NOAA Technical Memorandum NWS ER-65

A PROCEDURE FOR SPRAYING SPRUCE BUDWORMS IN MAINE DURING STABLE WIND CONDITIONS

Scientific Services Division
Eastern Region Headquarters
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U.S. DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration / National Weather Service

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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
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A PROCEDURE FOR SPRAYING SPRUCE BUDWORMS IN MAINE DURING STABLE WIND CONDITIONS

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ABSTRACT. A technique is developed to forecast winds and apply them for spraying "in-wind" beyond the morning inversion period but before adverse thermal activity begins. Nomograms are constructed which determine drift distances of all drop size categories within the spray cloud for a given pressure gradient, wind to block direction component, and aircraft type. This gives an estimate of the proper offset of planned flight runs and of spray deposition.

1. INTRODUCTION

A sudden increase in spruce budworm population from 1971 to 1979 has posed an extremely serious threat to one of Maine's most valuable resources, its spruce and fir trees. These insects are most destructive in their larval stages, when they consume the needles of the trees. Repeated feedings cause the trees to die. The spraying strategy is simply to deposit a poisonous chemical on the needles during the feeding stages (normally a two-week span within the period between late May and mid-June).

During selected years since 1954, the spraying for spruce budworms in Maine was confined to the fair weather inversion periods of the daylight hours (usually between 5 and 8 a.m., and 6 and 8 p.m.). The very stable and calm wind conditions allowed for fairly accurate chemical deposition of spray droplets, especially those larger than 150 microns in diameter. However, by not trying to spray "in-wind", during those stable* hours beyond the morning inversion, available spray time was severely limited. This was especially true when the relatively short feeding period coincided with a string of early mornings plagued with fog and low clouds or when inversion frequency was well below normal. Also, it has been noted, many droplets smaller than 100 microns, at times, remained suspended throughout much of the inversion period, and had drifted far from the target area by the time the inversion had broken.

According to De Marrais, et al. (1968), aerosols released within 150 feet of the forest canopy with winds up to 12 mph, would not experience excessive scattering. The marked vertical mixing due to mechanical turbulence would "readily mix the spray cloud into the tree crowns." Winds, however, would cause drifting of the spray. This paper describes a technique to forecast drift level winds and determines the spray drift so flight lines may be offset properly.

*Spraying when the atmosphere is neutral or unstable subjects the spray to adverse thermal activity causing unacceptable deposition.

2. DRIFT WIND LEVELS

Wind forecasts are applied to two levels between the release height and tree tops.

The first level, level 1, is halfway between the aircraft and the bottom of the downward propeller and wing tip vortex system. According to Jones (1970), photographs of spray clouds show that spray droplets are quickly swept into this vortex system and sink at a relatively rapid rate. The descent stops when the centers of the individual vortices within the system reach to about 1/2 wing span above the surface. See Figure 1.

The second level, level 2, is halfway between the bottom of the vortex system and the tree tops.

Therefore: $$\text{Level 1} = h + \frac{b}{2} + \frac{(H-\frac{b}{2})}{2} = h + \frac{H}{2} + \frac{b}{4} \text{ (AGL)*} \qquad (1)$$

*Above Ground Level

and $$\text{Level 2} = h + \frac{b}{4} \text{ (AGL)} \qquad (2)$$

where: h = effective height of tree canopy

H = flight altitude above tree canopy

b = wing span of aircraft

The development described is for C54 aircraft using SEVIN 4 oil. This was the combination for about 80% of the spraying in Maine in 1979 (a 3-million-acre project). The same procedure is followed to prepare working models for the other aircraft (and SEVIN 4 oil) used in Maine budworm spraying. The recommended flight altitudes are 150 feet above the tree tops during crosswind component situations (winds blowing within 45 degrees of perpendicular to the preplanned flight lines) and 250 feet above the trees during "along-wind" periods (winds within 45 degrees of parallel to the flight lines). The 100-foot increase in altitude for along-wind conditions results in a corresponding increase of horizontal deposition. This compensates for the lack of swath coverage observed during inversions with planes operating at 150 feet above the trees.

The average tree height was assumed to be 70 feet, and the wing span for C54 is 114 feet. So, for C54 operations, solving equations (1) and (2):

During crosswind periods (subscript C):

Level $1_C \sim 175$ feet AGL

and Level $2_C \sim 100$ feet AGL

During along-wind periods (subscript A):

Level $1_A \sim 225$ feet AGL

and Level 2_A = Level $2_C \sim 100$ feet AGL

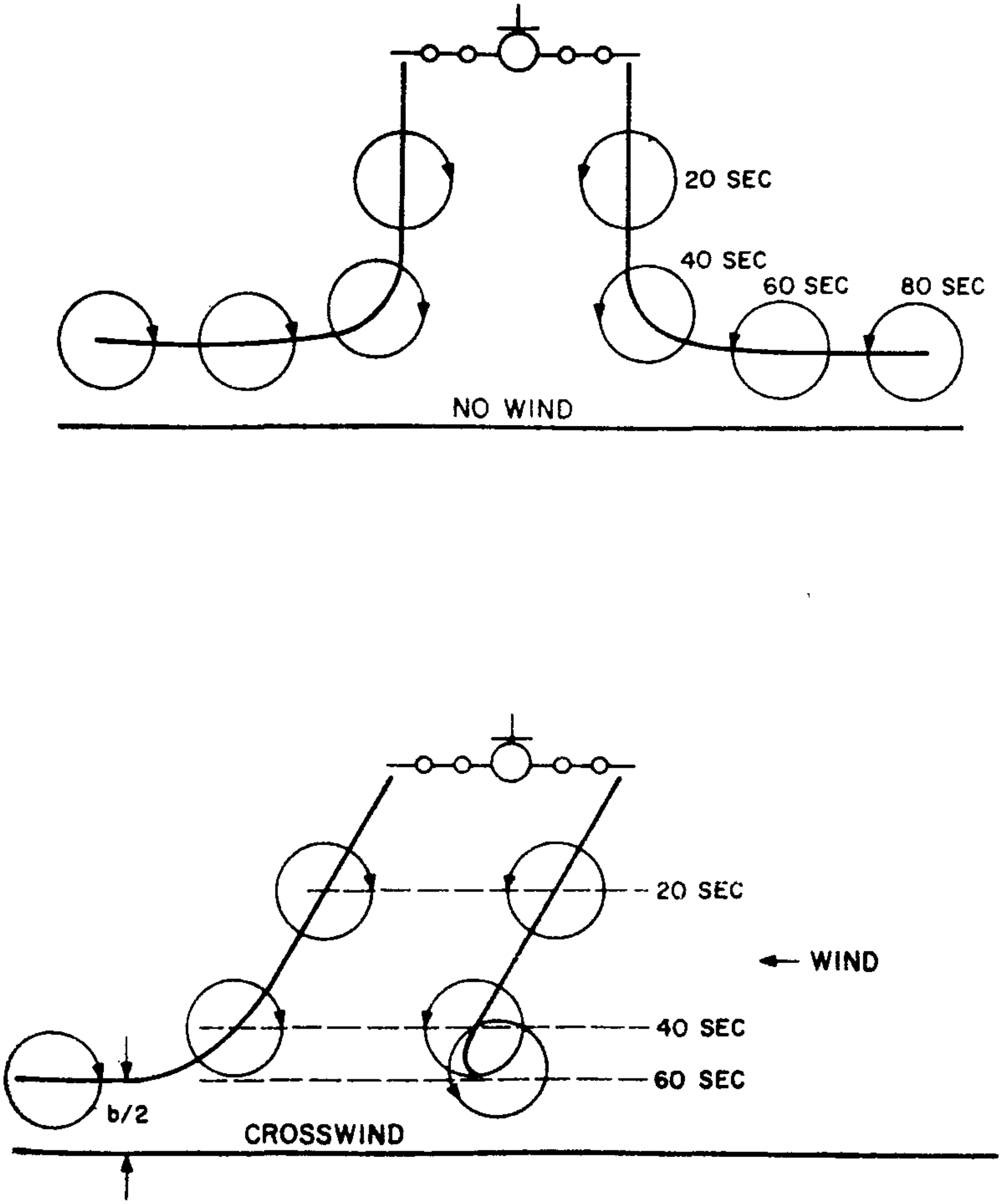


Figure 1. Descent and spreading of wing-tip vorticies from the aircraft in still air and in a light crosswind. The symbol b stands for aircraft wingspan. (From Boyle,Barry et al 1975)

3. GEOSTROPHIC WIND

It was determined that wind forecasts should be expressed as a percentage of the geostrophic wind. Individual anemometer site readings not only pose the problems of localized effects, but also do not normally give average wind conditions for large enough areas (the average spray block in Maine, in 1979, was about 30,000 acres). Furthermore, a better average of wind variation with time can be determined. (This is also true for wind components within the National Fire Danger Rating System.)

The pressure gradient (PG), can be expressed by:

$$PG = \frac{\Delta p}{L}$$

where Δp is the pressure difference in millibars between 2 points, one on each side of the spray area on an axis normal to the general wind flow, and, L is the distance between the two points in degrees latitude. These values can be readily determined from carefully analyzed weather maps using any map scale. Conversion of pressure gradient in these units to geostrophic wind (Vg) in miles per hour is shown in the first columns of Table 1. These values were developed using the graphical aids by N. A. Riley and presented by Byers (1937).

Table 1

		50% (Vg) $V1_C$		43% (Vg) $V2_A$		53% (Vg) $V1_A$	
Mb/Deg Lat	Vg(MPH)	MPH	Ft./Sec.	MPH	Ft./Sec.	MPH	Ft./Sec.
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.1	1.1	0.6	1.3	0.5	0.7	0.6	0.9
0.2	3.6	1.7	2.8	1.5	2.1	1.8	2.6
0.3	5.0	2.5	3.7	2.2	3.2	2.6	3.9
0.4	6.7	3.4	5.0	2.9	4.2	3.6	5.2
0.5	8.4	4.2	6.2	3.6	5.2	4.4	6.5
0.6	10.1	5.1	7.4	4.3	6.4	5.3	7.9
0.7	11.8	5.9	8.7	5.1	7.5	6.2	9.2
0.8	13.4	6.7	9.9	5.8	8.5	7.1	10.4
0.9	15.1	7.6	11.2	6.5	9.5	8.0	11.8
1.0	16.8	8.4	12.4	7.2	10.6	8.9	13.1
1.1	18.5	9.3	13.6	8.0	11.7	9.8	14.4
1.2	20.1	10.1	14.8	8.6	12.7	10.6	15.7
1.3	21.8	10.9	16.0	9.4	13.8	11.5	17.0
1.4	23.5	11.8	17.3	10.1	14.9	12.5	18.3
1.5	25.2	12.6	18.5	10.8	15.9	13.4	19.6
1.6	26.8	13.4	19.7	11.5	16.9	14.2	20.9
1.7	28.5	14.3	21.0	12.3	18.0	15.1	22.2
1.8	30.2	15.1	22.2	13.0	19.1	16.0	23.5
1.9	31.9	16.0	23.5	18.7	20.1	16.9	24.9
2.0	33.6	16.8	24.7	14.5	21.2	17.8	26.2

Conversion of pressure gradient (P.G.) to geostrophic wind (MPH) and to drift level winds (MPH) and Ft./Sec.).

4. DRIFT LEVEL WINDS

A generally accepted way to express the variation of wind speed with height is the general power law (as presented by Touma (1977):

$$\frac{V_u}{V_L} = \left(\frac{Z_u}{Z_L}\right)^p \qquad (3)$$

where: V_u = wind speed at upper level Z_u

V_L = wind speed at lower level Z_L

P = expotential parameter ($0 \leq P \leq 1$)

According to Touma the values of P for hilly terrain similar to Northern Maine at various stability classes (as defined by Pasquill, 1961) are shown in Table 2.

Table 2

Stability Class	P
A Very unstable	.109
B Moderately unstable	.085
C Slightly unstable	.078
D Neutral	.116
E Slightly stable	.261
F Moderately stable	.426
G Very stable	.516

Values of P for stability classes from Michigan data 1975-1976 by Touma.

By assuming 2500 feet (AGL) is about the level of the geostrophic wind, Vg, (Pettersen 1958), we can find an expression for the winds at the various lower levels. Substituting equation (3) for the C54 operation:

$$V1_C = \frac{Vg}{(14.3)^p} \text{ at 175 feet AGL} \qquad (4)$$

$$V2_{(C*A)} = \frac{Vg}{(25)^p} \text{ at 100 feet AGL} \qquad (5)$$

$$V1_A = \frac{Vg}{(11.1)^p} \text{ at 225 feet AGL} \qquad (6)$$

where: $V1_C$ = wind at level 1_C

$V2_{(C*A)}$ = wind at level 2 (C or A)

$V1_A$ = wind at level 1_A

In Northern Maine, during the spray season, stability class E (p = .261) best describes the conditions beyond the morning inversion period and before adverse thermal activity takes place.

Solving equations 4, 5, and 6 using p = .261 we get:

$$V1_C = 50\%\ Vg$$

$$V2_{(C*A)} = 43\%$$

$$V1_A = 53\%\ Vg$$

These percentages were used to complete the last columns of Table 1.

Note: Since all spray aircraft are assigned the same flight altitudes, the percent of geostrophic wind used at the other aircraft drift levels was the same as the C54 operation. Separate computations were considered unnecessary when also considering the state of the art and the degree of accuracy associated with some of the basic assumptions.

5. DRIFT DISTANCES

In a dispersion model developed by Cramer, et al., and described by Dumbald, Rafferty and Cramer (1976), the axis of the spray cloud is assumed to intersect the ground at a downwind distance, D, proportional to the product of the effective release height, Z, and the mean cloud transport wind, V, divided by the settling velocity, K. Therefore:

$$D = \frac{Z\overline{V}}{K} \qquad (7)$$

We substitute the vertical fall distance for Z for each of the two settling systems between the aircraft height and the tree tops and get an expression for the drift distance of each system. Adding the two distances gives the total drift.

A. Drift of the Vortex System

That portion of the total drift covered during the descent of the vortex system can be expressed (from equation 7) by:

$$D1 = \frac{\left(H - \frac{b}{2}\right)}{R} V1 \qquad (8)$$

where H is aircraft height above trees
b is wing span of aircraft
V1 is average wind speed of this system
R is sink rate of the vortex system

For C54 operation from equation 8:

$$D1_C = \frac{93V1_C}{R} \qquad (H = 150\text{ ft. } b = 114\text{ ft. ...crosswind}) \qquad (9)$$

and

$$D1_A = \frac{193\ V1_A}{R} \qquad \text{(H = 250 ft. b = 114 ft. ...along wind)} \qquad (10)$$

Jones, after Prandtl and Tietjens (1934) estimate R, the sink rate as:

$$R = \frac{8gW}{\pi^3 \rho b^2 S} \qquad (11)$$

where: g = gravitational acceleration (9.8 m/sec.^{2})
W = weight of aircraft (grams)
ρ = air density (1207.4 gm/m^3)
S = aircraft speed (m/sec.)
b = wing span (meters)

Table 3 shows the specifications of the various aircraft used for the Maine spraying operations.

Table 3

AIRCRAFT WEIGHT (W), WING SPAN (b), SINK RATE (R), SPEED (S) AND SWATH (SW)

Aircraft	W (grams)	b (meters)	S (m/sec.)	R* (m/sec.)	SW (meters)
C54	2.163604×10^7	34.62	80.46	.47	366
PV-2	1.121832×10	23.77	80.46	.56	183
TBM	6.824638×10^6	16.46	73.76	.72	122

(*solving Eq. 11)

For C54, from equation (11):

R = .47 m/sec. or 1.55 ft./sec.

and the drift distance of the vortex system in feet--for crosswind period is:

$D1_C = 60\ (V1_C)$ (when $V1_C$ is in ft./sec.)

and for along-wind periods:

$D1_A = 125\ (V1_A)$

(from 9 and 10, respectively)

B. Drift of the Lower System

That portion of the drift distance covered between the bottom of the vortex system and the tree tops can be expressed by:

$$D2 = \frac{\frac{b}{2}\ (V2)}{G_i} \qquad (12)$$

where b = wing span
V2 = average wind of this stratum
G_i = gravitational settling velocity of each drop size category

In a dispersion model developed by Dumbald and Bjorklin (1977), values of gravitational settling velocities, G_i, and fraction of total source, F_i, for 13 to 15 drop size categories were estimated for the various aircraft (with SEVIN 4 oil) used in Maine. These are shown in Table 4.

The term $\left(\frac{\frac{b}{2}}{G_i}\right)$ in equation 12 is the time it takes for each drop size category to descend through the lower system. This is referred to as τ_i in Table 4.* It is in seconds when G_i is in ft./sec., b is in feet, and V2 is in ft./sec. Then: $D2 = \tau_i \, V2$

Table 4

Drop Size Category i	C54				PV-2				TBM				Drop Size Category i
	$\overline{u}$	G_i	F_i	τ_i	$\overline{u}$	G_i	F_i	τ_i	$\overline{u}$	G_i	F_i	τ_i	
1	231	2.709	.008	21	277	3.16	.016	12	221	2.50	.02	11	1
2	220	2.567	.006	22	252	2.86	.009	14	178	1.86	.03	15	2
3	207	2.412	.010	23	231	2.61	.010	15	152	1.54	.05	18	3
4	194	2.211	.010	25	220	2.48	.022	16	139	1.28	.10	21	4
5	180	1.977	.035	28	207	2.33	.048	17	123	1.05	.10	26	5
6	166	1.742	.075	32	194	2.12	.051	18	112	.90	.10	30	6
7	151	1.521	.113	38	180	1.90	.093	21	99	.77	.20	35	7
8	135	1.277	.165	45	166	1.67	.084	23	86	.66	.10	41	8
9	117	1.010	.176	57	152	1.46	.121	27	77	.57	.10	47	9
10	93	.789	.204	72	135	1.22	.170	32	66	.42	.10	64	10
11	76	.591	.153	96	117	.97	.131	40	55	.29	.05	93	11
12	51	.257	.040	222	98	.76	.126	51	46	.20	.03	135	12
13	21	.046	.005	1239	77	.57	.084	68	31	.10	.02	270	13
14					51	.25	.035	156					
15					30	.10	.001	390					

where:

$\overline{u}$ is mean drop diameter in each i^{th} category (um)

G_i is gravitational settling velocity in each i^{th} category (ft./sec.)

F_i is fraction of total source in each i^{th} category

τ_i is time of suspension of each i^{th} category

C. Total Drift

Adding the drift of the vortex system (found in a) to the lower system (found in b) gives the total drift. For C54 operation:

$$D_C = D1_C + D2 = 60 \, V1_C + \tau_i \, V2 \text{ (crosswind)}$$

*These τ_i values are in good agreement with computations by Van Liere and Barry (1973) for particles of specific gravity 1.0 falling 50 feet in still air at an air temperature of 23 degrees celsius.

and

$$D_A = D1_A + D2 = 125\ V1_A + \tau_i\ V2 \text{ (along-wind)}$$

and since: $V1_C = .50\ Vg$; $V1_A = .53\ Vg$ and $V2 = .43\ Vg$, then:

$$V2 = .86\ V1_C = .81\ V1_A$$

For C54:

$$D_C = V1_C\ (60 + .86\ \tau_i) \text{ ...total crosswind drift...} \tag{13}$$

$$D_A = V1_A\ (125 + .81\ \tau_i) \text{ ...total along-wind draft...} \tag{14}$$

For PV2:

$$D_C = V1_C\ (61 + .86\ \tau_i) \tag{15}$$

$$D_A = V1_A\ (115 + .81\ \tau_i) \tag{16}$$

For TBM:

$$D_C = V1_C\ (52 + .86\ \tau_i) \tag{17}$$

$$D_A = V1_A\ (94 + .81\ \tau_i) \tag{18}$$

Solving equations 13 through 18 using the data in Table 4, 2 nomograms are constructed for each aircraft (Figures 2, 3, 4, 5, 6, and 7) that show drift distances of each drop size category for crosswind and along-wind components as a function of pressure gradient (and corresponding $V1_C$, $V1_A$ combination). Although these nomograms are based on the mathematical models of Dumbald and Bjorklund, the C54 charts are in good agreement with the observed data of Boyle, Barry, et al. (1975) using the similar DC-7B aircraft.

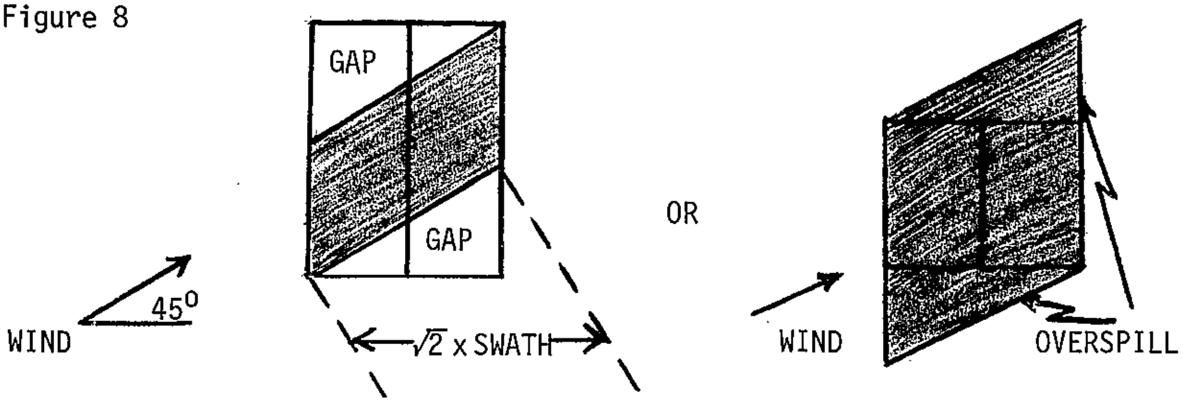
6. OFFSET PROCEDURE

With a given pressure gradient and wind to block component, an estimate of the downwind distance of each drop size category can be determined from either of the two nomograms of each aircraft. The offset is applied to the preplanned flight lines to determine the actual flight. Normally for crosswind periods, the offset distances will correspond to the center lines shown on the nomograms of Figures 2, 4, and 6. These are 1/2 swath width downwind of the largest diameter drop size category.

Each end point of a preplanned flight line is offset into the wind at the indicated distance. The variation of spray deposition across the entire swath is also indicated (including the degree of overlap or spillage into unplanned areas). The maximum deposition category (maximum F_i) is the heavy line on each crosswind nomogram. The deposition spectrum across the swath lies between the front edge and end lines. The dashed lines on the crosswind charts are $\frac{\sqrt{2}}{2}$ x swath and $\sqrt{2}$ x swath downwind from the front edge line.

These represent the center and end lines of the spectrum of deposition across the swath when winds are at a 45-degree angle to the spray block. Offset distances for winds intersecting the blocks between 90 and 45 degrees can be interpolated between these two center lines. Of course, when winds are at 45 degrees to the block, gaps in coverage, as well as overspillage must be realized, as shown in Figure 8.

Figure 8



These situations may require rescheduling or reassignment of operations.

The crosswind nomograms can also indicate a deficiency of deposition if winds are too light. For instance, if drop sizes of less than 50 microns are regarded as ineffective, wind speeds at the drift level of at least 4 1/2 mph would be needed to cover the entire block with the desirable deposition (if C54's are operating while winds are crossing the blocks at a 90-degree angle).

The offset for along wind spraying would correspond to the distance of the first (largest) size category when the blocks are downwind, and to the smallest effect size category when the blocks are upwind. To offset the shutoff points in these cases, the distances would be reverse, i.e., the smallest category for downwind flight runs and the largest for upwind runs. The path of the aircraft during along wind periods would be on the same lines of the preplanned lines, putting the maximum deposition through the center of the blocks.

7. SUMMARY AND CONCLUSION

Since 1954, spraying for spruce budworms in Maine was confined to the fair weather inversion periods of the daylight hours. This often severely limited the time available for spraying so a procedure is developed whereby spraying might continue during the stable hours beyond the morning inversion. It allows for spraying in-wind by determining spray drift and, therefore, proper offsetting of flight lines.

To compute the total spray drift, the drift of two layers between the aircraft and tree tops are tallied. The upper layer covers the vertical distance of the downward propeller and wing tip vortex system. The lower part comprises the remaining space to the tree tops and has been shown to be equal to about 1/2 wing span in size.

The top of the upper level, the aircraft altitude, is dependent upon the wind to block directional component. During crosswind periods aircraft are assigned an altitude of 150 feet above the tree tops. During along-wind periods, 250 feet above the trees is the recommended altitude. The winds at the midpoint of each segment (drift level winds) are developed from pressure gradient and the corresponding percentages of geostrophic wind.

The drift of the upper segment is a function of:

1. Its vertical distance
2. Its drift level wind, and
3. The reciprocal of the sink rate of the vortex system.

The drift of the lower segment is a function of:

1. Its vertical distance (1/2 wing span in size)
2. Its drift level wind, and
3. The reciprocal of the gravitational settling velocity of each drop size category within the spray cloud.

This results in a pattern of spray deposition in which smaller droplets are carried farther downwind than larger ones.

Using nomograms, for a given aircraft, wind to block component, and pressure gradient, one can readily obtain the drift distances of all drop size categories and, therefore, an estimate of spray deposition and proper offset.

ACKNOWLEDGMENTS

I would like to thank Joe Rogash and Art Francis for their assistance in the computations solving the drift distance formulas.

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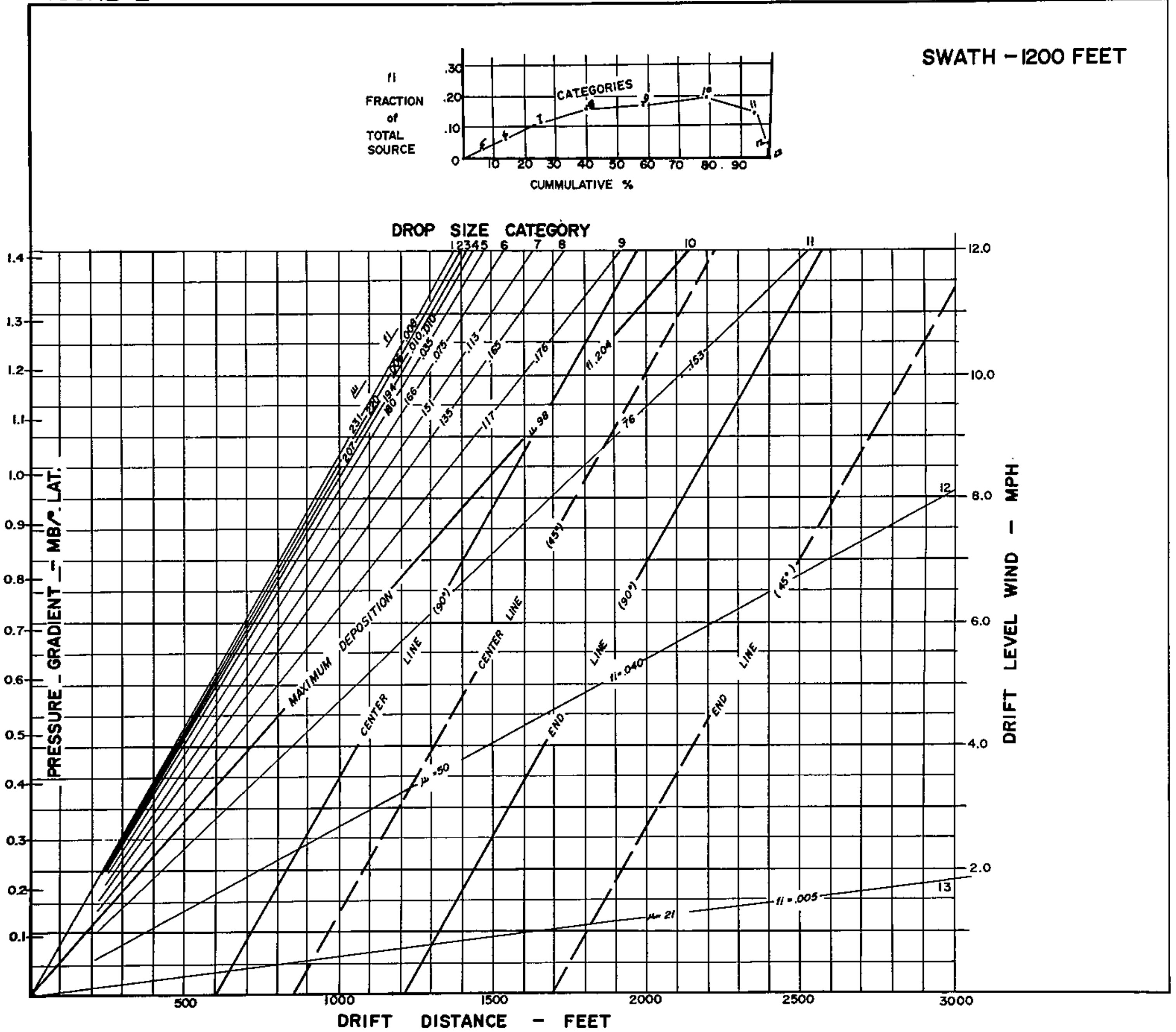
C54 - CROSSWIND

FIGURE 2



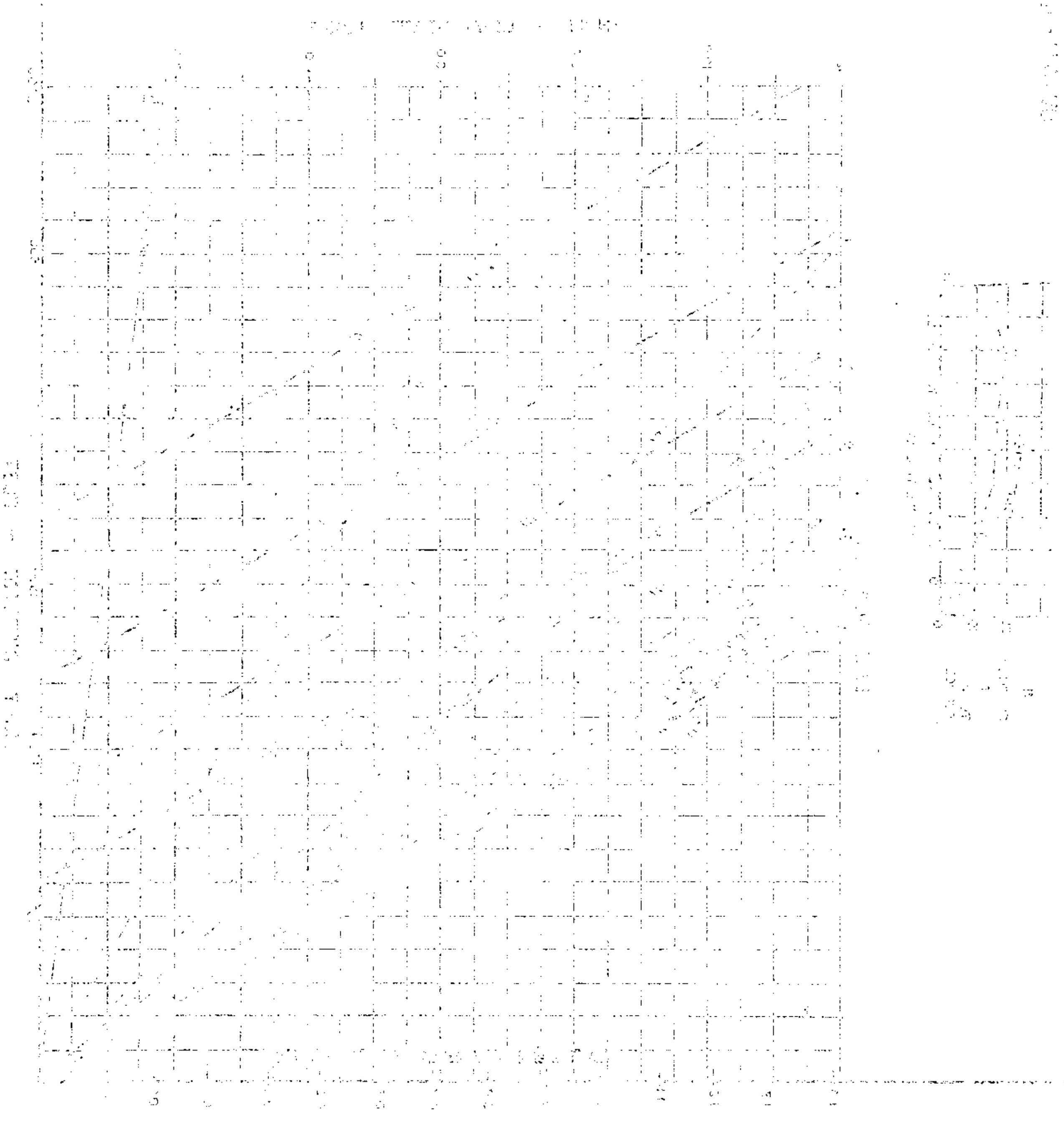
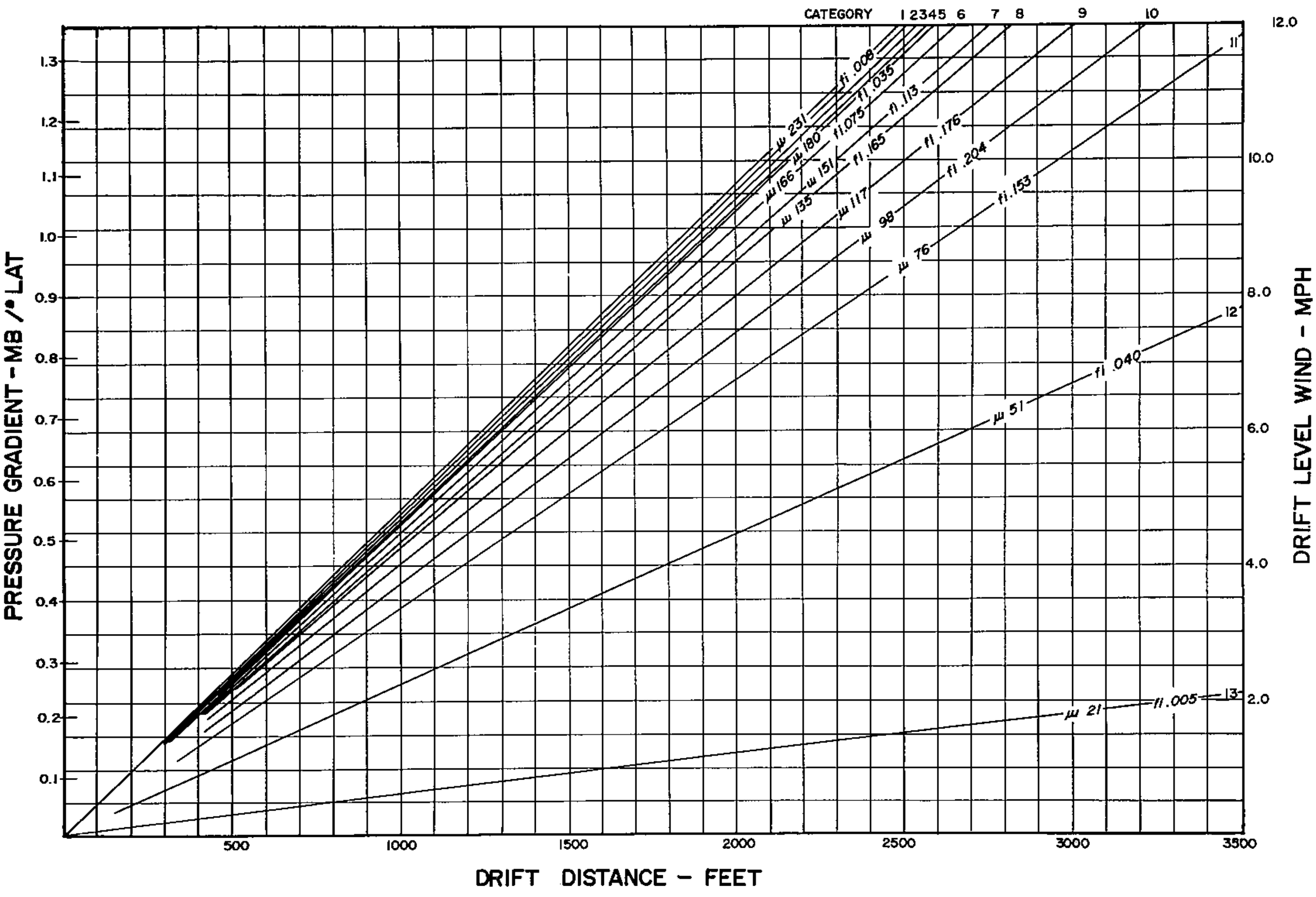


FIGURE 3

C54 ALONG WIND



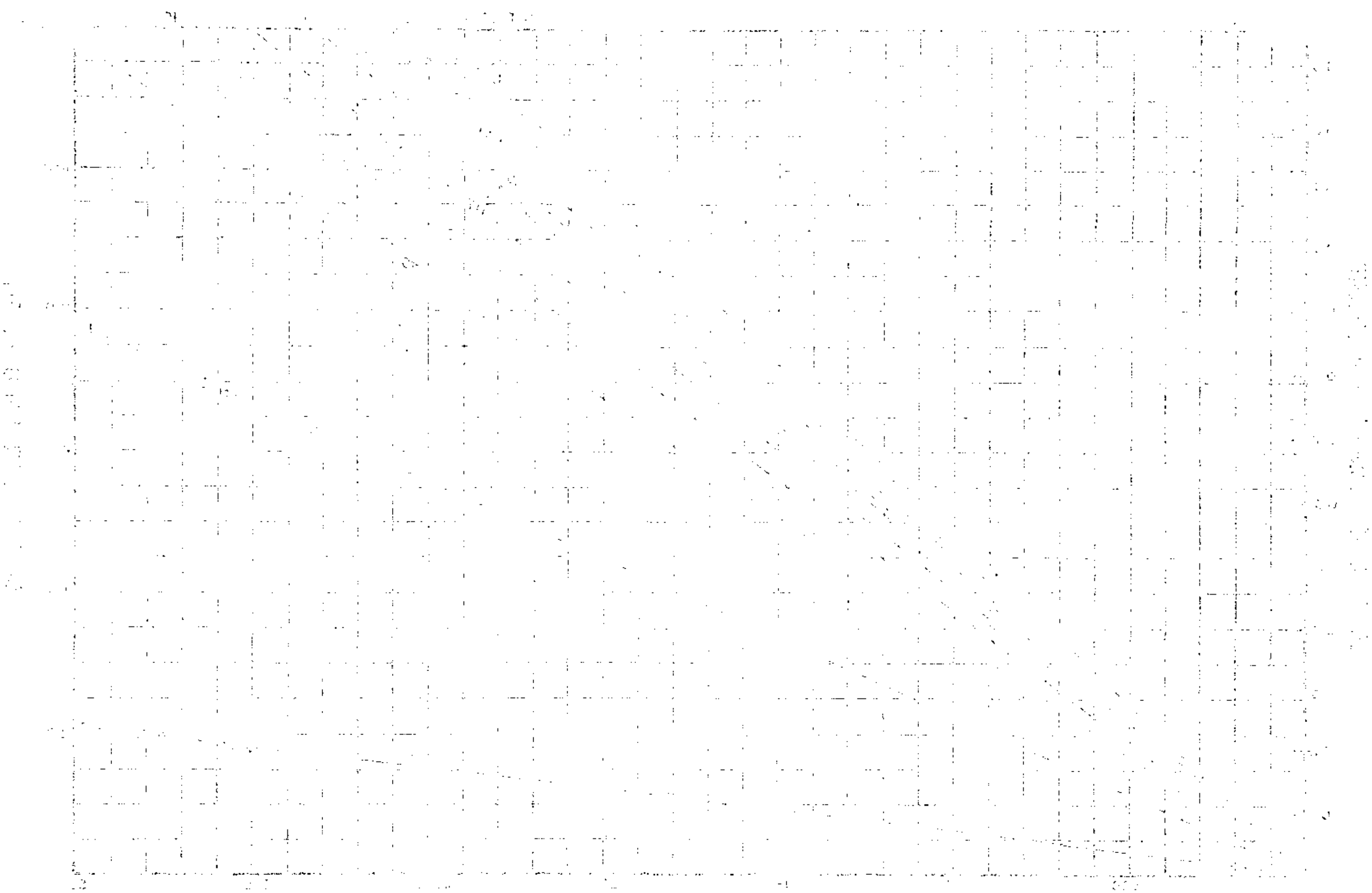
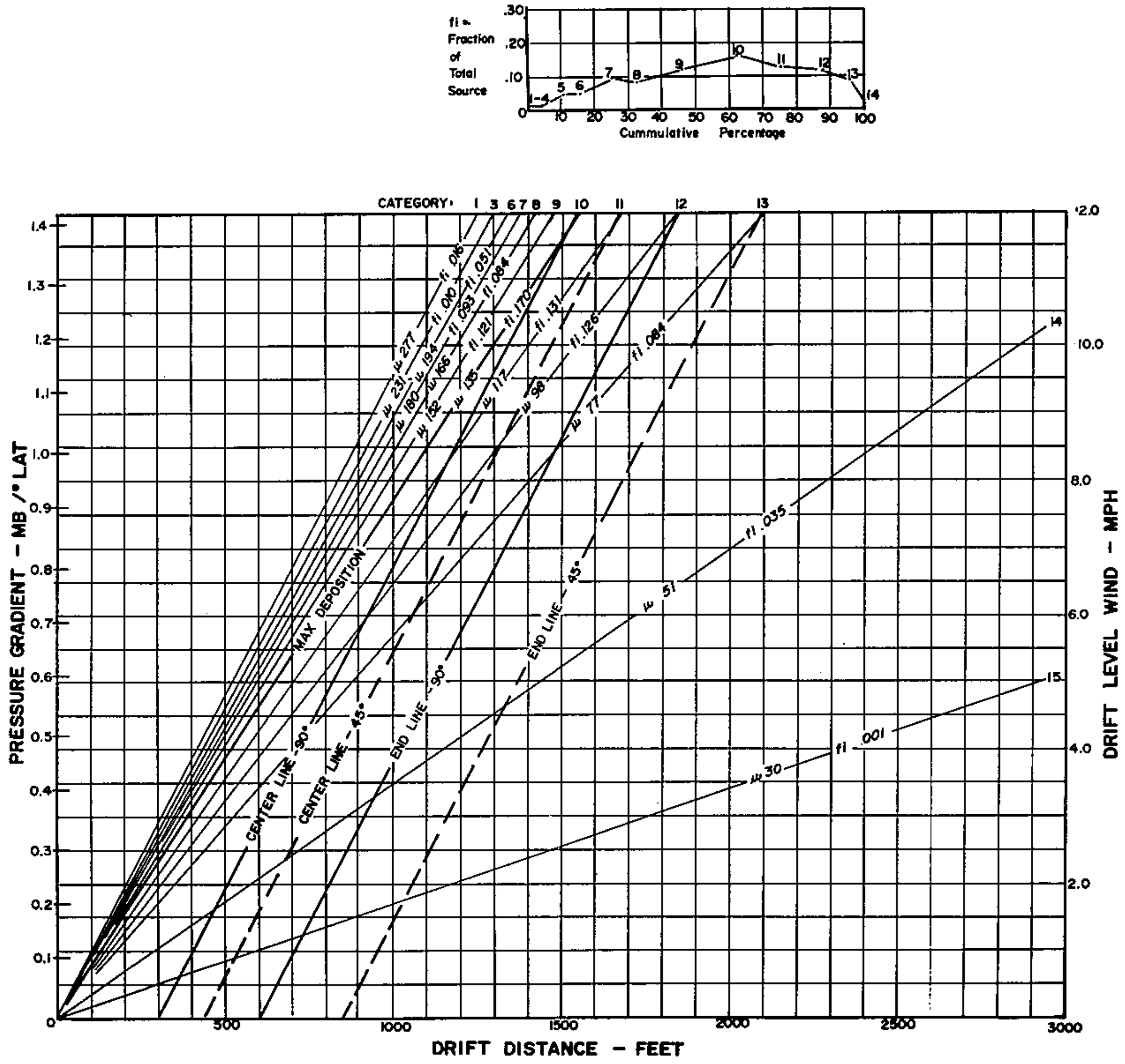


FIGURE 4 **PV-2 CROSSWIND** **600 FOOT SWATH**



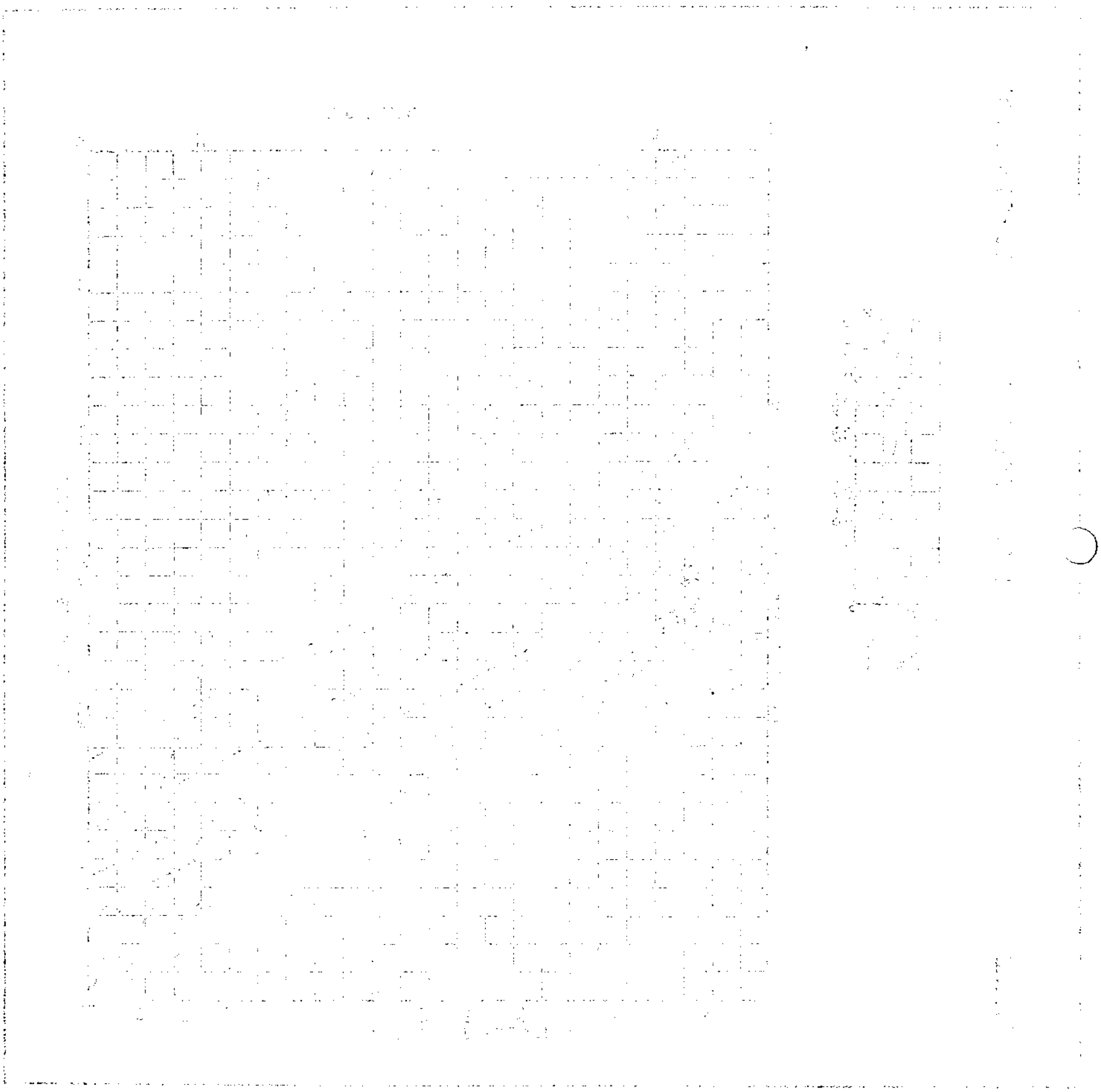


FIGURE 5

PV2 ALONG WIND

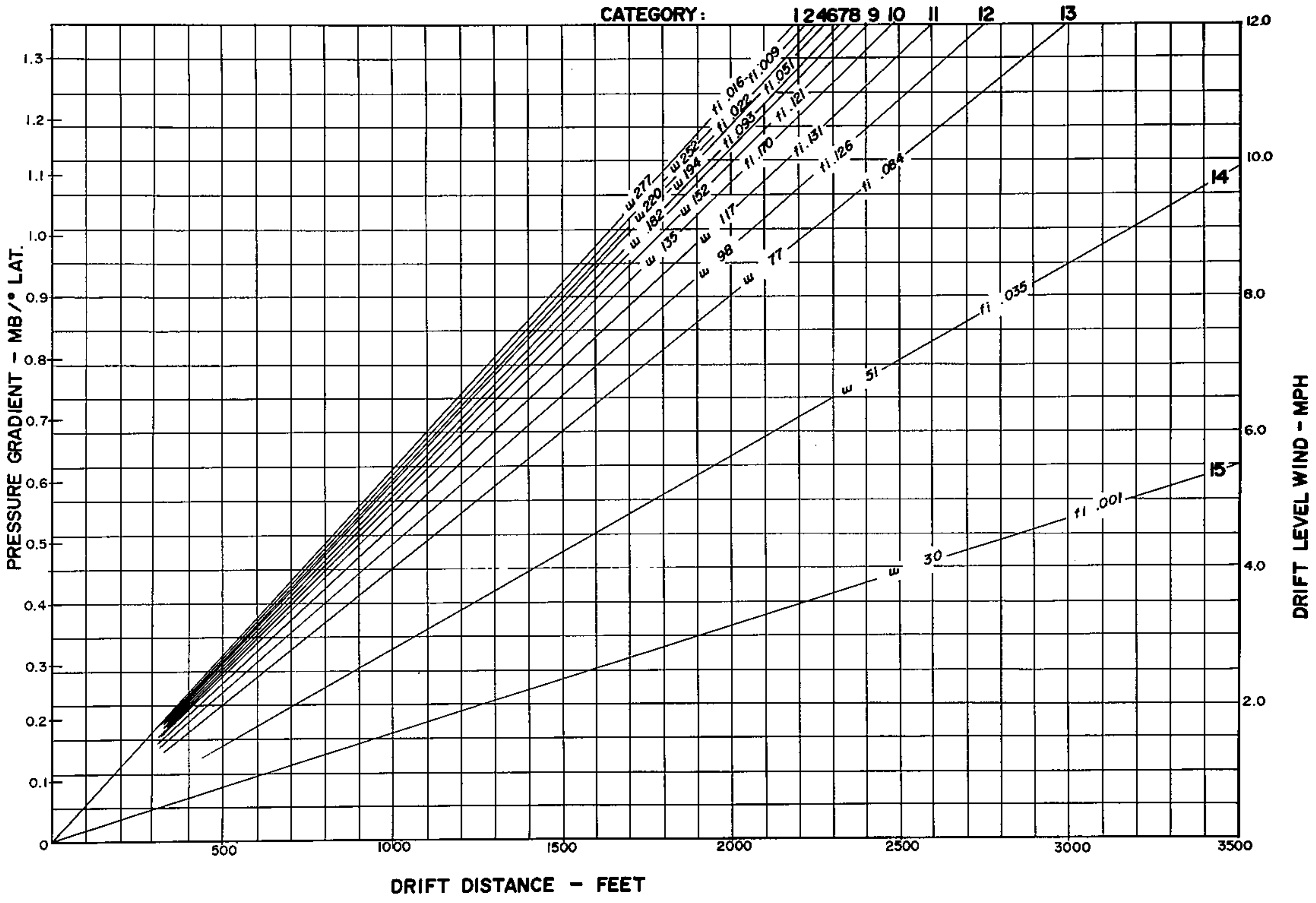
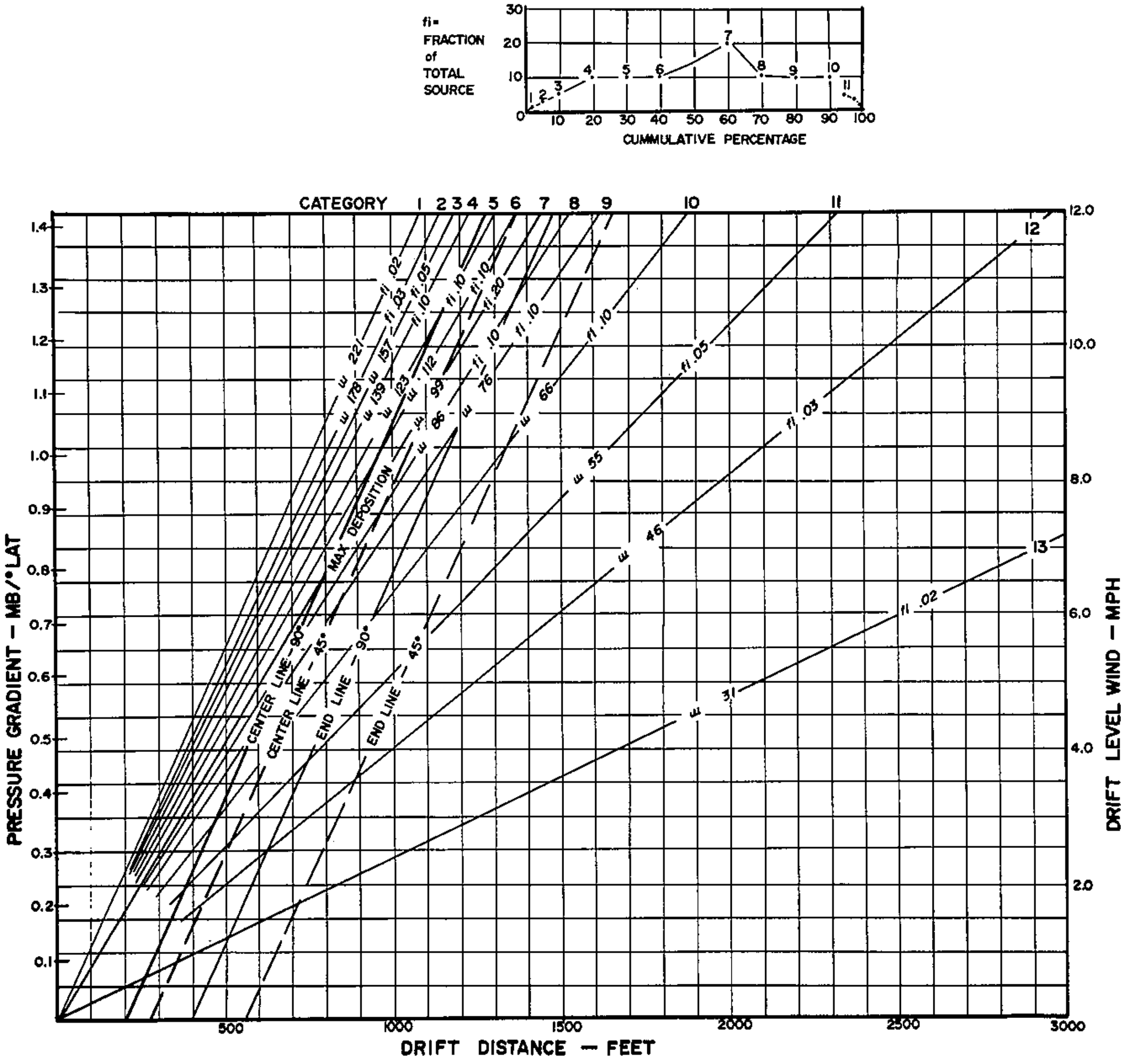


FIGURE 6 **TBM CROSSWIND** **400 FOOT SWATH**



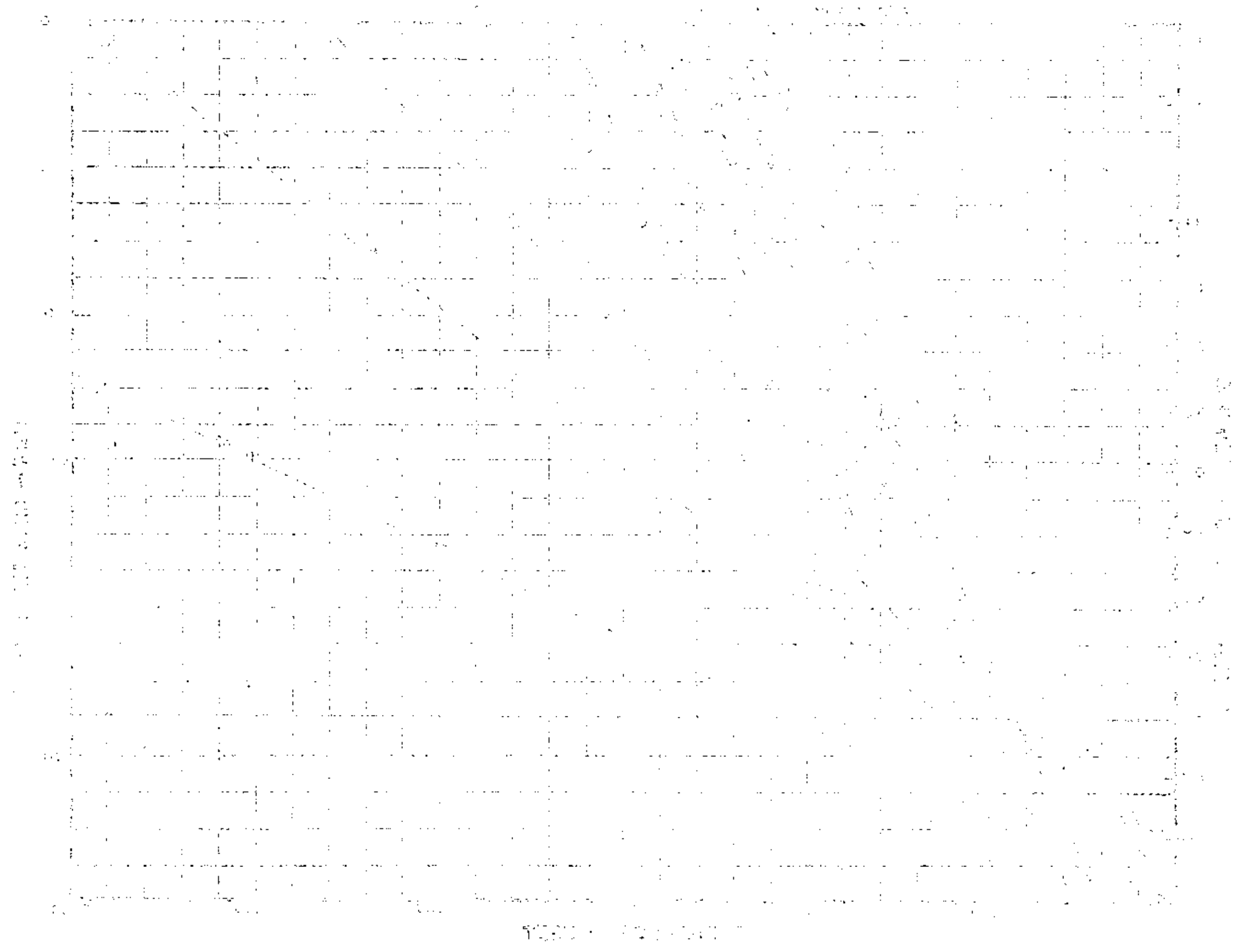


FIGURE 7

TBM ALONG WIND