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A Procedure for Estimating Downwind Deposition of Small Spray Droplets

by

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AIR PROVING GROUND CENTER

AIR FORCE SYSTEMS COMMAND • UNITED STATES AIR FORCE

EGLIN AIR FORCE BASE, FLORIDA

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FOREWORD

This report was prompted by some of the uncertainties arising during the 1964 field tests of APGC Projects 2525W3 and 5957W1 at the Air Proving Ground Center, Eglin Air Force Base, Florida. The report has been reviewed and approved by the 4th Weather Group Technical Services.

This technical report has been reviewed and is approved.

J. E. ROBERTS
Major General, USAF
Commander

ABSTRACT

A procedure is described for estimating the amount and the extent of downwind deposition of liquid spray droplets in the 10-200 micron diameter range in terms of mass per area. The approach is based on Stokes' Law and an assumed drop-size distribution. A sample solution of a practical problem follows the theoretical discussion.

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ILLUSTRATIONS AND TABLE

SECTION I

INTRODUCTION

Recent development tests of aerial spray systems at Eglin Air Force Base, Florida, have stimulated interest concerning downwind deposition of liquid spray droplets. This report describes a rough and rapid procedure for estimating the amount and the extent of deposition of droplets in the 10-200 micron diameter range in terms of mass per area. An application of the procedure to a practical problem follows the qualitative discussion.

Since, in view of the drop-size range, classical atmospheric diffusion theories do not quite apply here, horizontal and vertical motions other than gravity-induced fall and the horizontal wind have not been considered explicitly. This would reduce the applicability of the procedure to stable or near neutral atmospheric stability conditions. However, in an unstable atmosphere the relatively large vertical motions often decrease or reverse the fall velocities of droplets, thus stretching the deposition distances considerably. For a finite amount of released spray, an increase in the affected area then reduces the amount of deposited mass per area.

Although aerial dissemination of spray creates an elevated line source, a finite length line appears approximating a point when viewed from a sufficient distance downwind. In practical terms, a release of one-half mile or less in length from a distance of ten miles or more, for instance, may be considered a point source[1*]. In this case it is immaterial whether the release has been made normal or parallel to the wind. However, the procedure described in this report should be applied with reservations for shorter downwind distances, since the source would then have finite dimensions.

It is beyond the scope of this report to consider quantitatively such factors as surface roughness, temperature variations, and possible evaporation, which could vary the amount and the extent of deposition. For the present, the assumed conditions are:

1. A smooth surface.

2. Air temperature 70°F.

3. No evaporation.

*Small superscripts refer to References, page 16.

It should be noted that a rough surface increases turbulence and the diffusive processes. Thus in terms of the area involved, the first assumption is probably conservative. Since most spraying operations are conducted at low altitudes and during the relatively warm growing season, and the properties of fluids used for spraying usually inhibit any appreciable evaporation, the last two assumptions appear sufficiently reasonable.

Other simplifying assumptions that have been made are discussed in the text. Constants appearing in various equations generally include units of measurement, thus accounting for the apparent discrepancy in dimensional analysis.

SECTION II

DOWNWIND TRAVEL DISTANCE OF DROPLETS

Primarily, downwind travel distance of small particles is a function of wind speed, release altitude, and particle size and density. Particles with diameter larger than 5000 μ fall with increasing velocity, particles in the range of 0.1 -5000 μ diameter settle with constant velocity, while particles less than 0.1 μ in diameter behave like gas molecules (Brownian motion)[2]. Stokes' Law states

$$W = 3.0046 \times 10^{-3} \rho D^2$$

where

W is the fall velocity in cm/sec

ρ is the density of the particle in g/cm^3

D is the diameter of the praticle in microns.

It is generally applicable to spherical particles in the 1-200 μ diameter range. However, the fall velocities for particles with 1-10 μ diameter (aerosol-size) are sufficiently small to be often negligible.

The region of interest here, then, is the 10-200 μ diameter range; droplets larger than 200 μ settle rather rapidly, while droplets smaller than 10 μ remain, for most practical purposes, suspended in the air for a period in the order of days and weeks.

Assuming that the only forces acting upon the spray droplets are gravity and horizontal wind, and applying Stokes' Law, then by the geometry of motions and distances

$$X = \frac{33.28\ ZU}{SD^2} \qquad (1)$$

where

X is the downwind travel distance in kilometers

Z is the release altitude in meters

U is the mean wind speed from surface to Z in meters per second

S is the specific gravity of the droplet

D is the droplet diameter in microns.

For simplicity, specific gravity has been substituted for density in Eq. (1) and in subsequent equations. The dimensions of density are absorbed in the constant of the equation.

SECTION III

DROP SIZE AND MASS DISTRIBUTION

To find downwind deposition amounts, information concerning the drop-size distribution in terms of mass is needed. A measure commonly used in drop-size sampling is the mass median diameter, MMD; fifty percent of the spray mass is in drop sizes above the MMD and fifty percent below.

Experimental evidence from previous spray tests [3,4,5] indicates that it is appropriate to choose 200 μ as the representative MMD for the investigation of the drop-size distribution. Drops with diameter larger than MMD are not of particular interest here, since their fallout generally occurs within a mile from the area of release. It is the distribution of droplets smaller than MMD that is important for the calculation of downwind deposition. For droplets between 50 μ diameter and the 200 μ MMD, distribution of spray mass approximates the normal distribution. Because of paucity of data, the distribution of spray droplets in the 10-50 μ diameter range is rather uncertain. However, extrapolation of the mass distribution curve leads to the inference that the distribution of droplets with diameter 10-200 μ approximates the one-tailed normal distribution function, and that the mass of droplets less than 10 μ in diameter is 0.1% of the total mass.

Making these assumptions, Figure 1 shows the normal distribution of 49.9% of the mass for droplets in the 10-200 μ diameter range, in terms of cumulative percent of spray mass. The percentage of mass within any drop size interval can be determined directly from Figure 1, or it could be computed by using standard tables for normal distribution (for example, Ref. 6).

The percentage $_aP_b$ of total released mass M for 10 μ intervals is shown in Column (B) of Table 1. The symbol $_aP_b$ refers to the percentage of the area lying under the normal curve and bounded by droplet sizes D_a and D_b microns in diameter. Such twin-subscripted notation for the finite interval is also used later in reference to area $_aA_b$, mass $_aM_b$, deposition $_aC_b$, etc.

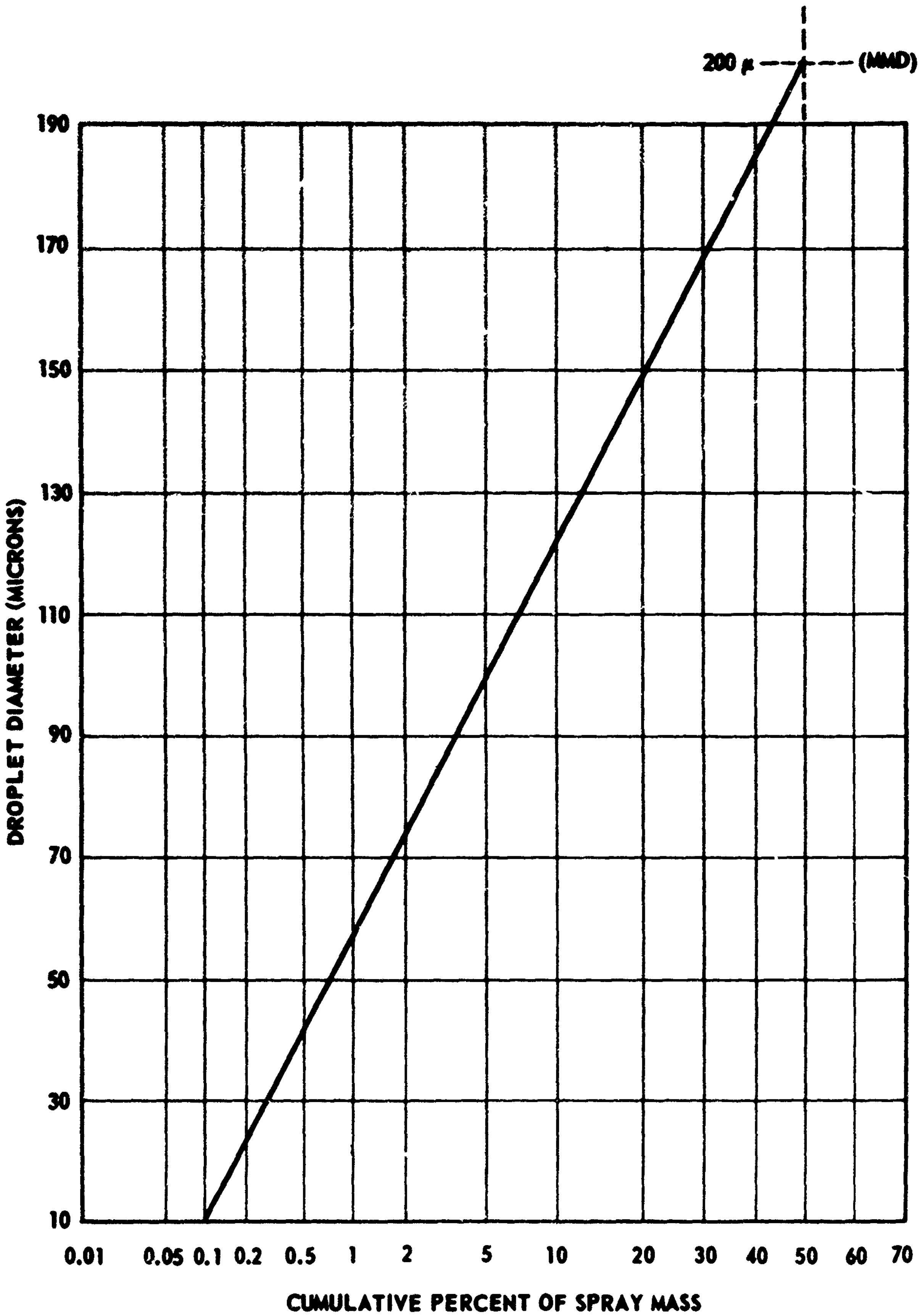

Figure 1. One-Tailed Distribution of Spray Mass.

TABLE I. QUANTITATIVE DATA ASSOCIATED WITH DROPLET DISTRIBUTION.

Droplet Diameter Interval D_a to D_b (μ)	${}_aP_b$ = % of mass M in interval	${}_a\Delta_b = D_a^{-4} - D_b^{-4}$ (μ^{-4})	${}_aR_b = {}_aP_b/{}_a\Delta_b$ (μ^4)
(A)	(B)	(C)	(D)
< 10	0.1	---	---
10 - 20	0.071	9.375×10^{-5}	7.57×10^{0}
20 - 30	0.114	5.015×10^{-6}	2.27×10^{2}
30 - 40	0.178	8.439×10^{-7}	2.11×10^{3}
40 - 50	0.272	2.306×10^{-7}	1.18×10^{4}
50 - 60	0.404	8.284×10^{-8}	4.88×10^{4}
60 - 70	0.584	3.551×10^{-8}	1.64×10^{5}
70 - 80	0.827	1.724×10^{-8}	4.80×10^{5}
80 - 90	1.13	9.172×10^{-9}	1.23×10^{6}
90 - 100	1.52	5.242×10^{-9}	2.90×10^{6}
100 - 110	1.96	3.170×10^{-9}	6.18×10^{6}
110 - 120	2.50	2.008×10^{-9}	1.25×10^{7}
120 - 130	3.08	1.321×10^{-9}	2.33×10^{7}
130 - 140	3.72	8.982×10^{-10}	4.14×10^{7}
140 - 150	4.35	6.278×10^{-10}	6.93×10^{7}
150 - 160	4.95	4.494×10^{-10}	1.10×10^{8}
160 - 170	5.52	3.286×10^{-10}	1.68×10^{8}
170 - 180	5.97	2.447×10^{-10}	2.44×10^{8}
180 - 190	6.29	1.853×10^{-10}	3.39×10^{8}
190 - 200	6.46	1.423×10^{-10}	4.54×10^{8}

SECTION IV

AREA AND MASS CALCULATIONS

Atmospheric diffusion theories developed for the treatment of vapors and aerosols are not directly applicable to spray droplets that have appreciable terminal velocities. The distribution of fluid is affected because the particle is continually falling out of the sample of eddies acting upon it at any instant, and the response to eddy motion is reduced by its inertia[7]. However, the effects of atmospheric turbulence and gravity fall dispersion are not independent. It appears that the atmospheric turbulent diffusion should be reduced by 30% for 200 μ diameter particles, and by about 10% for 100 μ diameter particles[8,9].

Data from recent diffusion experiments conducted by the Air Force Cambridge Research Laboratories were used to estimate the crosswind distribution of mass. The Ocean Breeze and Dry Gulch diffusion programs[10] utilized ground-based continuous point sources. The average standard deviation of crosswind mass distribution σ_y was calculated to be a 4.9° arc, with very little variation with respect to atmospheric stability. It should be noted, however, that σ_y varies with distance, although the relationship could not be easily evaluated. For the Sand Storm project[11], quasi-instantaneous small volume sources were generated under prevailing unstable conditions, and the average σ_y was found to be a 3.4° arc.

In view of the preceding discussion, σ_y equal to a 3° arc has been chosen for the purposes of this report for calculation of the area and the mass of downwind deposition. Thus $\pm 1\sigma_y$ from the center of the spray path, or a 6° sector of the circular area, will contain 68.27% of the spray mass, M. Assuming that this percentage of the mass within the 6° sector is uniformly distributed normal to the wind direction, the theoretical Gaussian distribution is transformed into a rectangular distribution. Errors thus introduced may range from underestimating deposition amounts by 10% to overestimating them by 30%.

It was seen earlier from Eq. (1) that the downwind distance of deposition is related to droplet size. For droplet diameters D_a and D_b, the corresponding radial distances X_a and X_b define the concentric boundaries of that portion of the sector which contains all droplets with diameters from D_a to D_b; the area ${}_aA_b$ of this portion is

$$
{}_aA_b = \frac{\pi(X_a^2 - X_b^2)}{60} \qquad (2)
$$

where X_a is the longer distance, associated with the smaller drop diameter D_a.

Substituting Eq. (1) into Eq. (2) and expressing the area in square kilometers

$$
{}_aA_b = \frac{57.99\ (ZU)^2\ {}_a\Delta_b}{S^2} \qquad (3)
$$

the symbol ${}_a\Delta_b$ being substituted for the expression

$$
1/D_a^4 - 1/D_b^4
$$

Computed ${}_a\Delta_b$ values for 10-μ intervals are shown in Column (C) of Table I.

Mass ${}_aM_b$ within the area ${}_aA_b$ is found from the relationship

$$
{}_aM_b = 0.6827\ M\ {}_aP_b
$$

or if the total released quantity Q is in liters, mass in grams is given by

$$
{}_aM_b = 682.7\ Q\ S\ {}_aP_b \qquad (4)
$$

SECTION V

AMOUNT AND EXTENT OF DEPOSITION

The amount of deposition in mass per area is found by dividing Eq. (4) by Eq. (3), or

$$ {}_aC_b = \frac{11.77\ {}_aR_b\ Q\ S^3}{(ZU)^2} \tag{5} $$

where

${}_aC_b$ is the deposition in g/km² or μg/m²

Q is the released quantity in liters

S is the specific gravity of the fluid

Z is the release altitude in meters

U is the mean wind speed from surface to Z in meters per second

${}_aR_b$ is the ratio $\frac{{}_aP_b}{{}_a\Delta_b}$, given in Column (D) of Table I for each ${}_aP_b$ and the corresponding ${}_a\Delta_b$.

It should be noted again that deposition ${}_aC_b$ is the mean amount for the area defined by the particle sizes D_a and D_b. It follows from Eq. (1) that the downwind travel distance from the origin o in kilometers for the mean particle diameter is

$$ {}_oX_{ab} = \frac{133.1\ ZU}{S(D_a + D_b)^2} \tag{6} $$

If Q, S, Z, and U are either known or assumed, the amount and the extent of deposition can be found by solving Eqs. (5) and (6) for various droplet sizes. Simultaneous solutions could then be represented graphically by a family of curves for any desired Z and U.

Since it is often convenient to use the U.S. system of measurements, Eqs. (5) and (6) are restated as

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Since it is often convenient to use the U.S. system of measurements, Eqs. (5) and (6) are restated as

$$ {}_{a}C_{b}^{*} = \frac{10.34\ {}_{a}R_{b}\ Q^{*}\ S^{3}}{(Z^{*}U^{*})^{2}} \tag{7} $$

and

$$ {}_{o}X_{ab}^{*} = \frac{12.98\ Z^{*}\ U^{*}}{S(D_{a} + D_{b})^{2}} \tag{8} $$

where for given particle diameters D_a and D_b in microns

${}_{a}C_{b}^{*}$ is the deposition in pounds/square mile

Q^{*} is the released quantity in gallons

Z^{*} is the release altitude in feet

U^{*} is the mean wind speed from surface to Z in knots

${}_{o}X_{ab}^{*}$ is the mean downwind travel distance in statute miles.

As before,

S is the specific gravity of the fluid

${}_{a}R_{b}$ is a numerical quantity, found in Column (D) of Table I.

SECTION VI

A SAMPLE SOLUTION OF A PRACTICAL PROBLEM

If during a spray mission, 100 gallons of a fluid code named "ORANGE" (specific gravity 1.28) were released, Eq. (8) reduces to

$$ {}_{o}X^{*}_{ab} = \frac{10.14\ Z^{*}\ U^{*}}{(D_a + D_b)^2} \tag{9} $$

Figure 2 shows a family of curves drawn for selected Z^* and U^* in Eq. (9), and depicting the deposition distances as a function of droplet diameters.

Similarly, for a 100-gallon release of "ORANGE", Eq. (7) can be restated as

$$ {}_{a}C^{*}_{b} = \frac{2167\ {}_{a}R_{b}}{(Z^{*}\ U^{*})^2} \tag{10} $$

Solving Eq. (10) for desired Z^* and U^*, and finding the ${}_{o}X^{*}_{ab}$ corresponding to ${}_{a}C^{*}_{b}$ either from Eq. (9) or, as in this example, from Figure 2, a new set of curves is found, as shown in Figure 3.

For a visual representation of the downwind area potentially affected by deposition, it suffices to draw a 6° sector from the area of release, bisected by a line which represents the mean wind direction and corresponds to the distance axis of Figure 3. Deposition amounts for a specific quantity of fluid, and for the applicable release height and wind speed, could then be readily depicted.

For convenience, the deposition conversion for "ORANGE" is given as

1 lb/sq mi = 1.464×10^{-4} gal/acre.

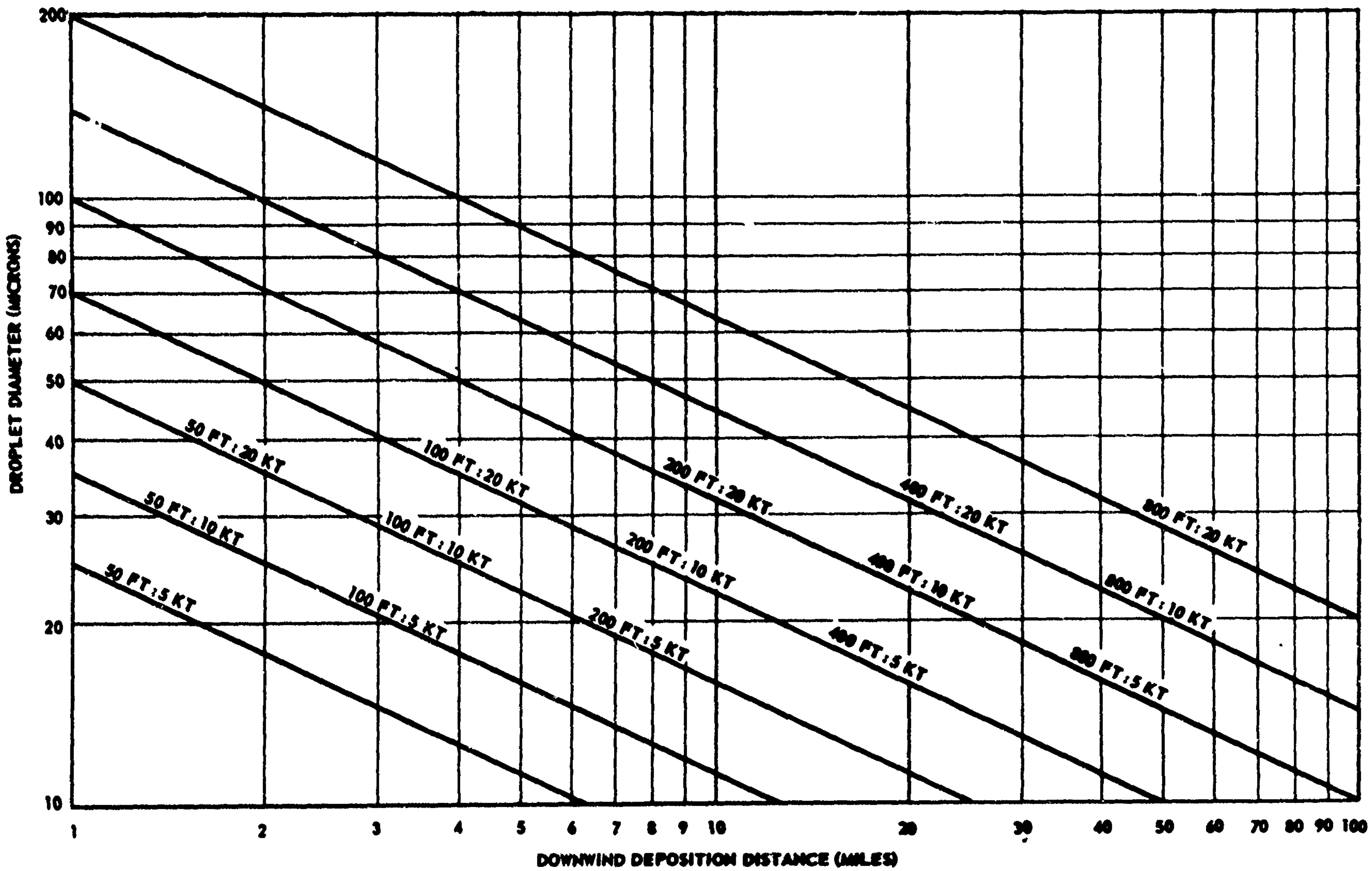

Figure 2. Downwind Deposition Distances of "ORANGE" Droplets for Selected Release Altitudes and Wind Speeds.

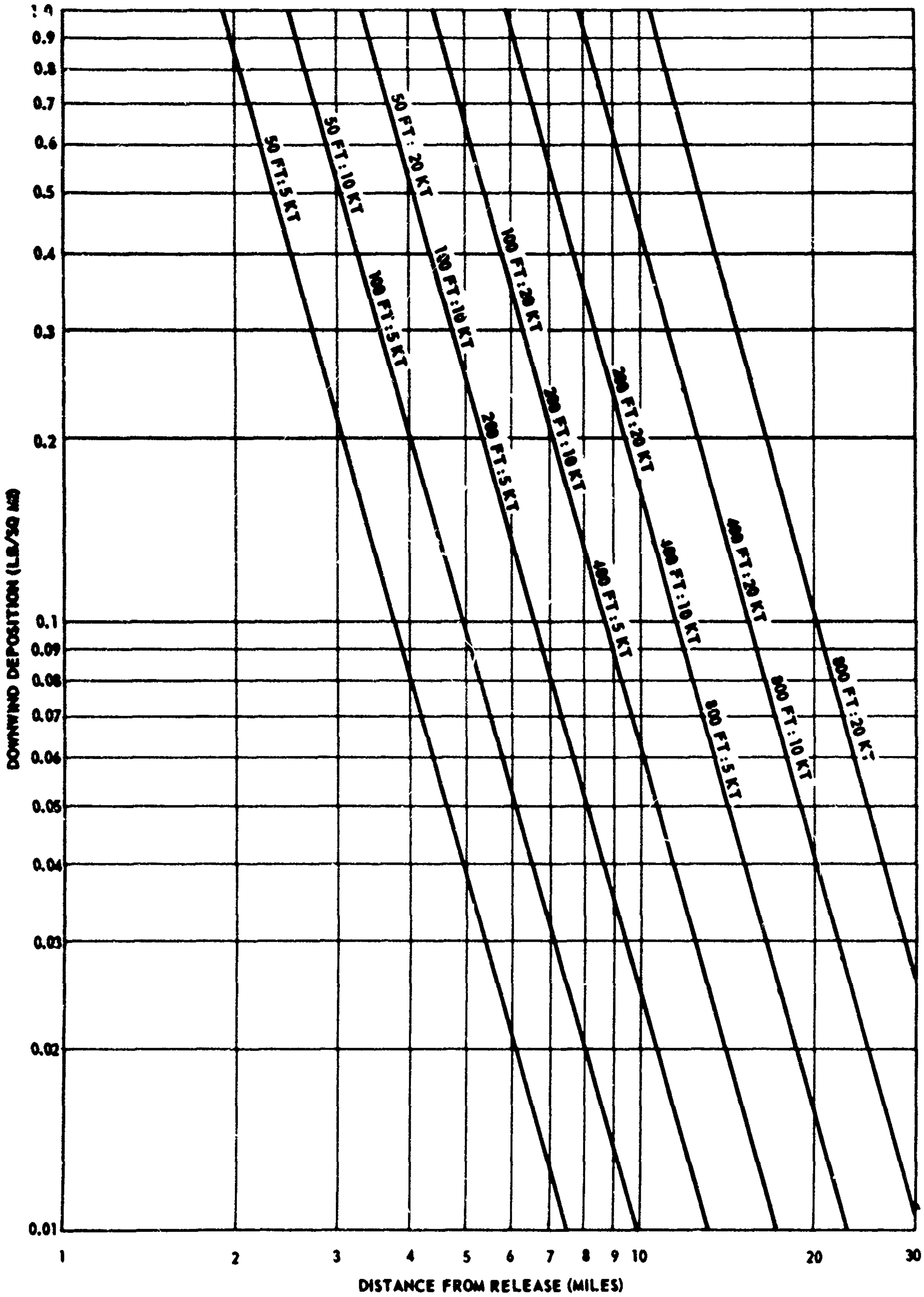

Figure 3. Downwind Depositions from a 100-Gallon Release of "ORANGE" for Selected Release Altitudes and Wind Speeds.

SECTION VII

CONCLUSIONS

Inspection of ${}_aR_b$ values (Table I) in conjunction with Eq. (5) reveals that as the particle diameter decreases one order of magnitude (100–10 μ); the deposition decreases six orders of magnitude. This once more brings attention to the fact that the deposition amounts decrease quite rapidly as particle diameters decrease with distance from the release area.

As illustrated by the sample solution, the amount of downwind deposition for any travel distance can be rapidly estimated from Figure 3. Similarly, the distance from the area of release within which the deposition equals or exceeds a specified amount can be readily determined from Figure 3.

The foregoing is but one procedure for estimating the downwind deposition, and necessitates a number of assumptions for a simplified application. Conceivably, on other occasions it might be desirable to consider a different MMD or drop-size distribution, or to make other estimates for the mass and the area involved, even though the basic approach might remain essentially similar to the one described in this report.

As pointed out by others[12], there are uncertainties associated with the calculational techniques in estimating depositions. Quantitative estimates should be treated with caution, since they might convey an erroneous impression of precision. If doubts should arise concerning the applicability of the procedure under a different set of circumstances, it is advisable to consult a qualified meteorologist for properly assessing the limitations and interpreting the results.

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13. ABSTRACT

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