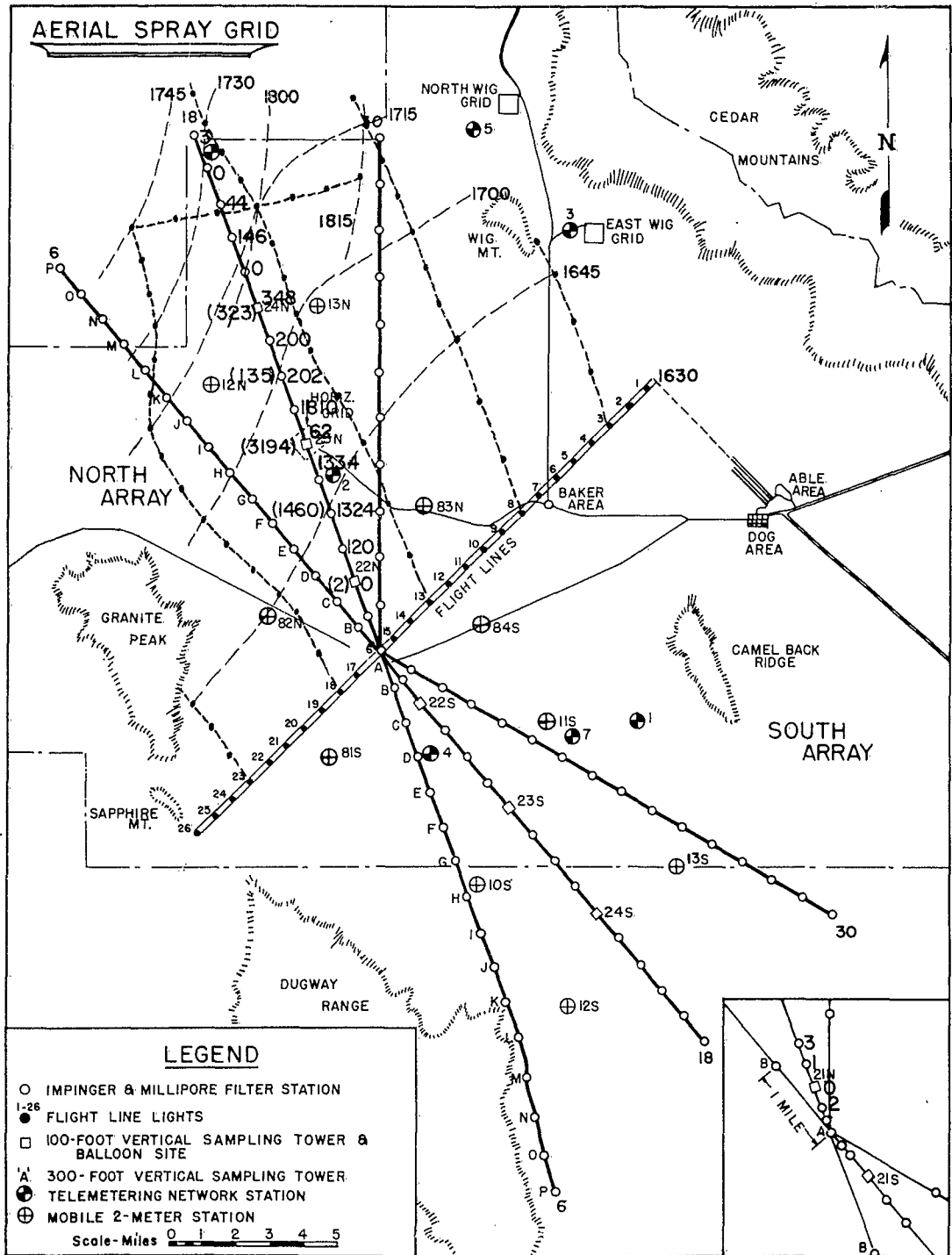


Fig. 20--Trial B-8: Green FP recoveries at 5 feet and trajectories calculated from 480-ft winds.

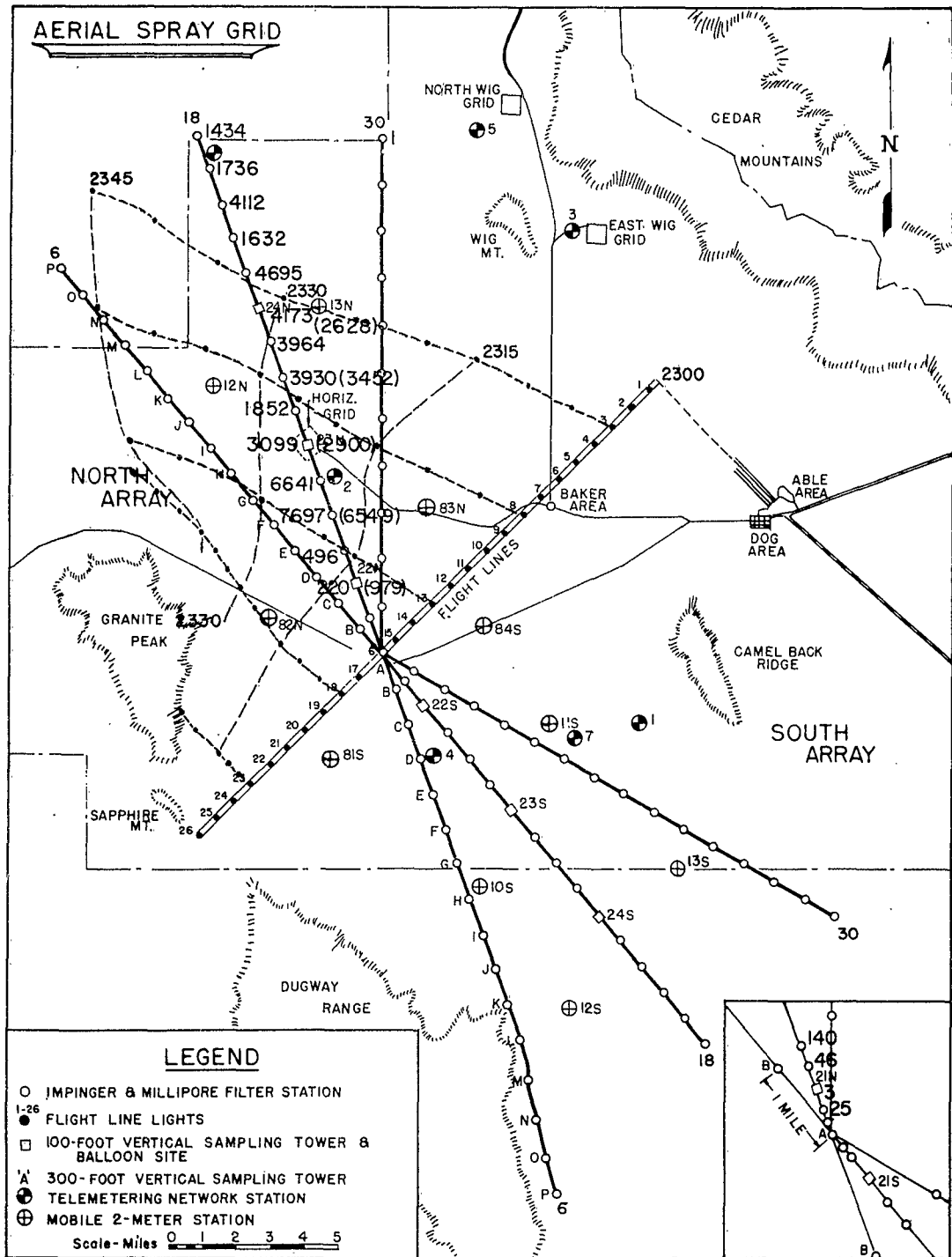


Fig. 21--Trial B-9: Yellow FP recoveries at 5 feet and trajectories calculated from 250-ft winds.



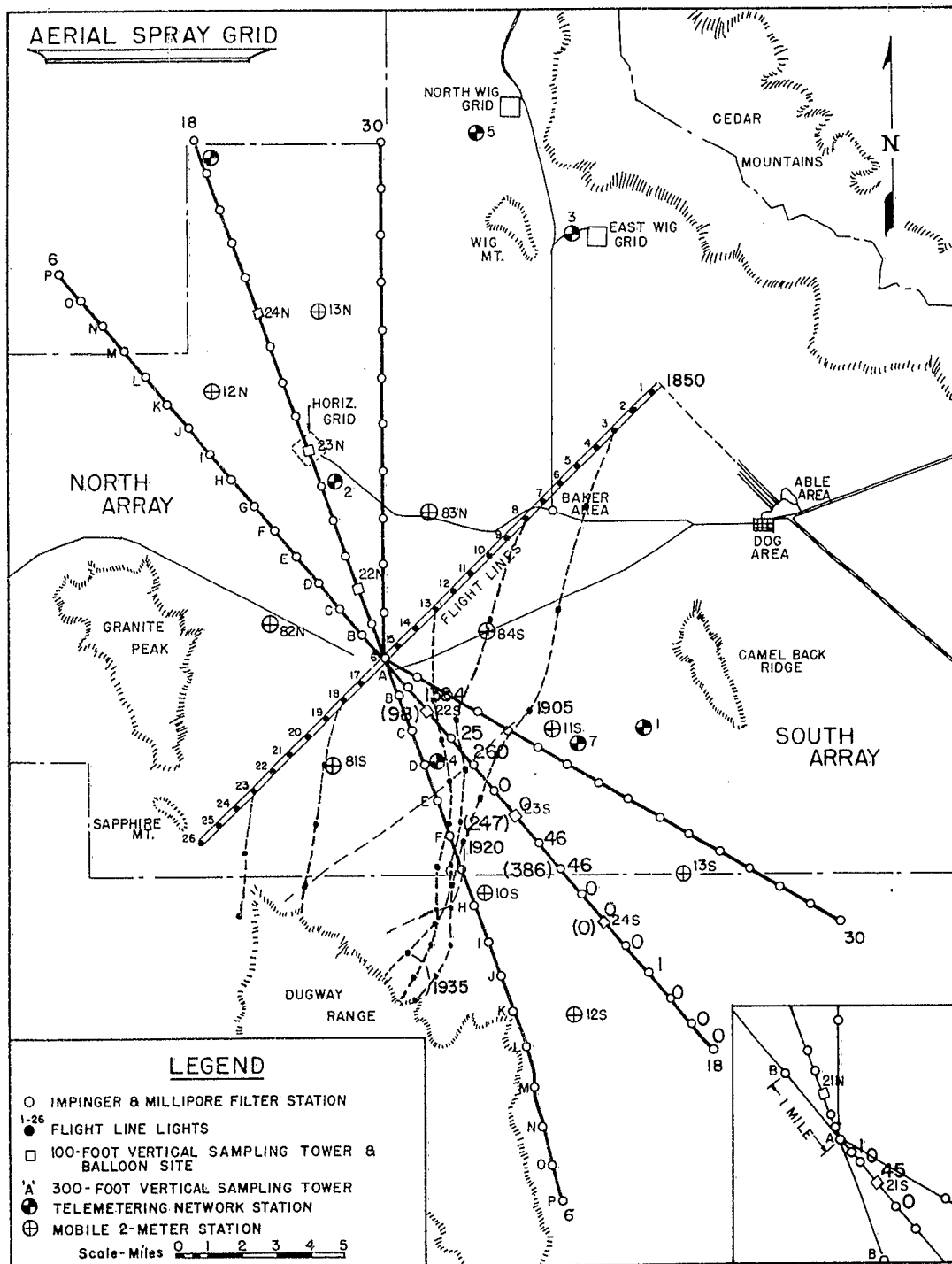


Fig. 22--Trial B-9: Green FP recoveries at 5 feet and trajectories calculated from 480-ft winds.

## B. Comparison Of Calculated and Observed Dosages

Recoveries from each sampler were converted to dosages per unit source strength,  $D/Q$ , by dividing by the sampler flow rate and the source strength in particles per unit distance. These  $D/Q$  values were plotted on a vertical cross-section down the sampling line and contours of equal  $D/Q$  were drawn. Contours of equal  $D/Q$  calculated by means of Eq. (12) were also drawn on the same cross-section. Comparisons of calculated and observed  $D/Q$  values are summarized below.

### Trial B-1

This trial was conducted under moderate inversion conditions (Fig. 23a) with wind speeds ranging from 6 mph at 2 m to 20 mph at heights above 200 feet (Fig. 23b). Calculated eddy diffusivities (Fig. 23c) were small, ranging from 0.1 to  $0.8 \text{ m}^2/\text{sec}$  with a mean value of  $0.42 \text{ m}^2/\text{sec}$ .

The dosage distribution at the ASG tower showed three distinct maxima at approximately 150, 180 and 225 feet. The largest maximum occurred at 150 feet although the release altitude was 250 feet. This distribution would not have been anticipated under the average meteorological conditions prevailing at the time of release and was probably caused by a local disturbance.

The aerosol cloud trajectory (Fig. 10) indicated possible overrunning of the cloud from the southwest end of the release line. The winds at this end of the line were almost parallel to the release which probably accounts for the very high dosages observed at heights up to 700 feet at the 1/2-mile position (Fig. 24). A similar dosage pattern occurred at two miles and to a lesser degree at six miles. Beyond six miles only the edge of the aerosol cloud traversed the sampling line and dosages fell off rapidly with distance. The vertical widths of the computed  $D/Q$  contours were in reasonable agreement with the observed widths at six miles but departed considerably at nearer and greater distance because of overrunning and enfilading at the nearer positions and edge effects at the greater distances. The lower portion of the aerosol cloud was displaced downward giving  $D/Q$  values at the 5-ft level which greatly exceeded the calculated values.

### Trial B-2

This release was made at about 450 feet under near-neutral conditions (Fig. 25a) with mean winds of 15 mph at 2 m and 20 mph above 100 feet (Fig. 25b). Wind speeds at the ASG tower were greater than 30 mph for approximately 10 minutes following the release.

Since the change of temperature with time appeared to be constant with height, the assumption of constant vertical heat flux was used and eddy diffusivities were calculated from Eqs. (7) and (8). The averaging period used for the temperature and wind data was two hours, so the calculated diffusivities are

somewhat lower than those which probably existed during the period of high winds following the release. Calculated diffusivities ranged from 0.13 at 0.5 m to 12.7 at 900 feet (Fig. 25c) with a mean value of  $6.34 \text{ m}^2/\text{sec}$ .

Calculated D/Q contours (Fig. 26) indicate D/Q values greater than  $100 \times 10^{-6} \text{ sec/m}^2$  at all levels below 800 feet from 1 mile to more than 15 miles downwind while observed values dropped to  $50 \times 10^{-6} \text{ sec/m}^2$  at the 6-mile position. Since the only balloon flown during this trial was at this position no samples above 100 feet were obtained at other locations. The ground level dosages were quite variable and it appeared that because of the initial high winds samplers may not have been turned on early enough at some positions to sample the entire cloud.

#### Trial B-3

This trial was characterized by a relatively strong ground inversion below 150 feet (Fig. 27a) with wind speeds ranging from 3 mph at 2 m to 15 mph above 200 feet (Fig. 27b). Calculated eddy diffusivities were very small ranging from  $0.01 \text{ m}^2/\text{sec}$  at 0.5 m to  $0.5 \text{ m}^2/\text{sec}$  above 200 feet (Fig. 27c) with a mean value of  $0.44 \text{ m}^2/\text{sec}$ .

An FP release was made at about 100 feet with a BG release at 250 feet. No FP samplers were operated on the ASG tower or the 100-ft towers, so only the membrane filter samples at the 5-ft level and the Rotorod samples from the balloons were available. The vertical diffusion was very slow as indicated in Fig. 28. There appeared to be a small secondary maximum in the dosage distribution between 600 and 700 feet at the 6-mile and 10-mile balloon positions. This may have resulted from lowering the balloon samplers before the entire cloud had passed at ground level, however, since the sequential samplers indicated substantial recoveries after the Rotorod samplers were shut off. The low wind speed and strong inversion near the ground greatly extended the time of cloud passage at ground level. In addition the downdraft from the plane brought the aerosol cloud down more rapidly and yielded much higher dosages at ground level than would have resulted from downward diffusion from 100 feet.

The calculated D/Q contours showed more rapid dispersion than observed within the first 6 miles of travel but gave better agreement at the 10-mile position. Better agreement would have been obtained if only values of diffusivity and wind below 300 feet had been used in averaging since the major portion of the cloud remained below this level out to 10 miles. It was considered preferable, however, to use a uniform averaging procedure for all trials.

Trial B-4

A relatively strong inversion up to 300 feet existed during this trial (Fig. 29a) with wind speeds ranging from 7 mph at 2 m to 20-25 mph above 150 feet (Fig. 29b). Calculated eddy diffusivities increased from  $0.2 \text{ m}^2/\text{sec}$  at 0.5 m to  $3 \text{ m}^2/\text{sec}$  at 300 feet and decreased above this level (Fig. 29c). The mean value was  $1.84 \text{ m}^2/\text{sec}$ .

The release altitude was 250 feet and the cloud was distributed from the ground up to 450 feet after 2 miles travel (Fig. 30) and did not diffuse upward beyond 500 feet even at the 10-mile position. This indicates that the eddy diffusivity decreased much more rapidly than the calculated values thus producing a sharp upper boundary to the diffusion.

The observed dosages appear to be high even for a bounded aerosol cloud. Assuming uniform vertical distribution through a 400-ft layer and using the mean wind speed of 21.3 mph the D/Q values should be less than  $900 \times 10^{-6} \text{ sec}/\text{m}^2$  while the observed values were generally much larger than this.

A large discrepancy between membrane filter and Rotorod data appears at the two and six-mile towers. The dosages for the filter appear to be too high by an order of magnitude while the Rotorod dosages are in agreement with those from the balloon-mounted Rotorods. Also the dosages at the 5-ft level are substantially lower than those at the 20-ft level even at the 10-mile position, indicating the possibility of a shallow layer of cold air preventing the diffusion to ground level.

Trial B-5

Slight inversion conditions prevailed during this trial (Fig. 31a) with wind speed 12 mph at 2 m increasing to 22-27 mph above 200 feet (Fig. 31b). Stable conditions existed in spite of the slight inversion, as evidenced by the strong wind shear. Calculated eddy diffusivities were small and decreased slightly with height from  $0.94 \text{ m}^2/\text{sec}$  at 8 m to  $0.39 \text{ m}^2/\text{sec}$  at 900 feet with a mean value of  $0.42 \text{ m}^2/\text{sec}$  (Fig. 31c).

The release was made at about 125 feet and the aerosol was brought rapidly to the ground giving high ground-level D/Q values within 1/4 mile from the release (Fig. 32). Vertical diffusion was slow and the vertical width of the aerosol cloud was only about 500 feet after 10 miles of travel. Calculated D/Q values were in good agreement with observed except at 10 miles where enfilading produced higher D/Q values than predicted.

Trial B-6

This trial was conducted under strong inversion conditions (Fig. 33a) with wind speeds of 5 mph at 2 m increasing to 22 mph above 200 feet (Fig. 33b).

Calculated eddy diffusivities were small and relatively constant with height (Fig. 33c) with a mean value of  $0.35 \text{ m}^2/\text{sec}$ .

This trial was the first in which two approximately simultaneous FP releases were made. Yellow FP were released at an altitude of 200 feet from an L-23 aircraft and green FP at 400 feet from an L-20 aircraft.

Diffusion of the yellow FP (Fig 34) was greater than for the green FP (Fig. 35) indicating a larger diffusivity at the lower level. Yellow FP reached the ground in measurable amounts at two miles downwind while no green FP were reported within the 15-mile sampling range. The peak dosages of yellow FP and green FP remained well above the ground for the entire 15-mile sampling distance. Calculated vertical dispersion was in good agreement with observed for the yellow FP, but the observed vertical dispersion of the green FP was considerably less than the calculated dispersion.

Both the yellow and the green FP aerosol clouds were displaced downward for the first 1 or 2 miles then upward between 2 and 10 miles so that the peak dosages at 10 miles were observed approximately 100 feet higher than the respective release altitudes. Since the mean potential temperatures within the aerosol clouds should have been relatively constant under such stable conditions, the potential temperatures were plotted at each planesonde position using temperatures taken at the time nearest the estimated cloud passage. A vertical potential temperature cross-section was constructed (Fig. 36) and the slopes of the isentropic surfaces are in reasonable agreement with the observed vertical displacements of the aerosol clouds.

#### Trial B-7

This was a late afternoon trial with slight lapse conditions at release time but rapid cooling at low levels produced slight inversion conditions during the period of cloud travel (Fig. 37a). Wind speeds were light and nearly constant with height above 4 m (Fig. 37b) with a mean value of 3.8 mph. Calculated vertical eddy diffusivities were erratic because of the small potential temperature gradients but increased from  $0.3 \text{ m}^2/\text{sec}$  at 1 m to  $4.2 \text{ m}^2/\text{sec}$  at 200 feet and decreased at higher levels (Fig. 37c) with a mean value of  $1.75 \text{ m}^2/\text{sec}$ .

The winds at higher levels shifted from northwesterly to easterly as the cloud traversed the sampling array (Figs. 17 and 18). This produced high dosages at levels up to 700 feet at 6 miles because of enfilading and low dosages at 10 miles because of edge effects (Figs. 38 and 39).

Because of the light winds both the yellow and the green FP were well distributed vertically within a very short distance downwind and the D/Q patterns for the two releases were virtually identical in spite of the difference in release altitudes (yellow FP at 225 feet and green FP at 400 feet).

Calculated D/Q contours for the two releases have a very different appearance from the observed. However, this is largely due to the shift in cloud trajectories. The predicted D/Q values are generally larger than  $1000 \times 10^{-6} \text{ sec/m}^2$  at all sampling levels beyond two miles, in reasonably good agreement with observed values to 6 miles downwind, after which only the edge of the cloud traversed the sampling array. Because of the wind shift the distances from release to sampler beyond about 6 miles were appreciably greater than the nominal distances down the sampling line.

#### Trial B-8

A slight inversion was present below 300 feet becoming near-neutral above this level (Fig. 40a). Winds were moderate, increasing from 5-6 mph at 2 m to 12-16 mph above 100 feet with a mean value of 12.9 mph (Fig. 40b). Calculated diffusivities were moderate, increasing from  $0.15 \text{ m}^2/\text{sec}$  at 1 m to  $2.3 \text{ m}^2/\text{sec}$  at 300 feet and decreasing at higher levels (Fig. 40c) with a mean value of  $1.0 \text{ m}^2/\text{sec}$ .

This was the first trial involving an aerial line release and a ground-level line release. The ground-level release of yellow FP was made from two vehicles starting near the center of the release line and travelling in opposite directions. Yellow FP was released from the vehicles and green from the L-20 flying at 400 feet.

Although the 2-8 m trajectories in Fig. 19 indicate that the yellow FP would not have traversed more than 4 miles of the sampling line, the cloud actually passed beyond the 10-mile sampling position because it was carried by the winds at higher levels (Fig. 20) which did not shift until later during the trial. There was some enfilading at the 10-mile position (Fig. 41) as evidenced by the high D/Q values. Since the efficiencies of the vehicle disseminators were not known the same source-strength factor as that for the aircraft dissemination was used to convert dosages to D/Q values. The source strengths of the two vehicle disseminators differed by about a factor of two because of a partial malfunction of the east vehicle disseminator. Since the low-level trajectories indicated most of the sampling line was traversed by aerosol from the west vehicle, this source strength ( $0.030 \text{ gm/ft}$ ) was used to convert dosage to D/Q values.

Calculated D/Q isopleths for yellow FP are in excellent agreement with observed for the first 6 miles of travel but depart at the 10-mile position because of enfilading of the cloud at higher levels as the winds shifted from southeasterly to westerly.

Small secondary maxima observed near 400 feet at the 1/2 and 2-mile positions undoubtedly resulted from the green FP release at 400 feet and may be

due to some yellow FP mixed with the green. These D/Q values were only a very small fraction of those for the green FP (Fig. 42) in spite of the fact that the source strength, Q, for the green FP was approximately 20 times that for the yellow. Thus, the ratios of actual yellow recoveries to actual green recoveries were 1/20 of the D/Q ratios which themselves were small.

The green FP were released at 400 feet but the cloud was displaced downward for the first six miles giving peak D/Q values at 250-300 feet at 6 miles (Fig. 42), then upward between 6 and 10 miles. The peak value at the 10-mile balloon was at 350 feet. The agreement between calculated and observed dispersion was good except at the 10-mile position where enfilading occurred.

#### Trial B-9

Temperature gradients were superadiabatic below 8 m during this trial becoming nearly neutral at higher levels (Fig. 43a). The negative gradient of potential temperature at low levels implies an upward flux of heat. However, the integrated temperature change computed by the method outlined in Section II gives a net downward heat flux from the upper levels. It is probable that heat was transferred upward by convection through the entire layer thus giving a relatively uniform temperature change with time which would be included in the estimate of the advective temperature change, A. Hence, the estimate of  $F(z_1)$  was assumed to represent the downward transfer of heat by turbulent diffusion, which may be less than the upward convective heat flux. Only the positive potential temperature gradients (above 8 m) were used to compute eddy diffusivities. The computed eddy diffusivities (Fig. 43c) were large, increasing from  $7.75 \text{ m}^2/\text{sec}$  at 16 m to  $26.7 \text{ m}^2/\text{sec}$  at 500 feet and decreasing rapidly to  $4.83 \text{ m}^2/\text{sec}$  at 900 feet, with a mean value of  $13.0 \text{ m}^2/\text{sec}$ .

Wind speeds were moderate, ranging from 12 mph at 2 m to 15-24 mph above 16 m with a mean value of 17.0 mph (Fig. 43b).

The calculated aerosol cloud trajectories (Figs. 21 and 22) show that both the yellow FP and green FP traversed only 3 or 4 miles of the sampling line and this is borne out by the D/Q values at 6 miles (Figs. 44 and 45). Only a few FP were recovered on the tower and balloon samplers at 6 miles and none at 10 miles.

Vertical diffusion was rapid, in accord with the high diffusivities and the agreement between calculated and observed D/Q values is reasonable for the first 2 miles of cloud travel. Observed D/Q values are somewhat higher than the computed values because no correction was made for the relatively large deviation of wind direction from normal to the release line. Enfilading also was evident for the green FP (Fig. 45) giving higher D/Q values at 2 miles than at 1/2 mile.

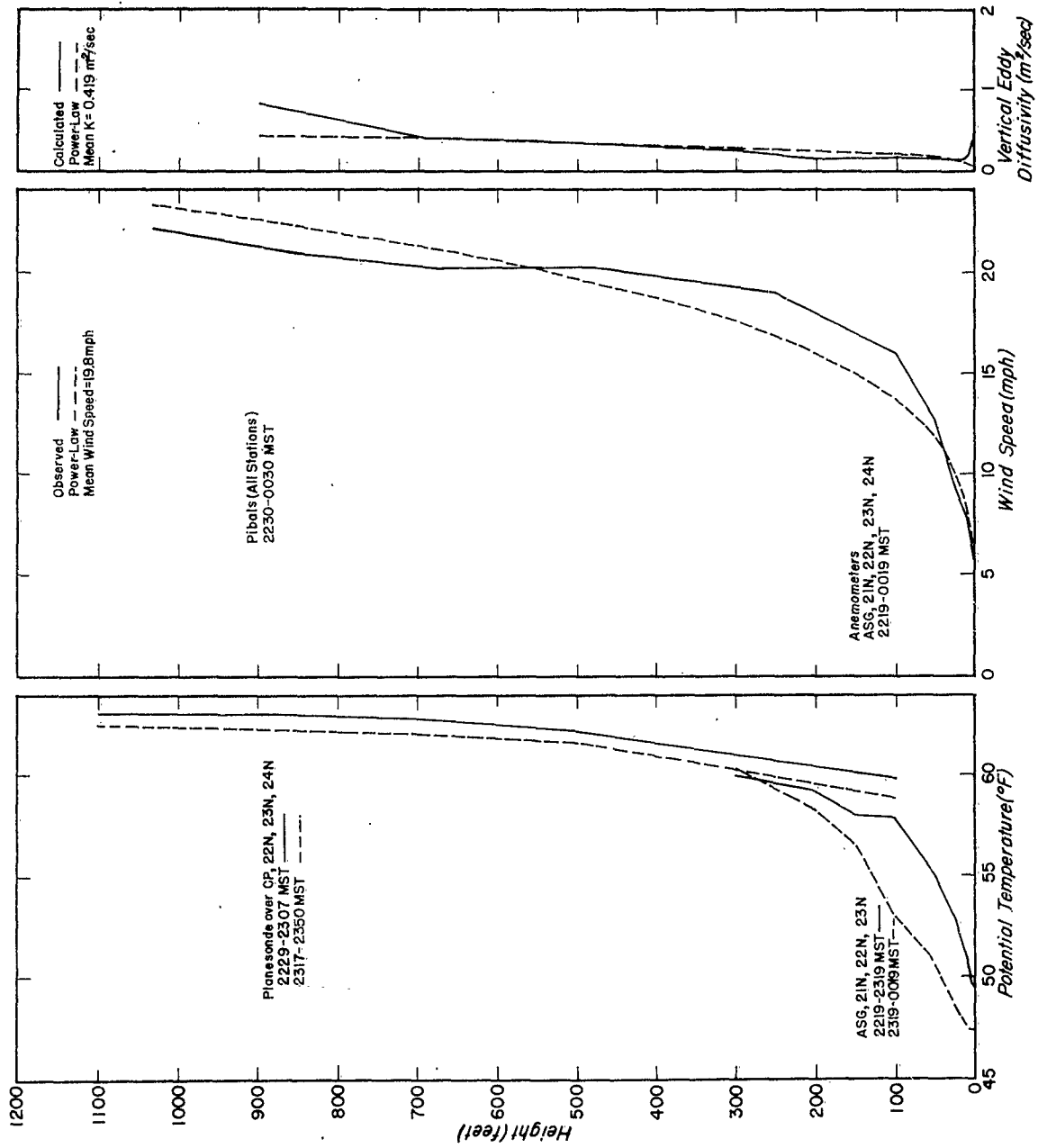


Fig. 23--Trial B-1: a) Potential temperature, b) wind speed and c) vertical eddy diffusivity as functions of height.



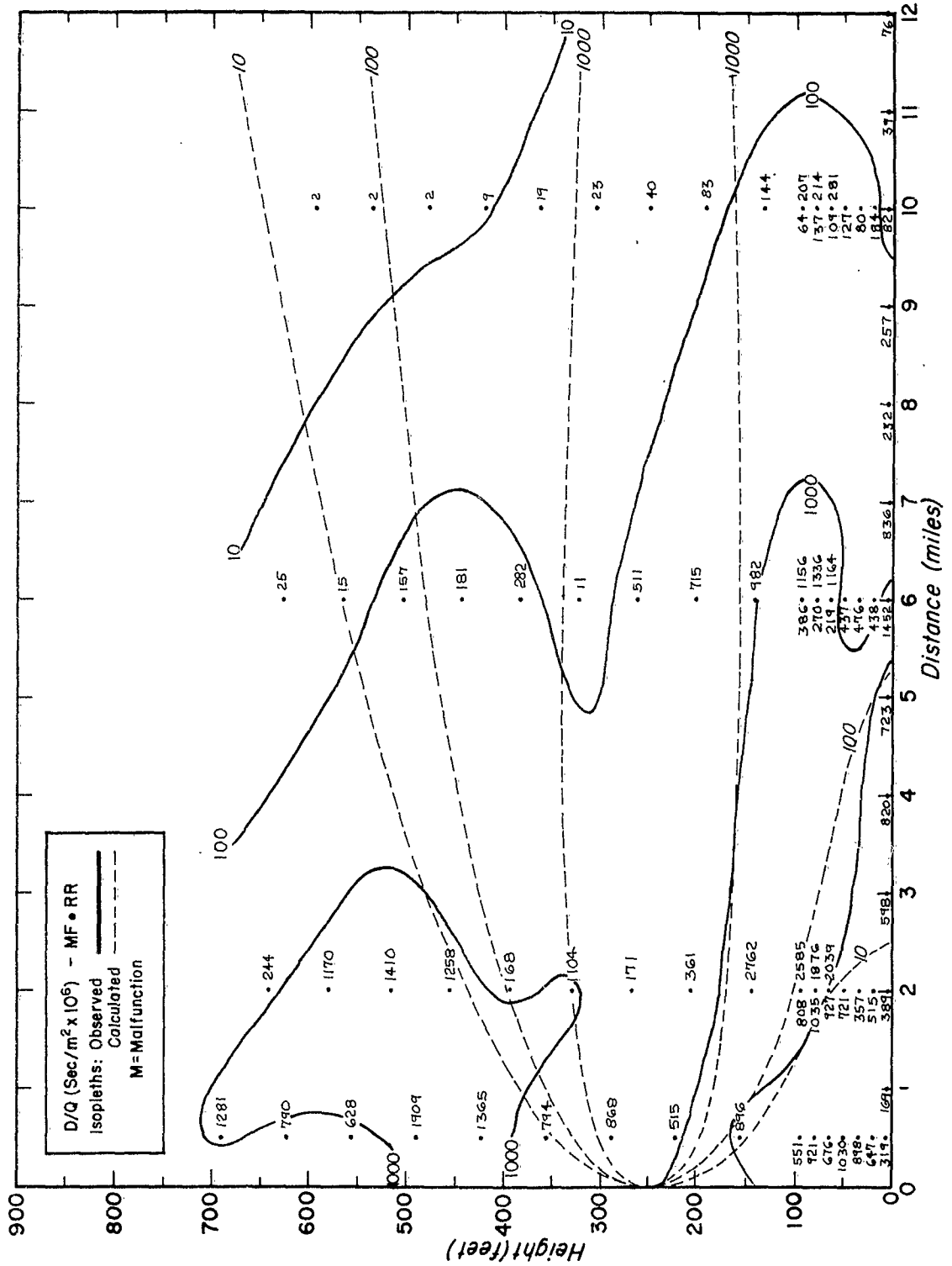


Fig. 24--Trial B-1: Vertical distribution of dosage per unit source strength from yellow FP release at 250 feet. (MF values to left and Rotorod values to right of sampling positions)

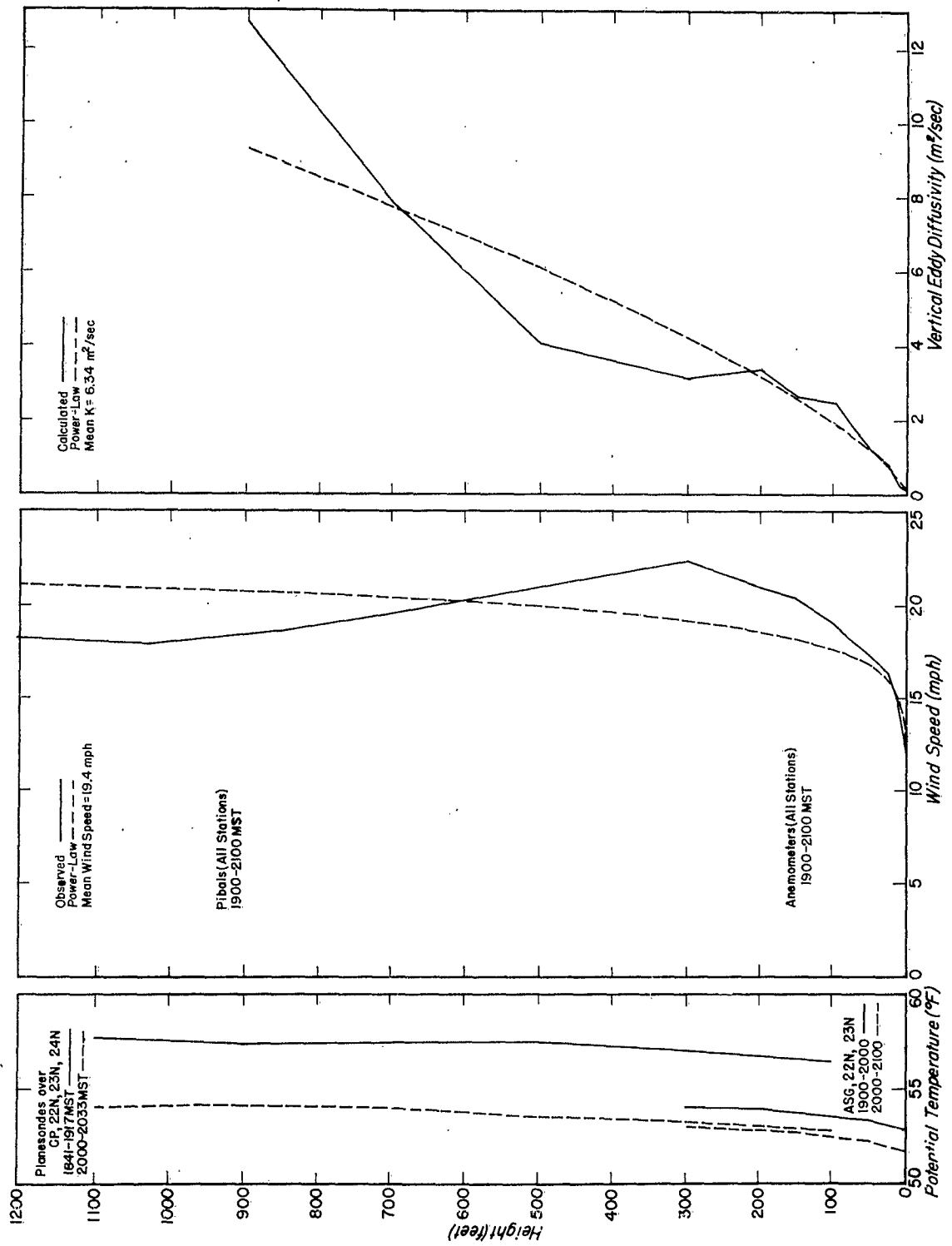


Fig. 25--Trial B-2: a) Potential temperature, b) wind speed and c) vertical eddy diffusivity as functions of height.

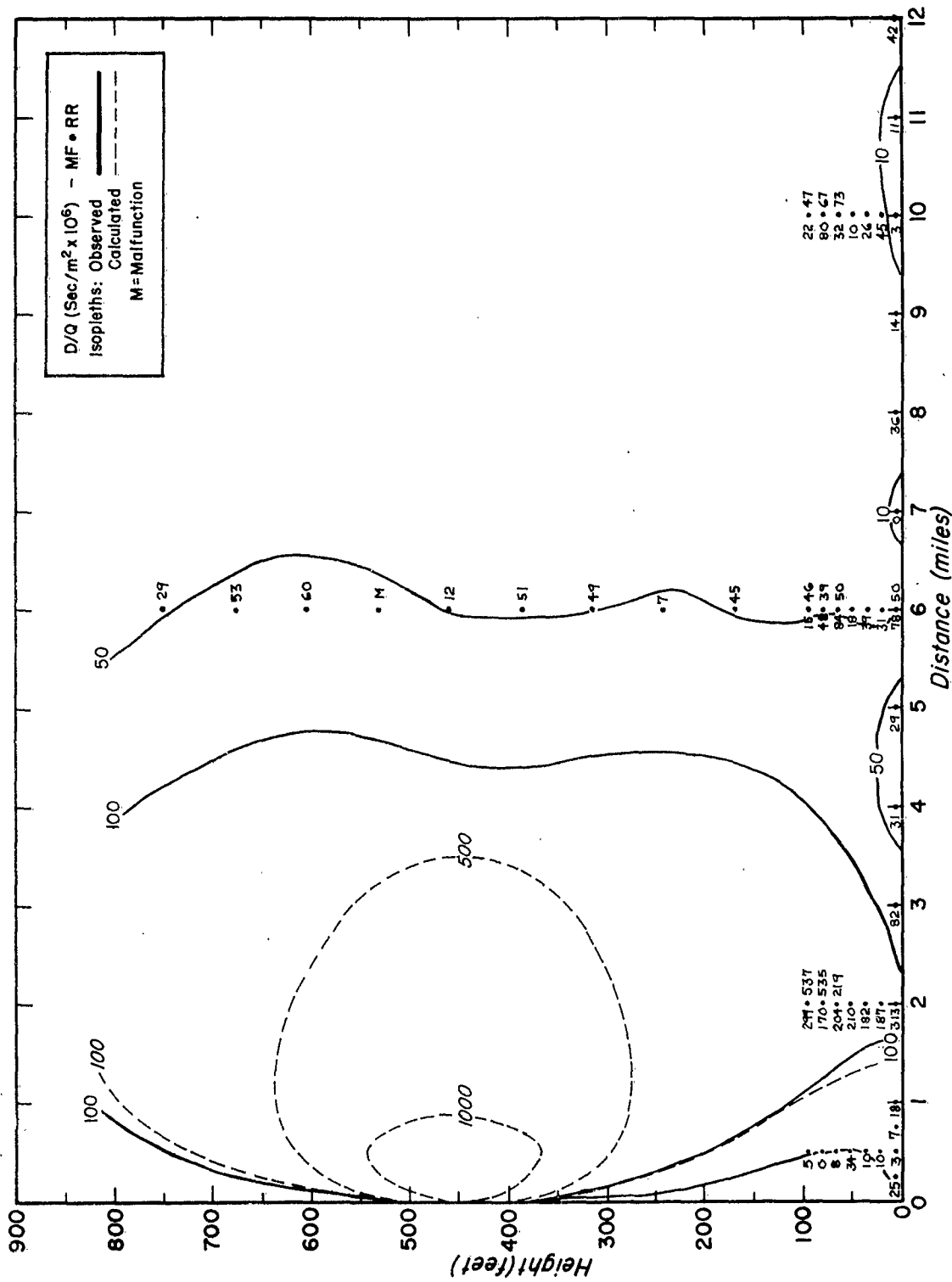


Fig. 26--Trial B-2: Vertical distribution of dosage per unit source strength from yellow FP release at 455 feet. (MF values to left and Rotorod values to right of sampling positions)

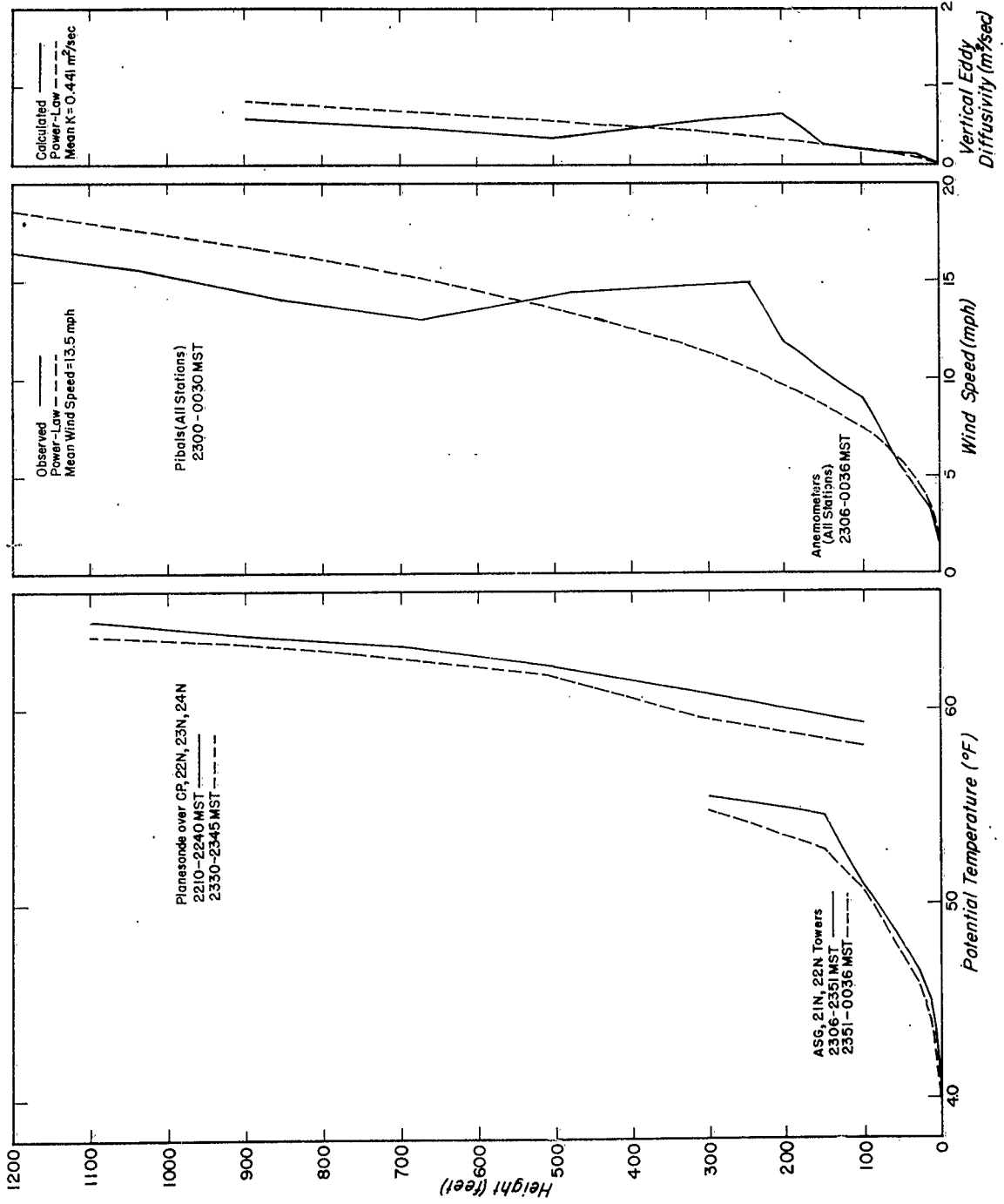


Fig. 27--Trial B-3: a) Potential temperature, b) wind speed and c) vertical eddy diffusivity as functions of height.

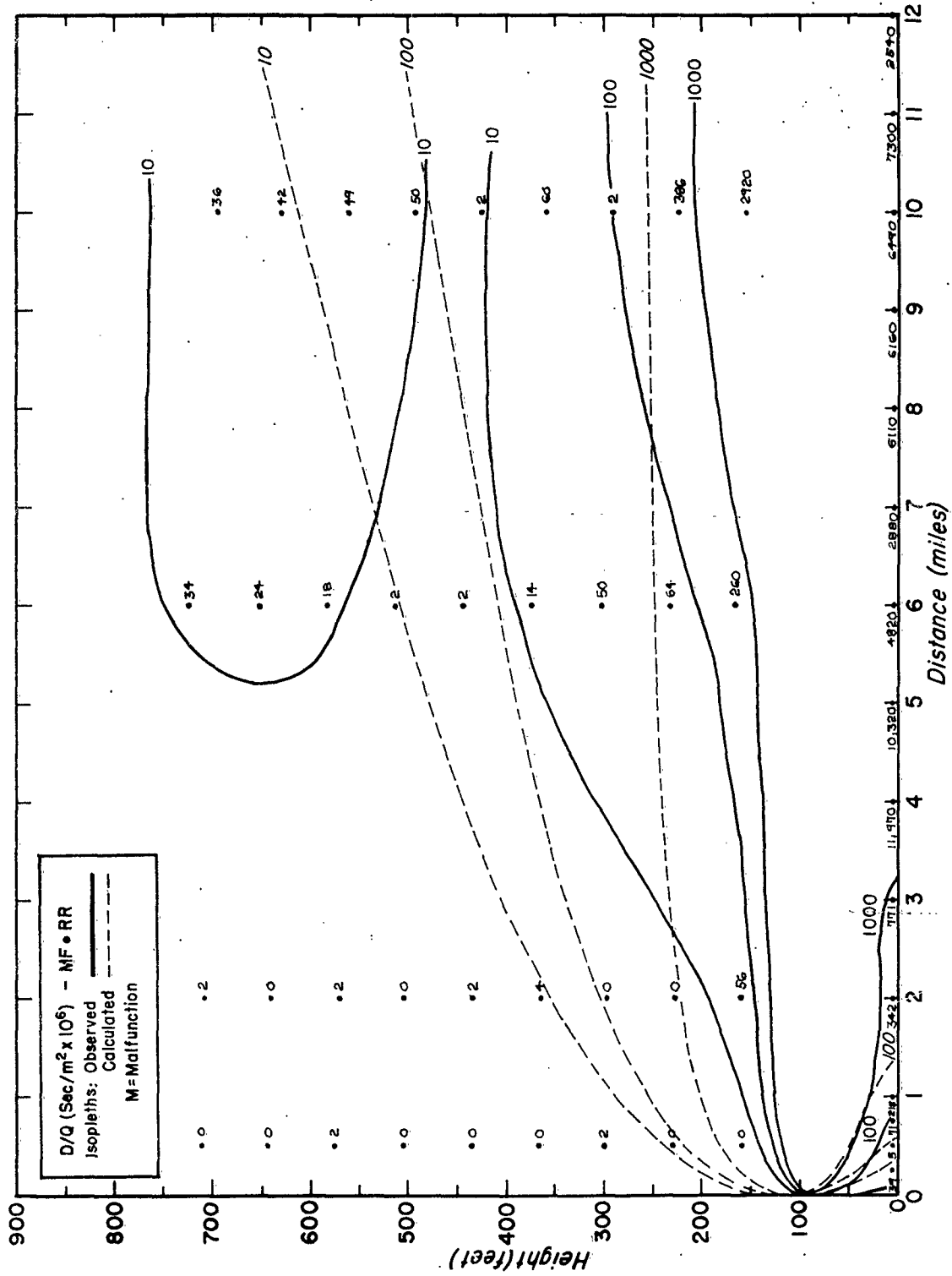


Fig. 28--Trial B-3: Vertical distribution of dosage per unit source strength from yellow FP release at 115 feet. (MF values to left and Rotorod values to right of sampling positions)

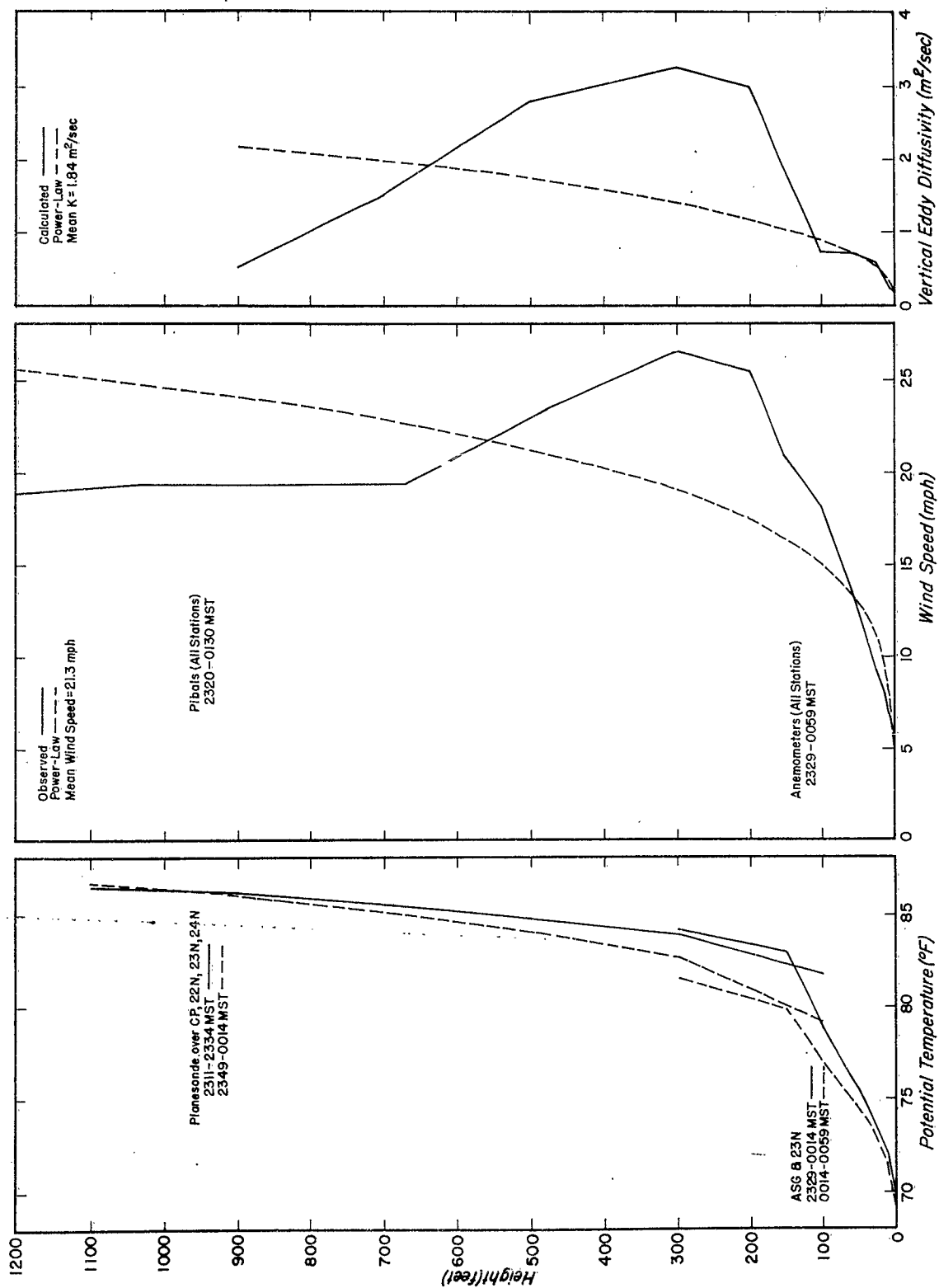


Fig. 29--Trial B-4: a) Potential temperature, b) wind speed and c) vertical eddy diffusivity as functions of height.

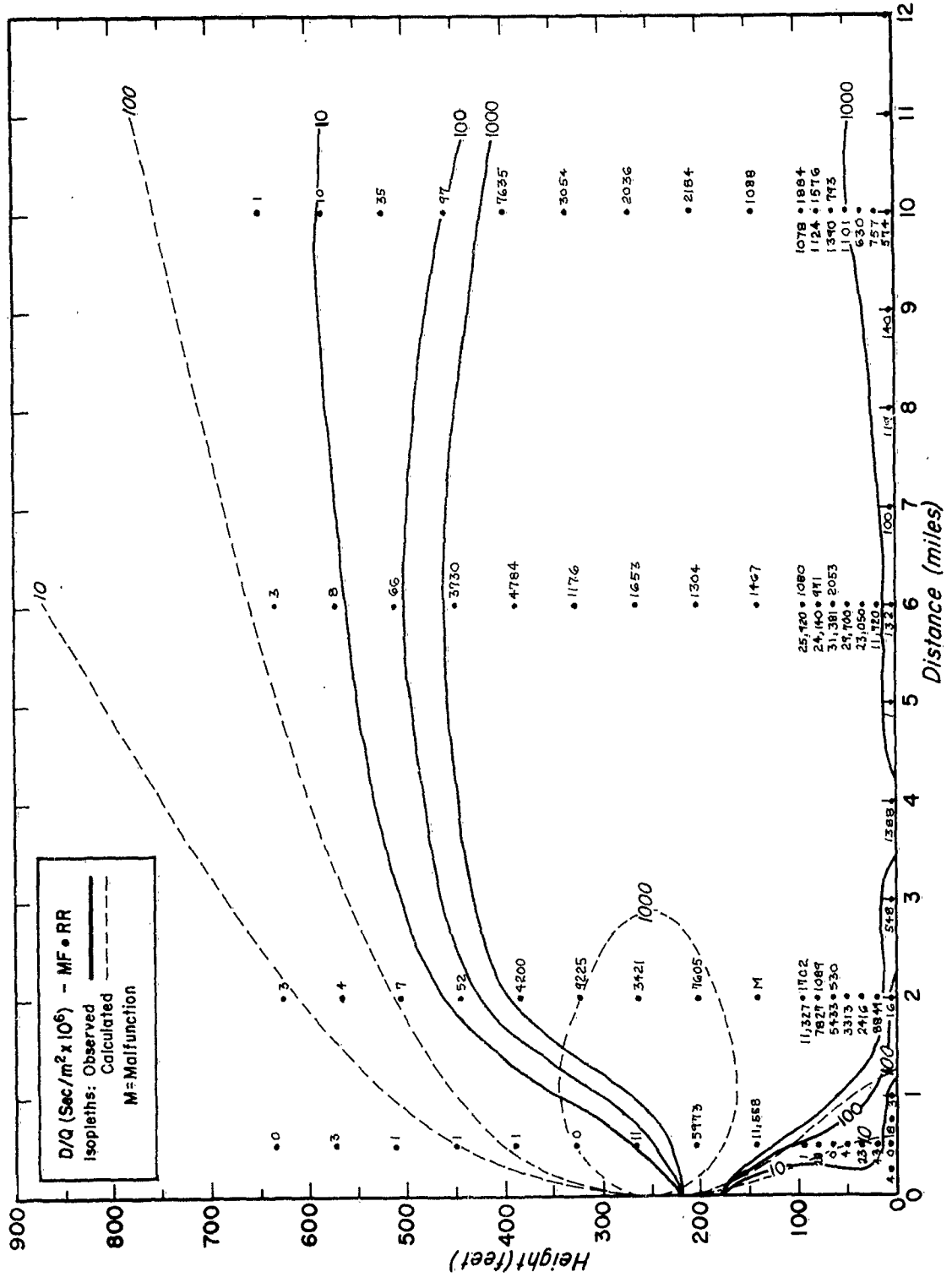


Fig. 30--Trial B-4: Vertical distribution of dosage per unit source strength from yellow FP release at 255 feet. (MF values to left and Rotorod values to right of sampling positions)

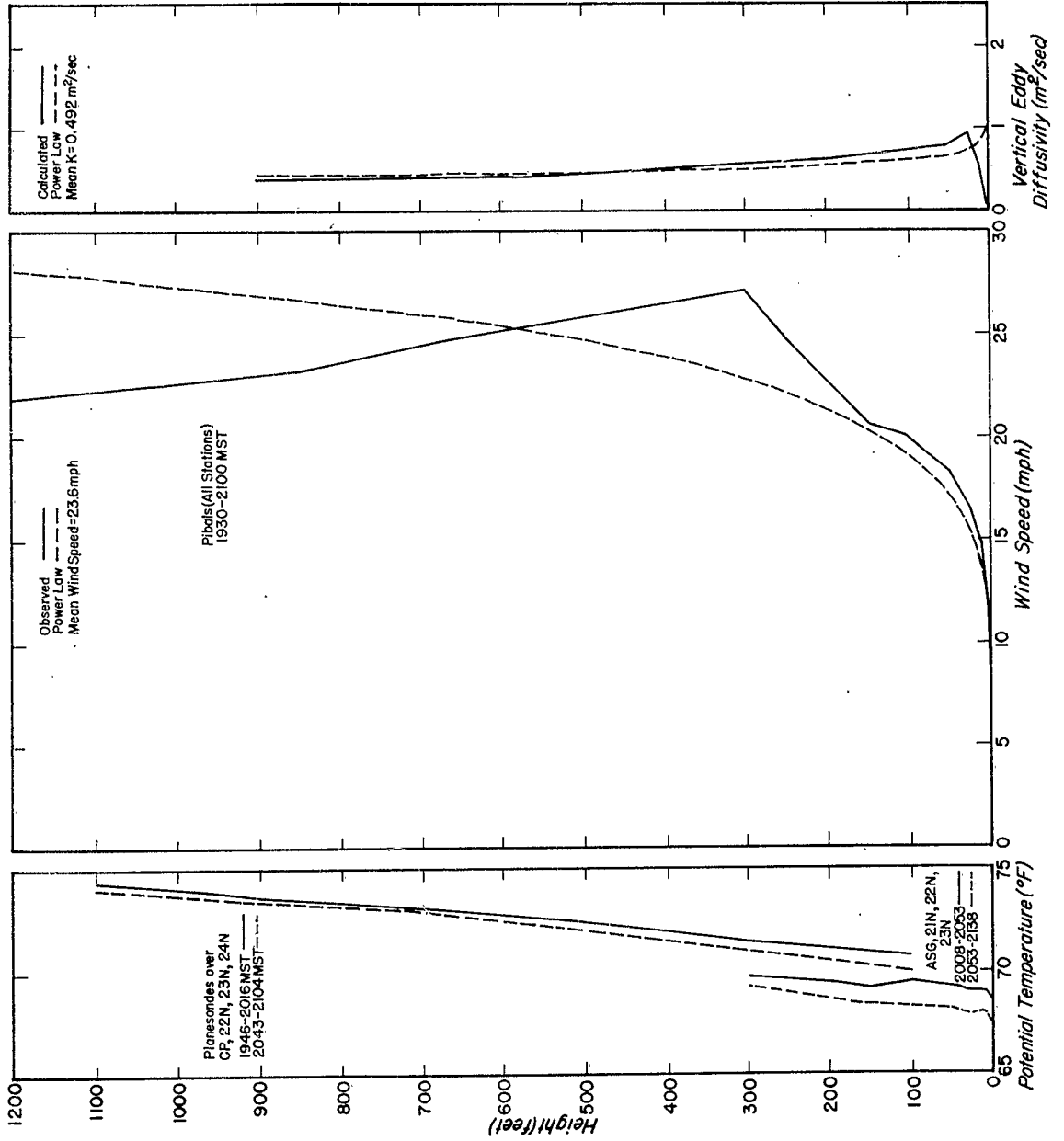


Fig. 31--Trial B-5: a) Potential temperature, b) wind speed and c) vertical eddy diffusivity as functions of height.



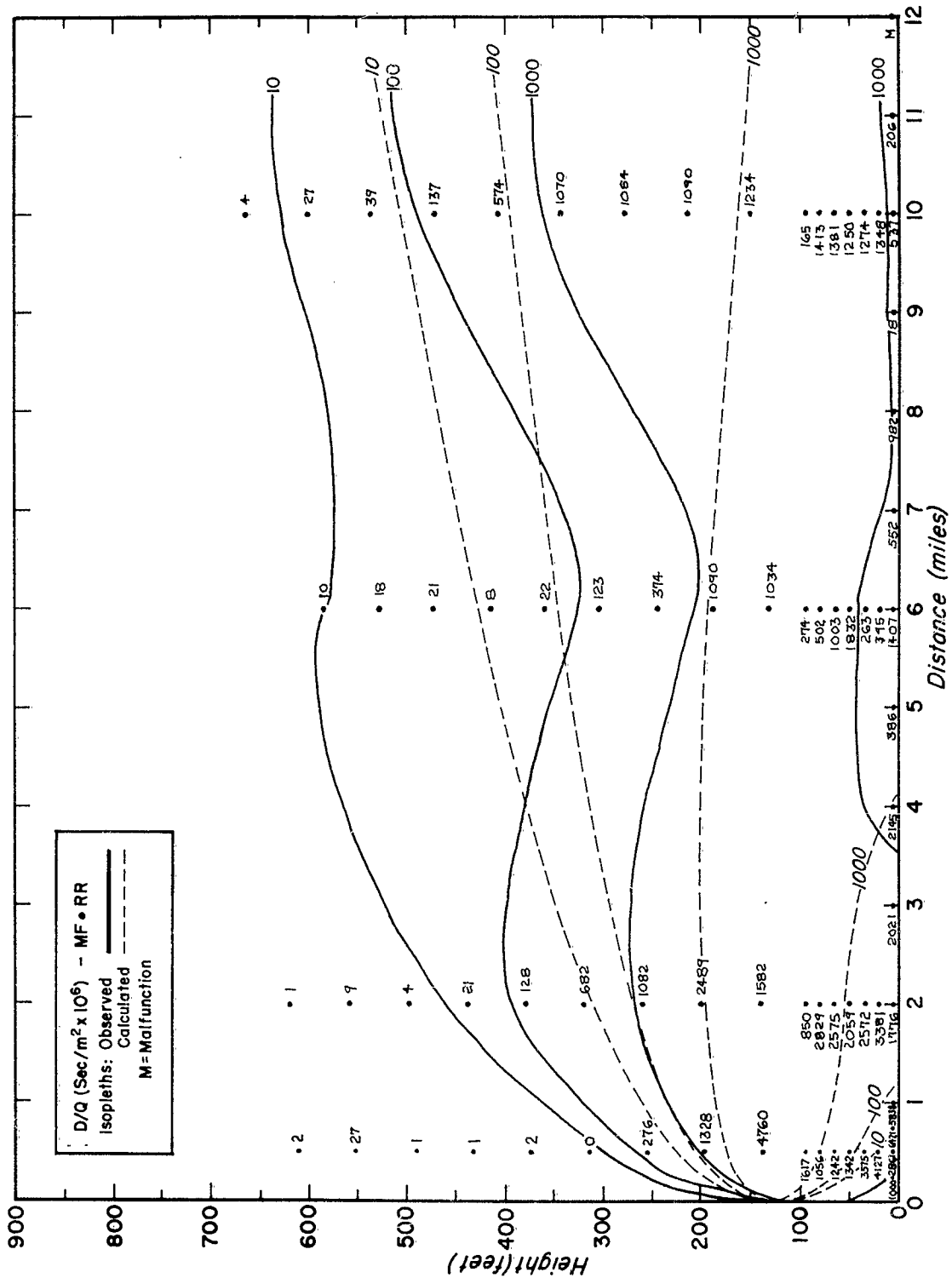


Fig. 32--Trial B-5: Vertical distribution of dosage per unit source strength from yellow FP release at 125 feet. (MF values to left and Rotorod values to right of sampling positions)

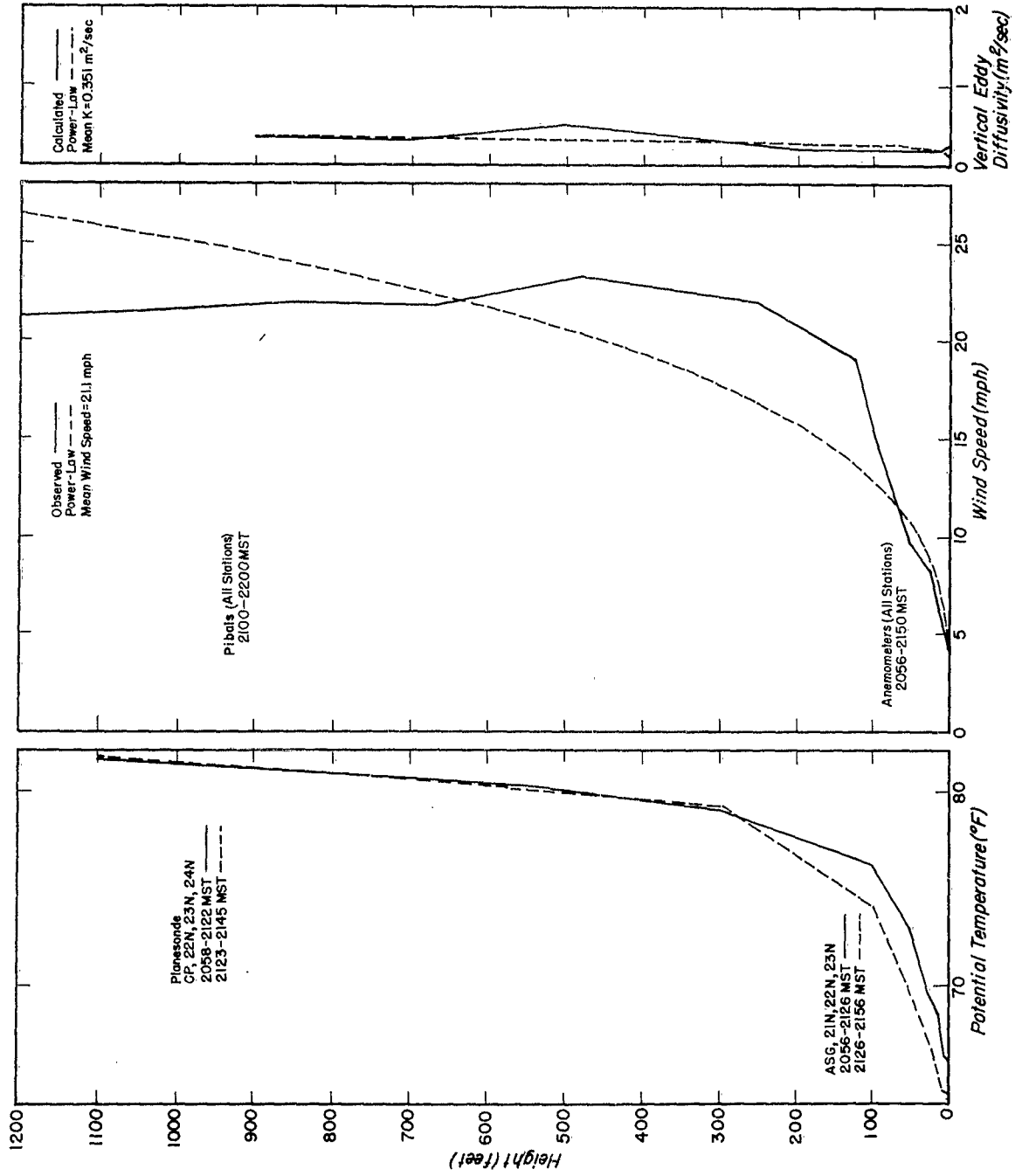


Fig. 33--Trial B-6: a) Potential temperature, b) wind speed and c) vertical eddy diffusivity as functions of height.

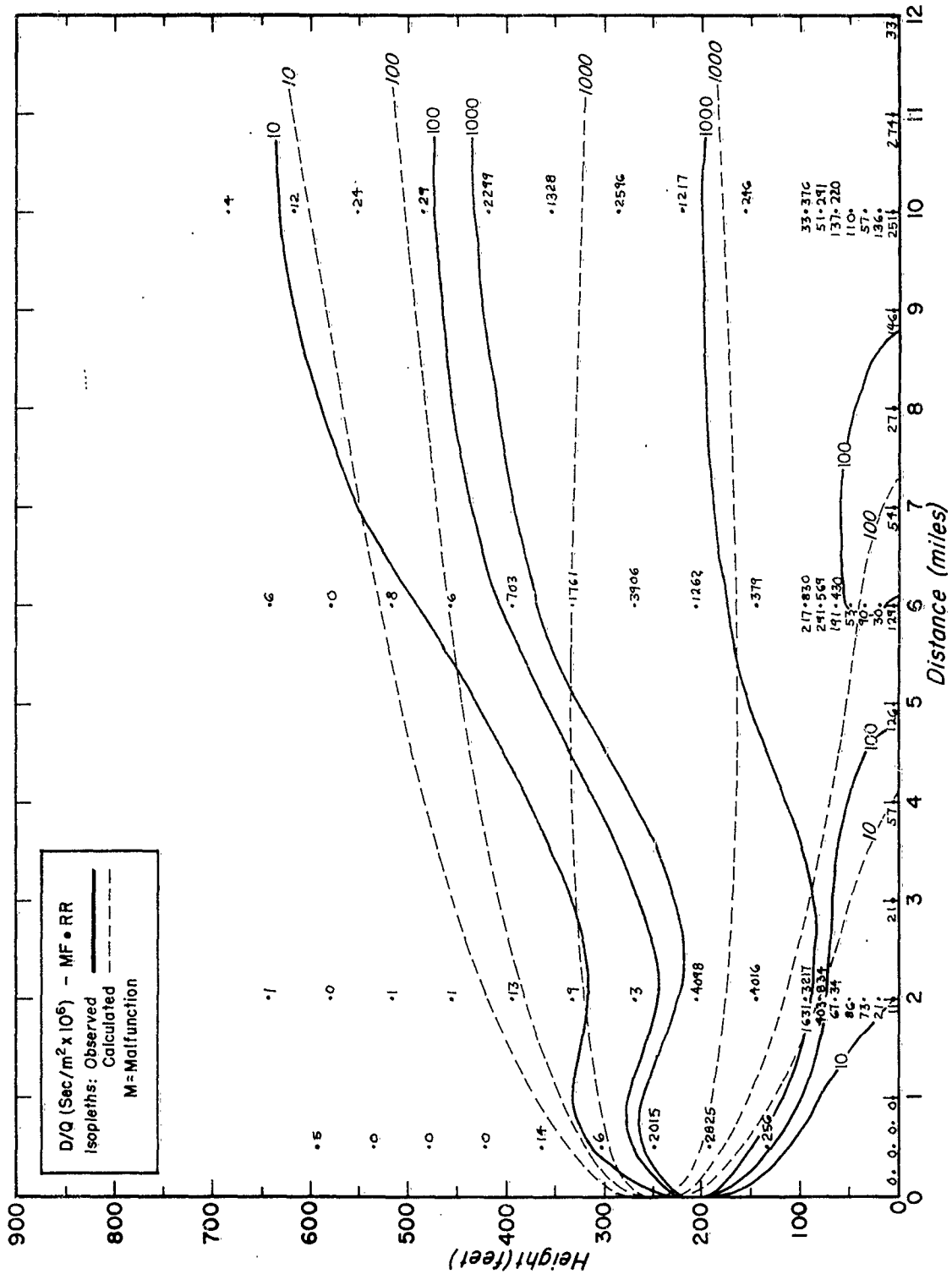


Fig. 34--Trial B-6: Vertical distribution of dosage per unit source strength from yellow FP release at 250 feet. (MF values to left and Rotorod values to right of sampling positions)

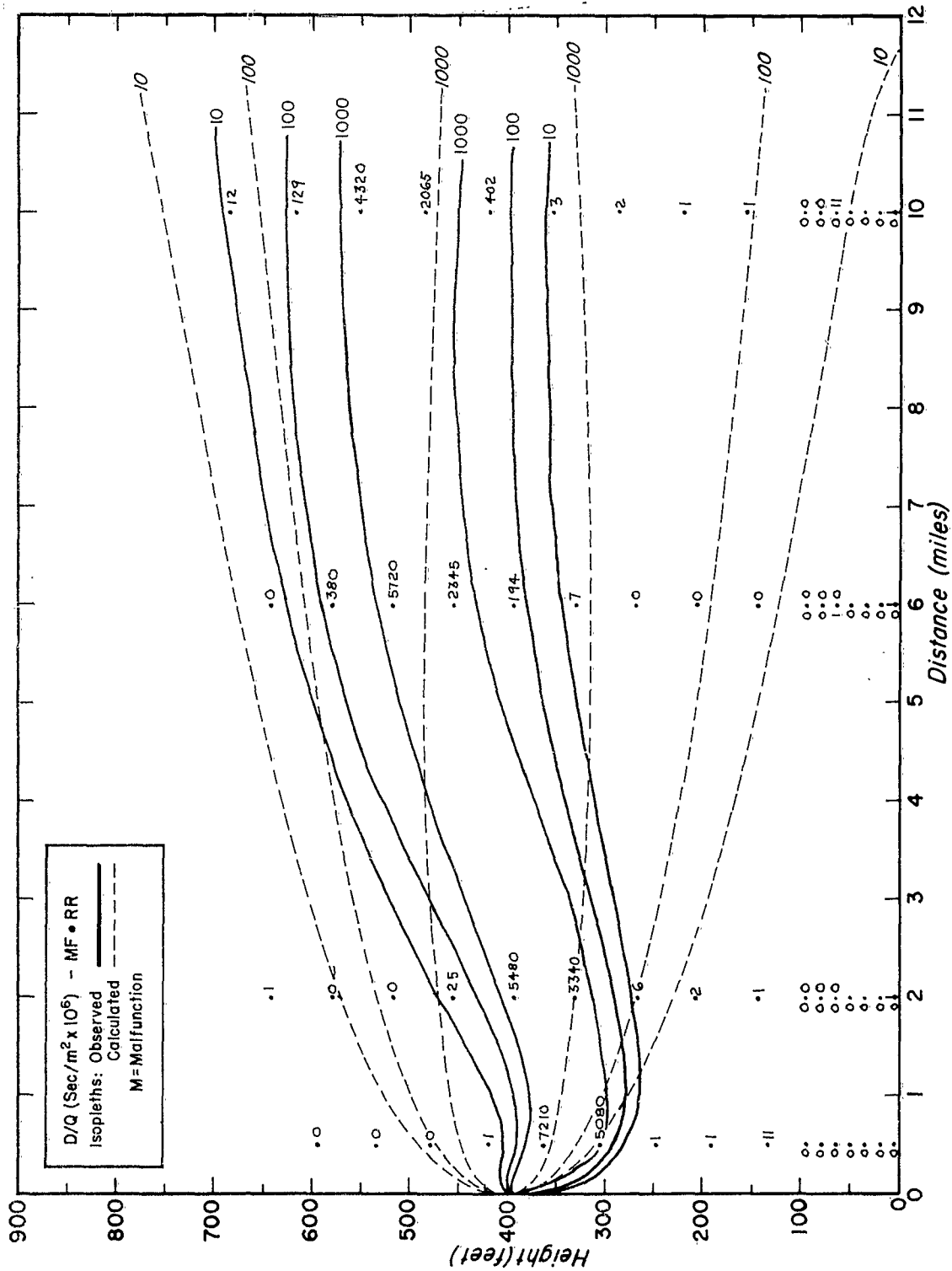


Fig. 35--Trial B-6: Vertical distribution of dosage per unit source strength from green FP release at 400 feet. (MF values to left and Rotorod values to right of sampling positions)

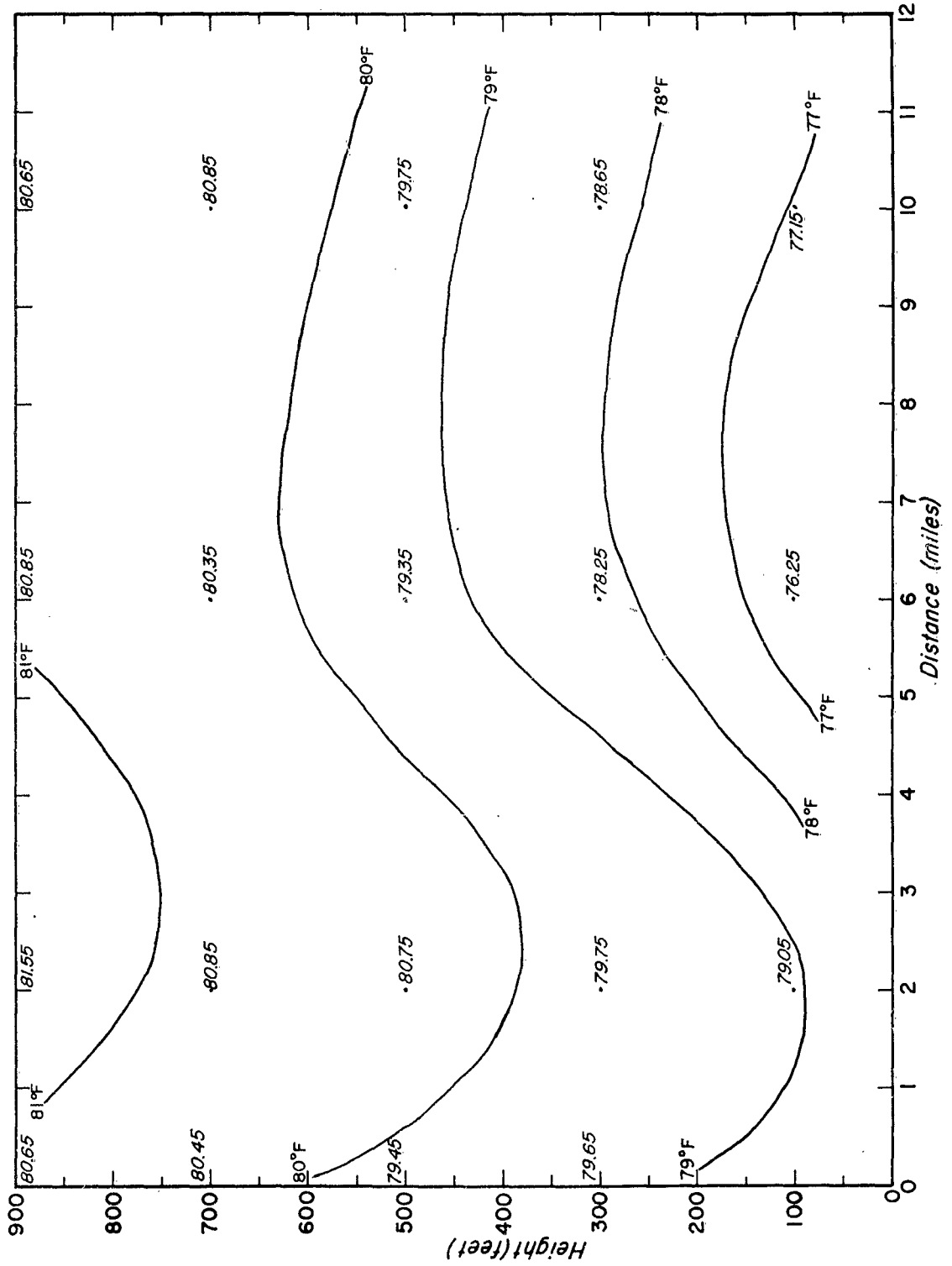


Fig. 36--Trial B-6: Vertical potential temperature cross-section along downwind sampling line.

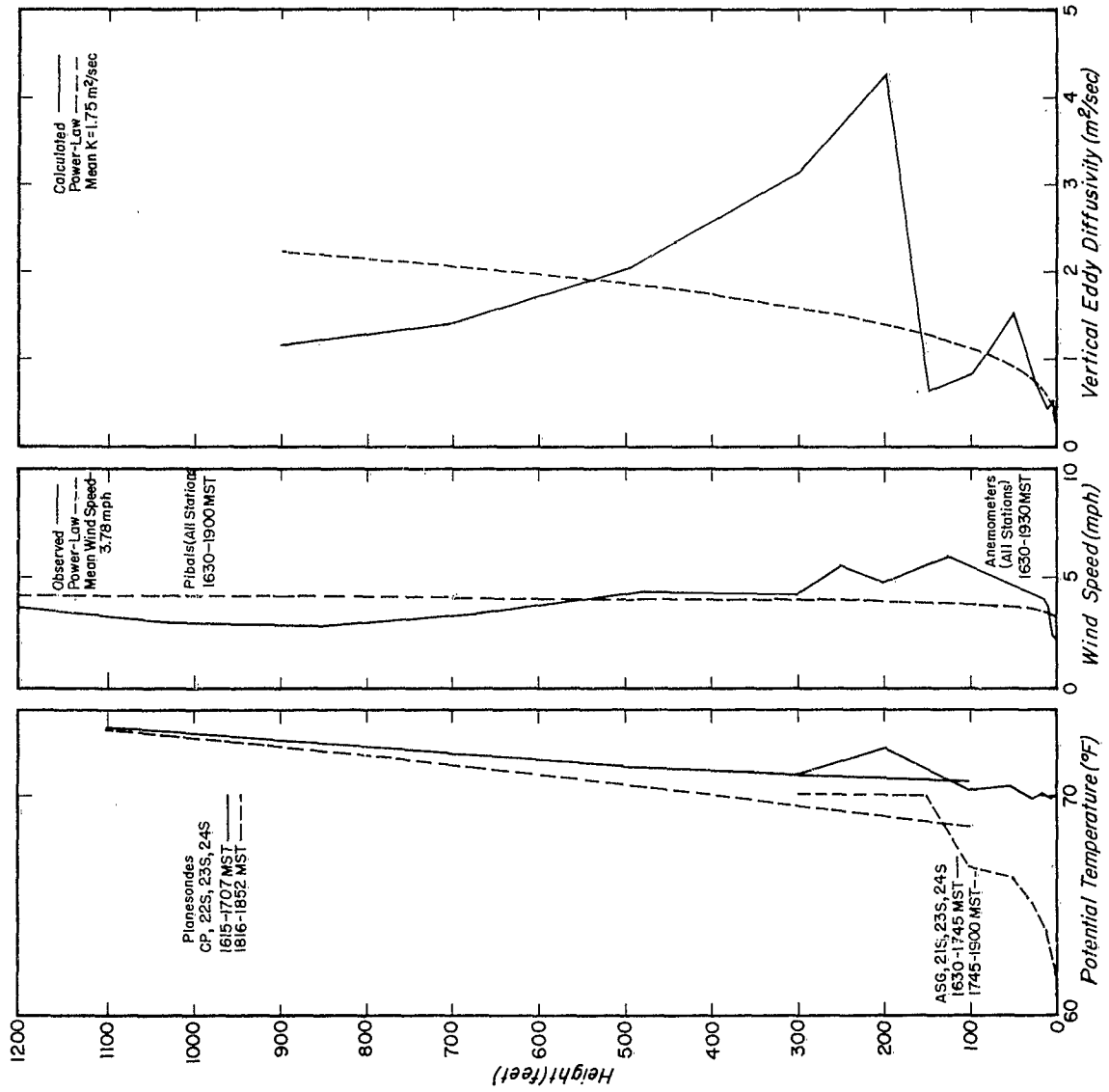


Fig. 37--Trial B-7: a) Potential temperature, b) wind speed and c) vertical eddy diffusivity as functions of height.

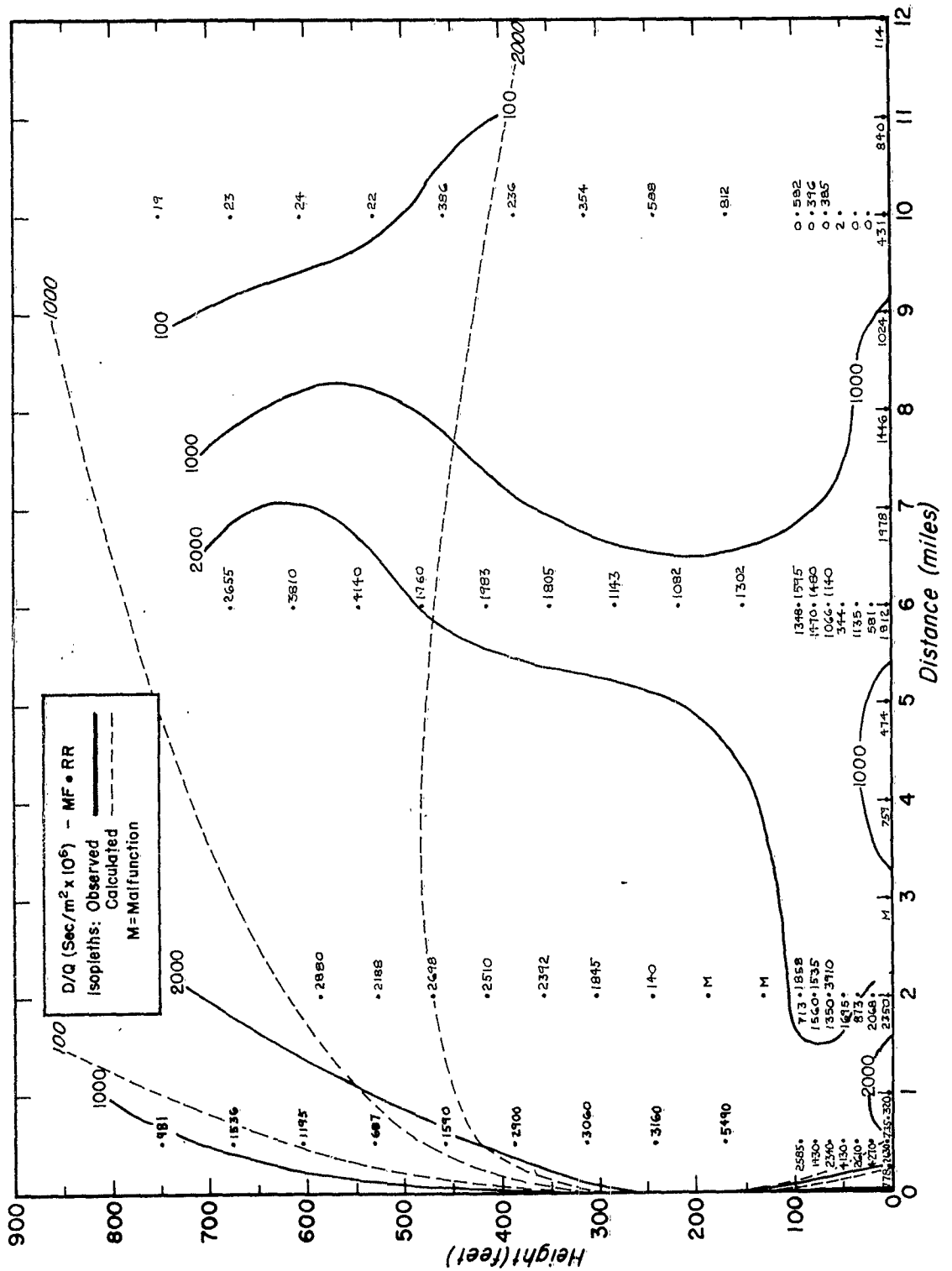


Fig. 38--Trial B-7: Vertical distribution of dosage per unit source strength from yellow FP release at 225 feet. (MF values to left and Rotorod values to right of sampling positions)

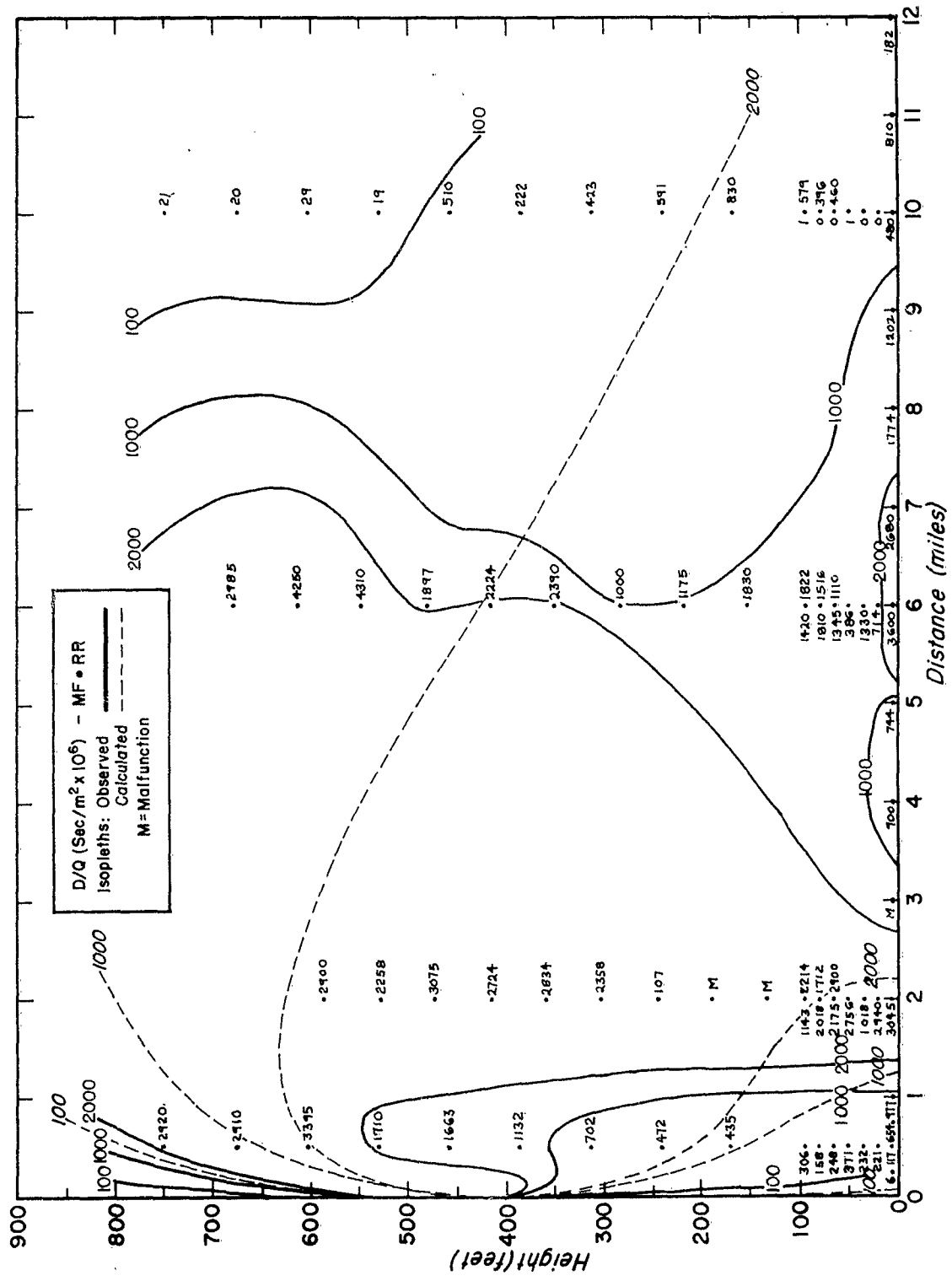


Fig. 39--Trial B-7: Vertical distribution of dosage per unit source strength from green FP release at 400 feet. (MF values to left and Rotorod values to right of sampling positions)



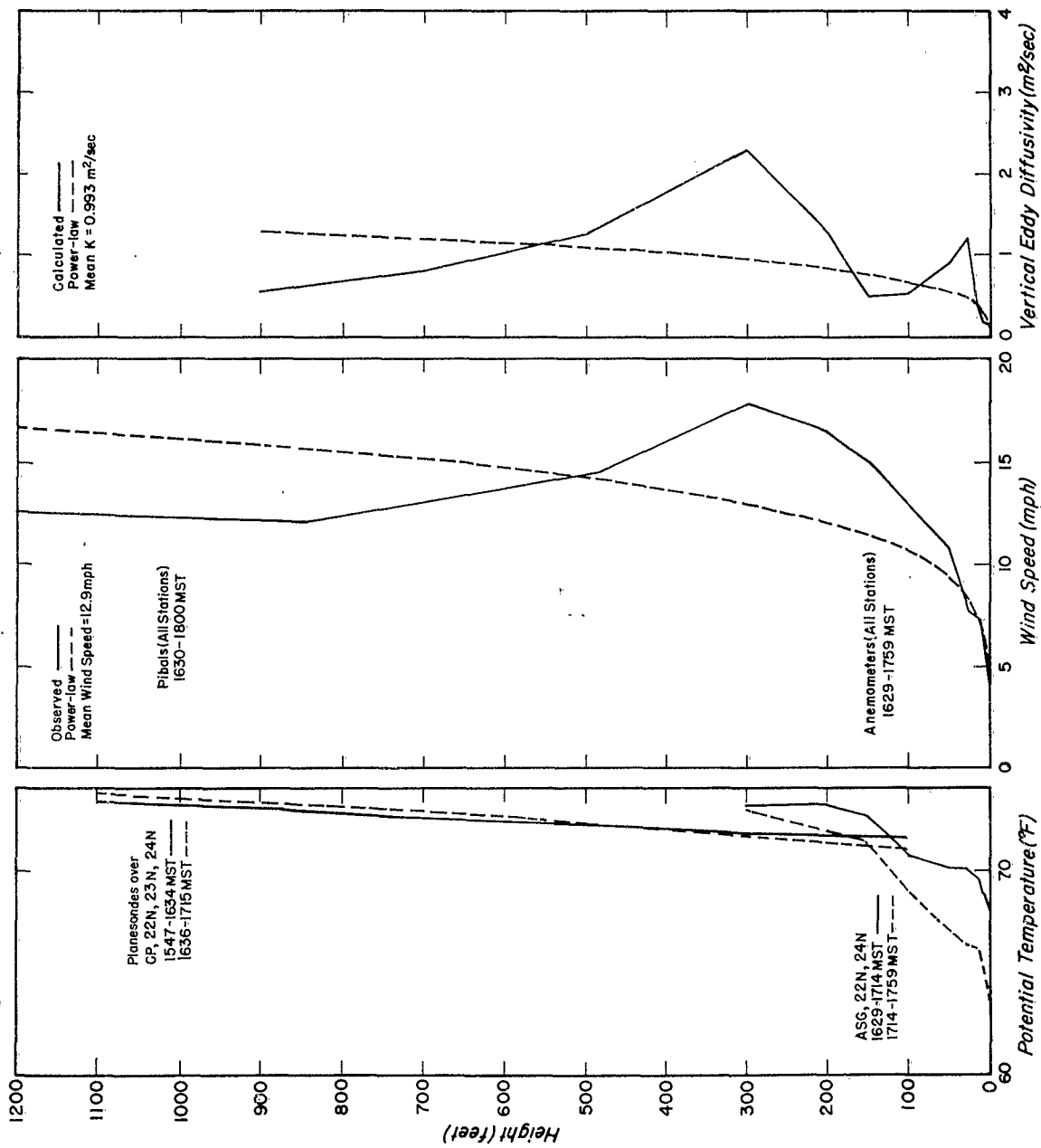


Fig. 40--Trial B-8: a) Potential temperature, b) wind speed and c) vertical eddy diffusivity as functions of height.

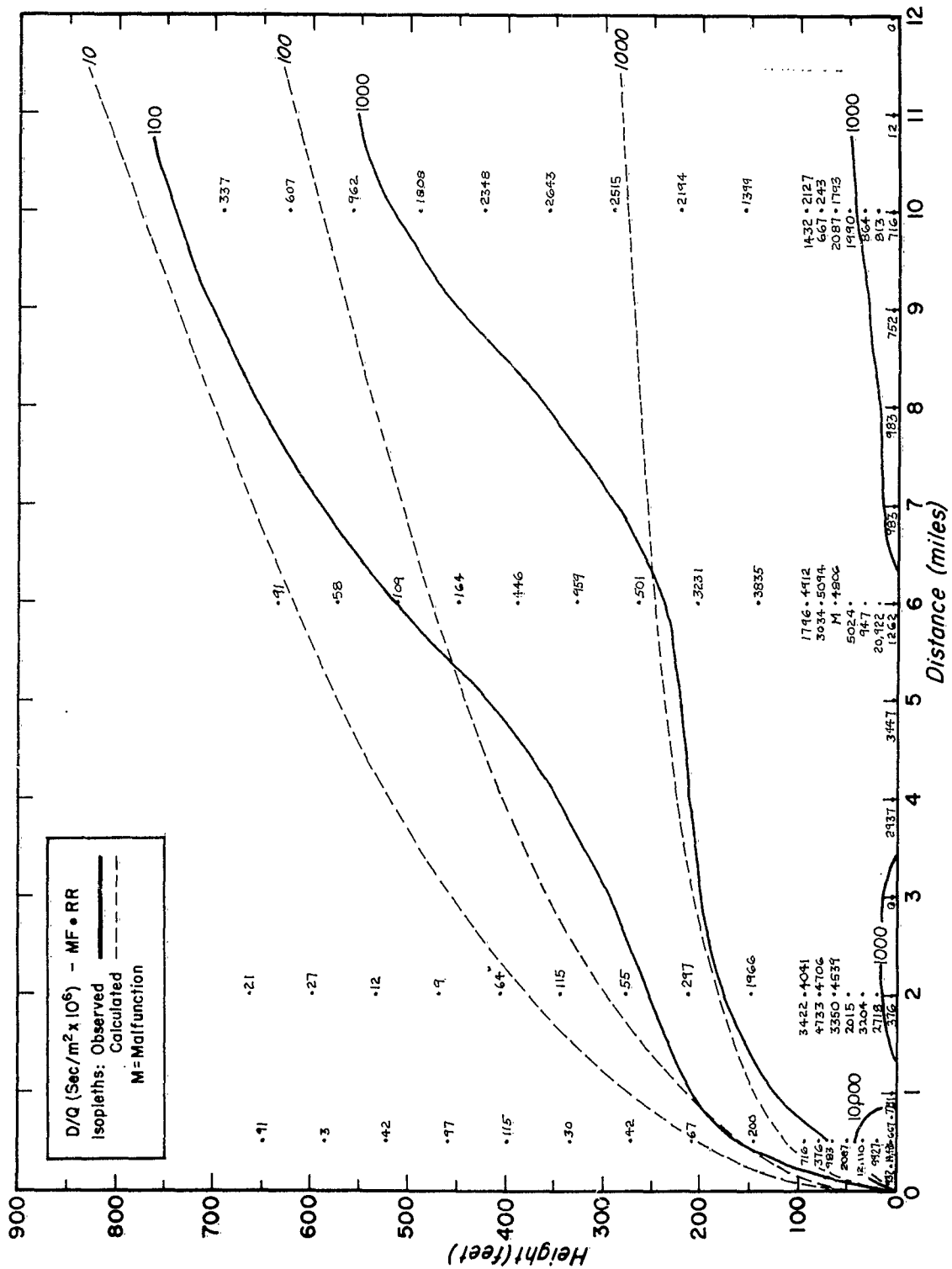


Fig. 41--Trial B-8: Vertical distribution of dosage per unit source strength from yellow FP release from ground vehicles. (MF values to left and Rotorod values to right of sampling positions)

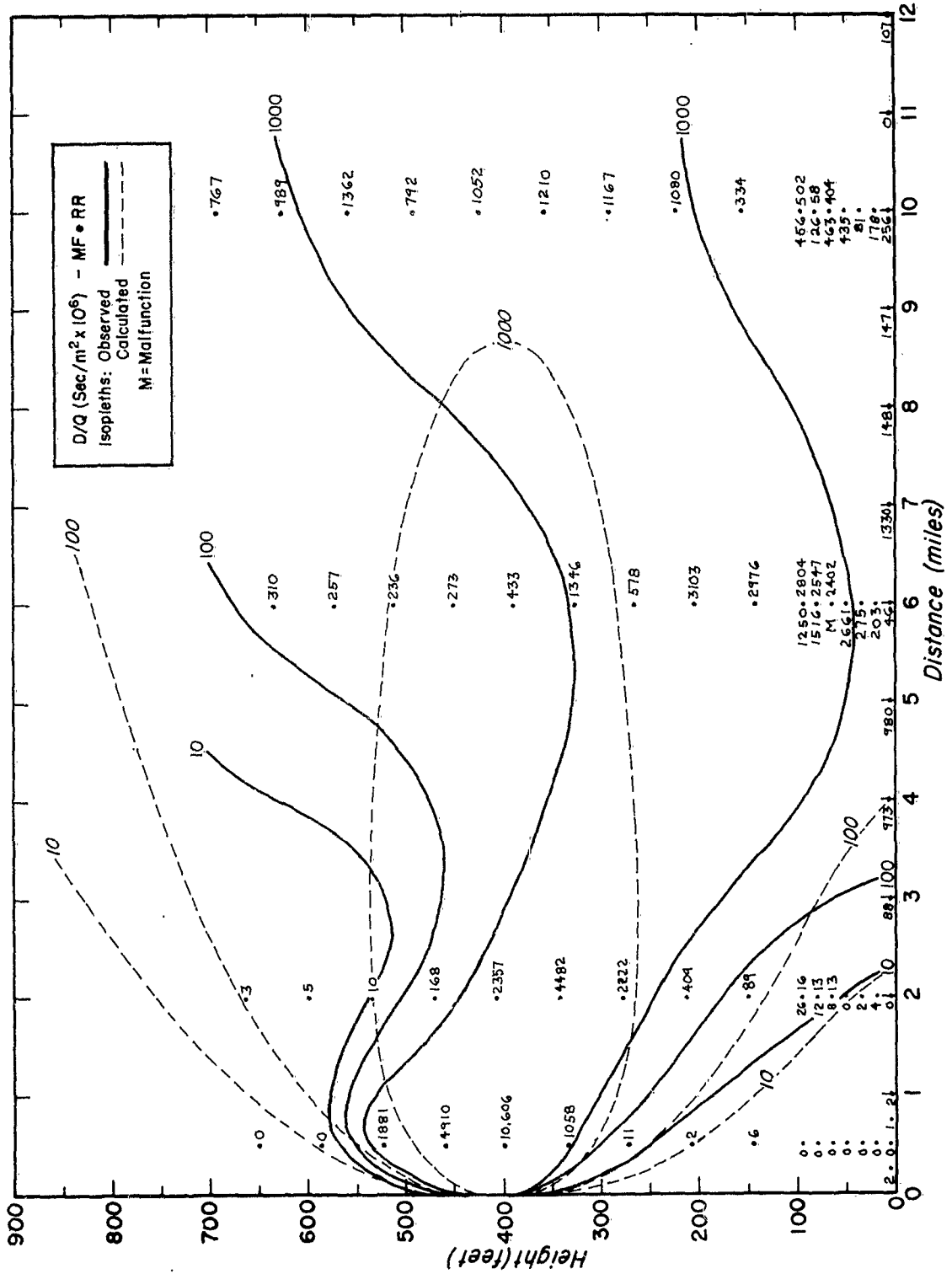


Fig. 42--Trial B-8: Vertical distribution of dosage per unit source strength from green FP release at 400 feet. (MF values to left and Rotorod values to right of sampling positions)

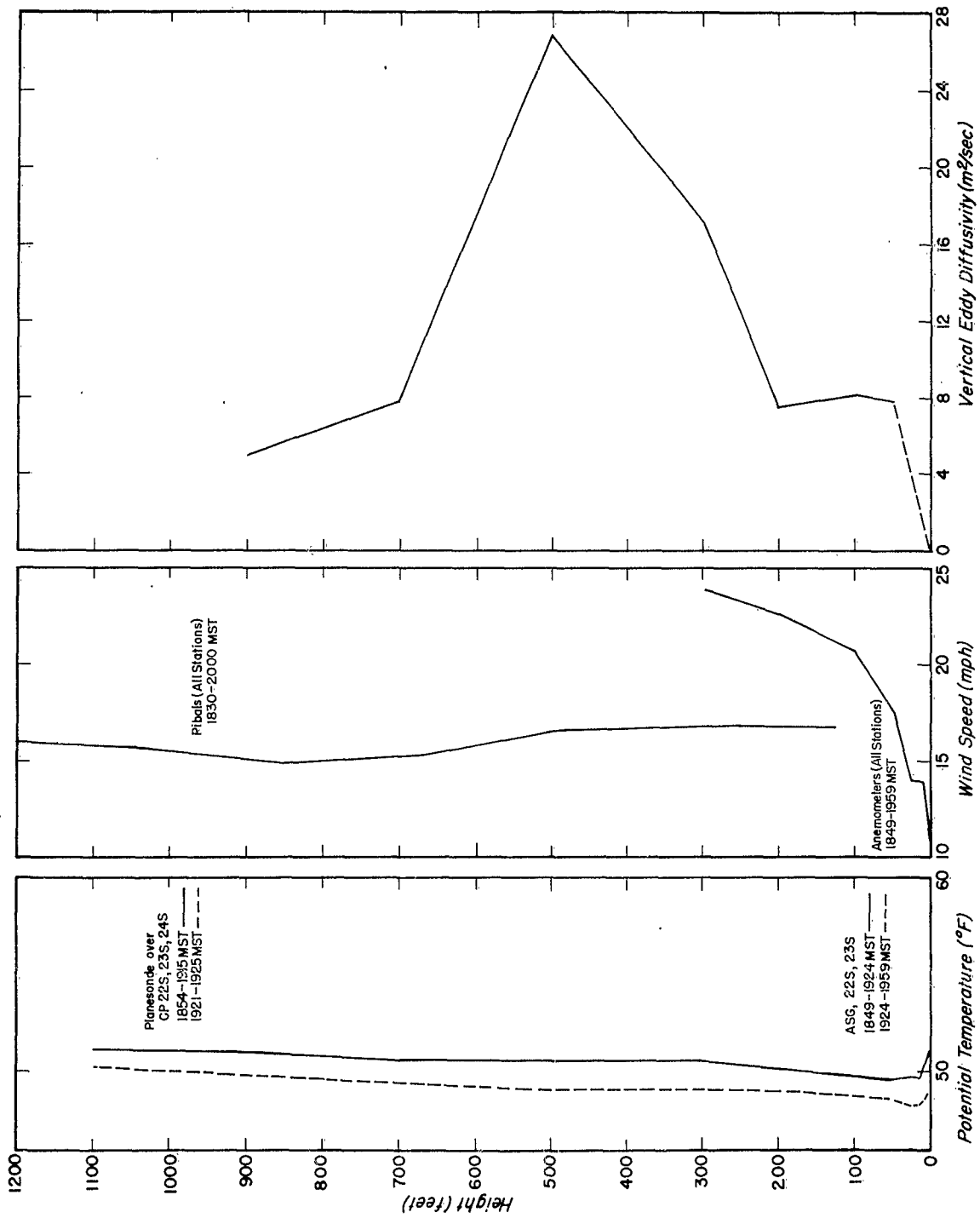


Fig. 43--Trial B-9: a) Potential temperature, b) wind speed and c) vertical eddy diffusivity as functions of height.

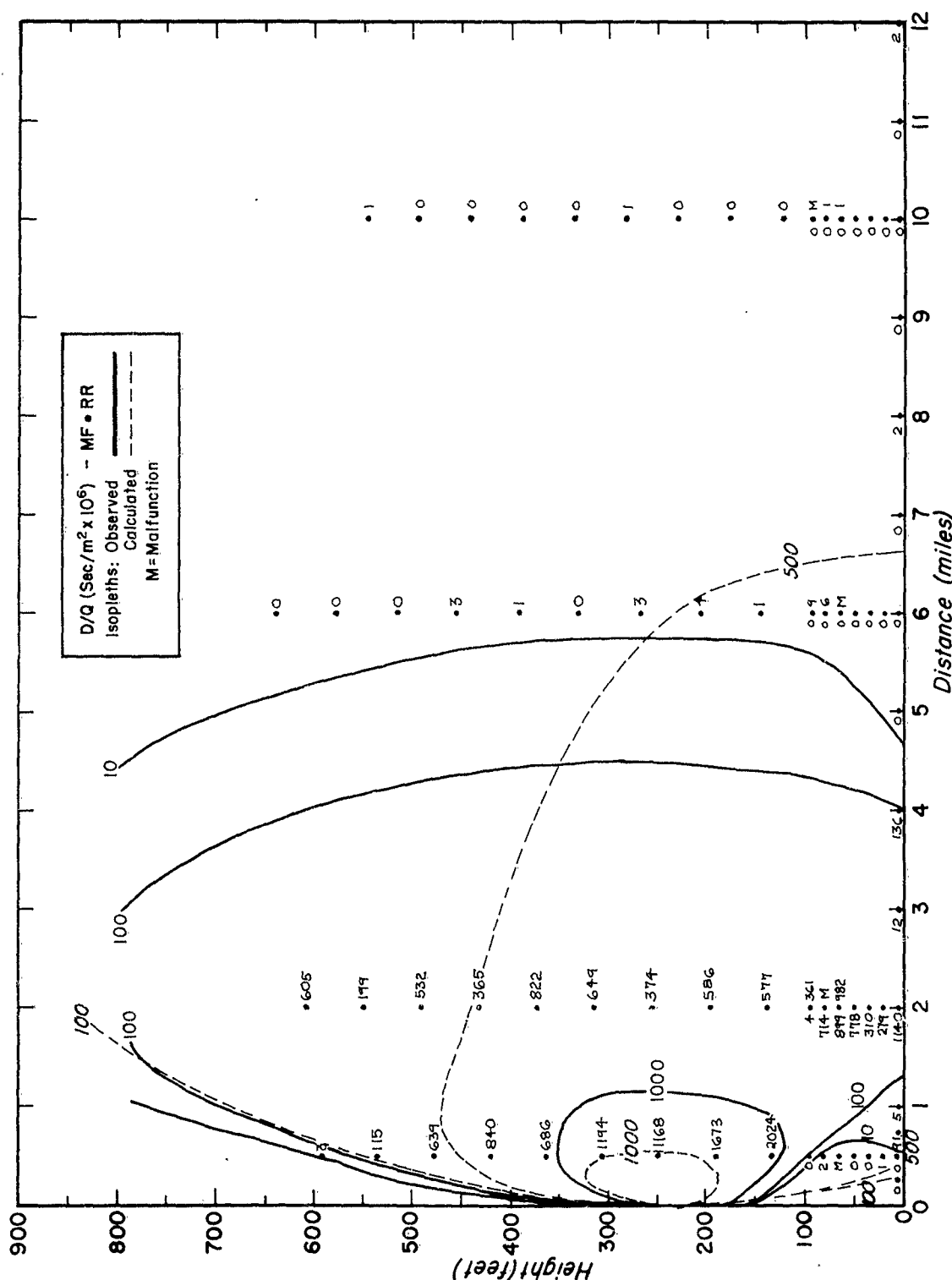


Fig. 44--Trial B-9: Vertical distribution of dosage per unit source strength from yellow FP release at 250 feet. (MF values to left and Rotord values to right of sampling positions)

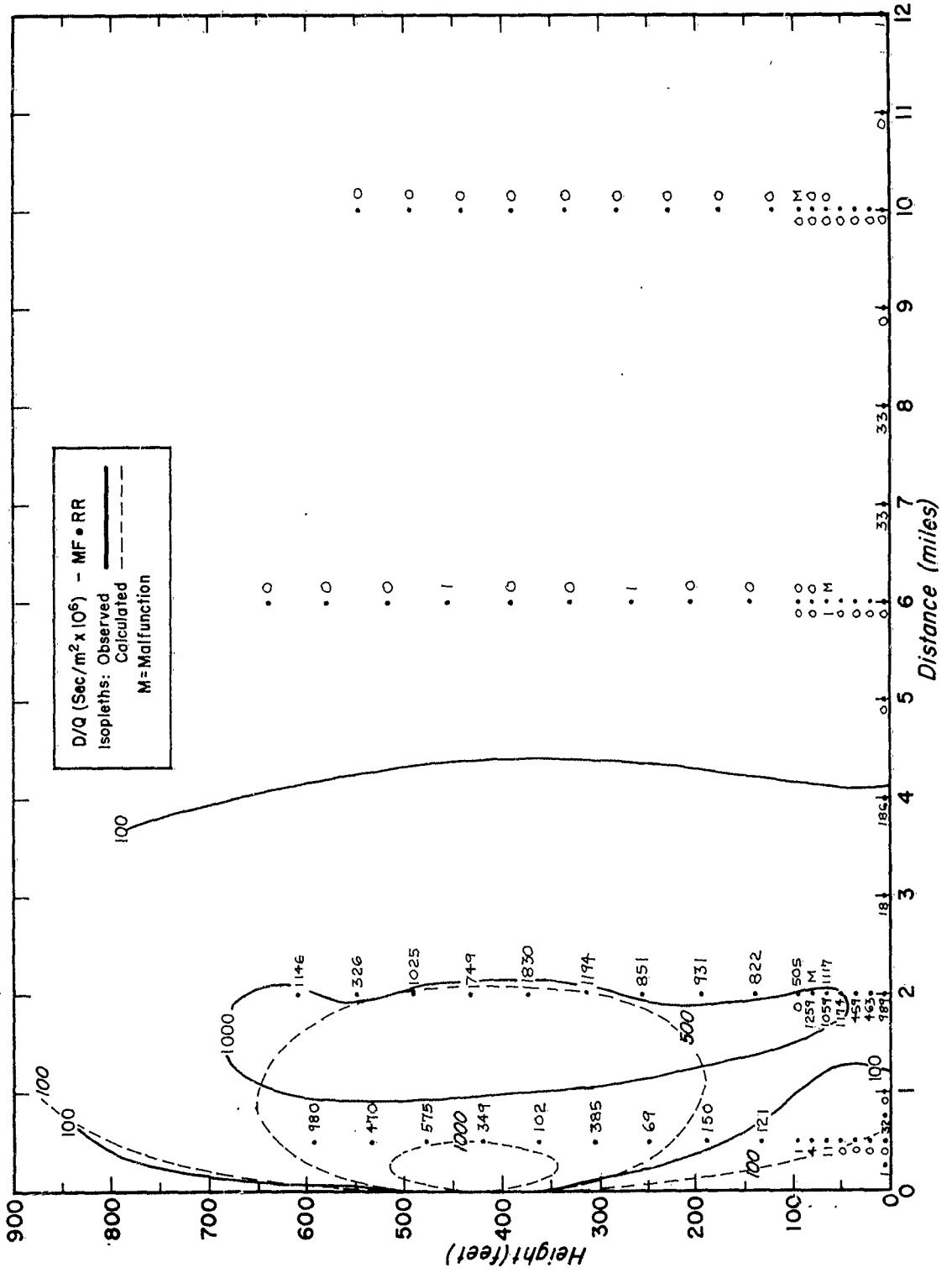


Fig. 45--Trial B-9: Vertical distribution of dosage per unit source strength from Green FP release at 430 feet. (MF values to left and Rotorod values to right of sampling positions)

### C. Comparison of Calculated and Observed Maximum Ground-Level Dosages

Using mean values of wind speed and vertical eddy diffusivity the ground-level dosage downwind from an elevated line release may be computed from Eq. (12) with  $r = 0$ , i.e.

$$\frac{D(x,0)}{Q} = \frac{2s^{\frac{1}{2}}}{\sqrt{\pi}uh} e^{-s}$$

The maximum ground-level dosage will be obtained when  $S = 0.5$ . At this distance the dosage will be given approximately by

$$D_{\max} = 0.5 \frac{Q}{uh}$$

It is evident that the maximum value of dosage is independent of vertical eddy diffusivity and depends upon the source strength, release altitude and mean wind speed. The distance at which the maximum should occur, however, is very dependent upon the eddy diffusivity.

The maximum ground-level dosages were calculated for all elevated releases in Trials B-1 through B-9 of the BW 502 B Series. In addition, the distances at which the maximum should occur and at which one-tenth of the maximum should first occur were calculated, i.e. when  $S$  equals 0.5 and 3.8 respectively. These values are given in Table 2 on the following page.

Agreement between calculated and observed maximum dosages is reasonably good except for Trials B-3, B-5 and B-6. In Trials B-3 and B-5 the releases were made at very low altitude (slightly over 100 feet) and the initial downward displacement of the aerosol cloud in the aircraft wake produced very high ground-level dosages. In Trial B-6 the turbulence was so slight that the main portion of the yellow FP release at 250 feet did not reach ground level within the 15-mile sampling range and the green FP from the 400-ft release did not reach ground level in detectable amounts.

Distances from release to point of maximum observed dosages were highly variable as might be expected for single line releases. Calculated values of maximum dosage and corresponding distances are based on average values of temperature and wind and should give a reasonable estimate of the mean dosage to be expected from repeated trials under the same meteorological conditions.

Table 2

Comparison of Calculated and Observed Maximum Ground-Level Dosages from Elevated Line Releases

Trial	Release Altitude (m)	Mean wind Speed (m/sec)	Q part/m x10 <sup>9</sup>	K (m <sup>2</sup> /sec)	Maximum Dosage (part-min/l)		Distance to Max. (miles)		Distance to 1/10 of Maximum (miles)	
					Calculated	Observed	Calculated	Observed	Calculated	Observed
B-1	76	8.84	6.25	0.419	78	151*	38	6	5.0	0.4
B-2	139	8.66	7.08	6.34	49	37	8.2	2	1.1	1.0
B-3	35	6.02	6.53	0.441	258	1283	5.2	4	0.7	3.0
B-4	78	9.52	7.63	1.84	86	179	9.8	4	1.3	2.2
B-5	38	10.53	6.80	0.492	142	725	9.6	0.75	1.3	0.2
B-6Y <sup>△△</sup>	76	9.43	7.08	0.351	82	32 <sup>△</sup>	48	11	6.3	3.2
G <sup>△△</sup>	122		11.4		82	0 <sup>△</sup>	125		16.5	
B-7Y	68	1.69	6.80	1.75	492	285**	1.4	0.25	0.2	0.1
G	122		11.9		480	597	4.5	2	0.6	0.6
B-8G	122	5.78	13.6	0.993	161	302	27	7	3.6	3.1
B-9Y	76	7.59	7.90	13.0	114	148	1.0	2	0.1	1.1
G	131		14.2		119	231	3.1	2	0.4	1.1

\* Enfilading is involved.

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

△ Maximum not reached within 15-mile sampling range.

△△ Y = yellow FP, G = green FP.

The distance at which the ground-level dosage reaches one-tenth of the maximum value may be a good indicator of when the aerosol cloud first reaches the ground. The calculated distances were in reasonable agreement with observed except for Trials B-1, B-3 and B-5. In Trial B-1 the calculated aerosol cloud trajectories indicated possible enfilading from the southwest end of the release line and the positions of maxima in Trials B-3 and B-5 were influenced by the downdraft from the aircraft as mentioned above.



## VII. CONCLUSIONS

1. In general the aerosol cloud travel and diffusion from low-level aerial line releases may be adequately predicted from trajectories computed from winds near release altitude and vertical eddy diffusivities based on estimates of the vertical eddy heat flux. Calculated dosages per unit source strength represent mean values from repeated trials under the same meteorological conditions and dosages from individual trials may depart considerably from calculated values because of changes in wind directions and speed and vertical displacements of the cloud by large eddies.

2. For intermediate-scale cloud travel the use of mean values for wind speed and eddy diffusivity yields dosage predictions which are almost as good as the use of power-law functions of height or other more complicated functions.

3. Under stable conditions, the aerosol cloud appears to follow the isentropic surface at which the aerosol is released.

4. A substantial increase in ground-level dosages may be obtained by release at altitudes near 100 feet because of the downdraft from the aircraft.

5. The maximum ground-level dosage attainable from one aerial line release is relatively independent of atmospheric stability and depends primarily upon release altitude and mean wind speed. The maximum dosage is approximately one half the source strength divided by the product of release altitude and mean wind speed. The distance at which the maximum occurs is highly variable for individual releases but is very dependent upon stability. Release altitudes below 250 feet are necessary under strong inversion conditions in order to reach a maximum within 15 miles or less. Under neutral and unstable conditions the maximum is reached within 2 miles for release altitudes up to 400 feet.

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## APPENDIX A

## L-23 Disseminator Efficiency

The Phase B trials provided an opportunity to obtain new estimates of the efficiency of the L-23 generator disseminating yellow FP. In six of the nine trials, the cloud of yellow FP released by the L-23 disseminator was bounded by the MF sampler array on the 300-ft ASG tower.

The efficiency calculation involves the determination of the particle flux per unit horizontal distance passing through a vertical plane which extends from the lower to the upper limit of the cloud. The assumption was made in this calculation that the recovery at a particular height reflects the mean flux within the height range from halfway to the sampler next below to halfway to the sampler next above. Then,

$$F = \Delta z \sum u_z \cdot D_z (\sin\theta)_z$$

where

F = flux per unit distance, particles/ft.

$\Delta z$  = vertical spacing of samplers; equals 5 feet except for Trial 5 where spacing was 10 feet.

u = wind speed, ft/min.

D = dosage, particle  $\cdot$  min/ft<sup>3</sup>; equal to number of particles recovered divided by flow rate of 0.212 ft<sup>3</sup>/min (6 l/min).

$\theta$  = angle between wind direction and dissemination line.

The value of F divided by the number of particles disseminated per foot provides a value of the efficiency of the dissemination system. These calculated values are shown in Table A-1. The table identifies the lot and carton number of FP used in each trial and shows the number of particles per gram for a sample of the material from each carton as determined in the laboratory at Metronics Associates, Inc. This value was then used to convert the source strength in grams per foot of line to particles per foot. This latter source strength value divided into the flux value gives the efficiency. The effective number of particles per gram using a particular carton of FP in the L-23 dissemination system is also shown in the table. This value may be calculated by multiplying the efficiency by the laboratory-determined number of particles per gram. Alternatively, the value may be determined from the trial data alone by dividing the flux value

by the source strength in gm per ft.

The flux value, and hence the efficiency and the number of recoverable particles, for Trial 9 may be subject to appreciable error since the wind direction crossed the dissemination line at about a 45° angle. At such an angle, and particularly at smaller angles, normal uncertainty with regard to the true wind direction at the time of cloud passage may lead to considerable error in the value of  $\sin \theta$  used. When  $\theta$  is near 90°, this error is negligible.

The median efficiency value, i.e. the mean of the two central values, is 66%. The median value of recoverable particles per gram is  $0.74 \times 10^{10}$  particles per gram. This value is quite close to the value of  $0.83 \times 10^{10}$  used in the analysis of these trials based on calibration trials for the L-23 disseminator run prior to the Phase A trials. Thus, while the variability in the recoverable particles values shown in Table A-1 is large--as it was in the calibration trials--the central values are in excellent agreement.

Table A-1

VALUES OF L-23 DISSEMINATOR EFFICIENCY OBTAINED DURING BW 502 PHASE B TRIALS 1-9

Trial	FP Ident. (Lot-carton)	Particles per Gram ( $\times 10^{10}$ )	Source Strength		Flux (particles per ft ( $\times 10^{10}$ ))	Efficiency	Recoverable Particles per gram ( $\times 10^{10}$ )
			( $\frac{\text{gram}}{\text{per ft}}$ )	(particles per ft ( $\times 10^{10}$ ))			
1	12-15	1.69	0.229	0.387	0.065	0.17	0.29
4	12-18	1.49	0.284	0.423	0.553	1.31	1.95
5	12-19	1.44	0.249	0.359	0.125	0.35	0.50
6	12-20	1.10	0.260	0.286	0.211	0.74	0.81
7	12-21	1.18	0.239	0.282	0.161	0.57	0.67
9	12-23	1.59	0.293	0.466	0.385	0.83	1.32

## APPENDIX B

## Rotorod Collection Efficiency

Rotorod samplers were placed adjacent to MF samplers at the upper three sampling levels on the three 100-ft towers at the 2, 6 and 10-mile sampling stations during those Phase B trials involving only FP. These paired values of FP recovery provide a basis for calculating the Rotorod collection efficiency under field conditions.

The reference dosage is obtained by dividing the MF recovery by the MF flow rate of 6  $\ell$ /min; the Rotorod dosage is obtained by dividing the Rotorod recovery by 41.3  $\ell$ /min, the volume of air swept out per minute by the Rotorod sampler. The ratio between the Rotorod dosage and the MF dosage is the Rotorod efficiency.

Considering only those ratios where the recoveries by both the MF and the Rotorod samplers exceeded 50, there are 54 ratio values available from Trials B-1 through B-9. There is a wide variability among these 54 values. However, as the trials progressed the values became more consistent; moreover, the median value for the later trials is in good agreement with values obtained from trials run by Metronics Associates specifically for the purpose of determining Rotorod efficiency.

There are 27 ratio values, i.e. efficiency values, which were obtained from Phase B trials through B-6. The median of these values is 1.03 and the middle 50% of the values lies within the range from 0.34 to 1.49.

The 27 values obtained from Trials B-7, B-8 and B-9 have a median value of 0.63 and a middle 50% range from 0.53 to 0.83. The median value is virtually the same as the value of 0.61 obtained by Metronics.

## APPENDIX C

Comparison of Sum of Recoveries by Sequentially-Operated Filters  
and the Recovery by a Single Total-Dosage Filter

Provision was made in the test plan for Phase B of the BW 502 trials for the operation of ten sequentially-operated filters for 15 minutes each adjacent to a filter operated to obtain total dosage at each of the ground-level positions at 2, 4, 6, 8 and 10 miles. During the first of the Phase B trials it became apparent that there was considerable uncertainty as to exactly what time period was covered by the operation of a particular sequentially-operated sampler. This uncertainty was partially eliminated in some of the later trials when the test officer included in his test report the serial number of the last filter that was sequentially operated at a particular station. However, this additional information created some doubt about the reported recovery values as a whole since this knowledge concerning exactly which filters had been exposed and which had not revealed that in some cases greater recoveries were being reported on unexposed filters than on those which had been operated. Thus, comparisons between the sum of sequential recoveries and the recovery from a single total-dosage filter can be made but without a great deal of confidence in the results.

Recovery values were reported for yellow FP on all nine trials and for green FP at ground level for Trials 7, 8 and 9. Thus, with five stations where comparisons were possible in each trial, there were potentially 60 pairs of values which might be compared. However, since comparison of small values might be misleading 26 pairs of values were not included because at least one of the reported values was less than 50 (in the case of the sequential samples, the sum is considered to be the value). Two other pairs of values were eliminated because of equipment malfunction and seven more because of suspected malfunction.

The ratios between the total dosage recovery and the sum of the sequentials for the 25 pairs of values considered ranged from 0.22 to 3.3 with the middle 50% lying in the range from 0.63 to 1.1. The median value was 0.85. The ratios would tend to be higher if the recovery obtained on a control filter operated prior to release was subtracted from each filter operated during cloud passage since there would be a single subtraction from the numerator of the ratio and a multiple subtraction from the denominator. However, although the median value might more nearly approach unity, the range of values would still be unduly large.