TECHNICAL REPORT
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AEROSOL LABORATORY

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

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ABSTRACT

A method used for calibrating aircraft-mounted aerosol generators has involved a "fly-by" of the aircraft upwind of a sampling array on a tall tower. This method is reexamined to determine whether it is suitable for calibrating aerosol generators mounted on slow-moving ground vehicles. It is shown that when the vehicular speeds are as small as only twice the wind speed, the calibration results are likely to be erratic and many trials must be run to obtain a reasonably good estimate of the aerosol generator's efficiency.

TABLE OF CONTENTS

I. INTRODUCTION

A large number of field trials have been run with the purpose of determining the efficiencies of various aerosol generating devices. Generally, the device being tested has been mounted on an aircraft and has disseminated either dry powder or liquid droplets along an extended crosswind line at a low altitude. A portion of the cloud so disseminated has been sampled at fixed vertical intervals on a tall tower as the cloud drifted downwind through and around the tower. These sampling recoveries provide a basis for making an estimate of the total material contained within a downwind slice of the cloud. The number of particles* found in this slice when divided by the weight of material disseminated over the same crosswind distance as the thickness of the slice provided an estimate of the number of particles disseminated per unit weight. This information alone is useful since it is a calibrated value of the particle output per unit weight for the particular combination of the material disseminated, the aircraft used and the disseminator. This calibrated value of the number of particles per unit weight may be converted to an efficiency value by dividing by the actual number of particles per unit weight if the latter is known.

Generally, as mentioned above, long-line disseminations have been made from aircraft but, in a few cases, truck-mounted aerosol generators have been used.** Inevitably, the use of a much slower vehicle has changed the ratio of the wind speed to vehicular speed within the normal range of operating wind speeds encountered. This change prompts a reexamination of the flux calculation methods that have been employed in the past to see whether assumptions and approximations acceptable for the fast-moving aircraft are indeed acceptable for a slow-moving vehicle.

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*Discussion in this report will be in terms of dry material; the principles involved are equally valid for sprays.

**A wheelbarrow-mounted aerosol generator used in the Cibo trials provided more an enlarged "point" source than an extended crosswind line.

II. INITIAL ORIENTATION OF CLOUD

An attempt is usually made when particulate material is disseminated along a line to orient the line crosswind However, the combination of the wind speed and direction values and the course followed by the vehicle, whether aircraft or truck, rarely results in a true crosswind orientation of the cloud. The course followed by the vehicle is generally fixed and hence no adjustment can be made in vehicular direction to compensate for any non-ideal wind direction

On occasion, the wind direction may be perpendicular to the vehicular direction of motion.* In this situation, the orientation of the cloud cannot be exactly crosswind since the vehicular speed is not infinite. In the past, the line disseminations from aircraft have been treated as having been instantaneously created insofar as the orientation of the cloud is concerned This assumption has probably been justified, particularly for high-speed aircraft or for any aircraft when wind speeds were low The effect of higher wind speeds or slower-moving vehicles is shown in Figure 1.

Figure 1 shows the orientations which would result from three different ratios of vehicular speed to wind speed where the wind direction is perpendicular to the vehicle's course Two downwind lines, X and Y, inclose a segment of the cloud disseminated by the vehicle which approached from the left, crossed from X to Y along the dashed line, and has proceeded slightly to the right of Y Case AA' shows the resulting orientation when the vehicular speed is infinite with respect to the wind speed; Case BB' shows the orientation of the cloud when the ratio of vehicular to wind speed is approximately 8/3, i.e. a vehicle moving 40 mph in a 15 mph crosswind Case CC' shows an extreme situation with the vehicular and wind speeds approximately equal.

In theory for any of the three cases shown the calculated flux values should be identical if the same numbers of particles were disseminated along the course from X to Y If each of the three clouds traverses a downwind sampling position with no change in wind direction, the particle flux through a unit-crosswind-distance segment of an infinitely tall vertical crosswind plane will be identical for all three. Any existing crosswind diffusion should result in a zero net exchange of material across X and across Y, as a result, no change occurs in the average crosswind flux between X and Y since the total flux between X and Y remains constant and the perpendicular distance between X and Y remains constant

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*The direction of motion of an aircraft will be considered here to be that of the course made good along the ground and not the orientation of the aircraft heading which because of crosswind drift cannot be the same as the orientation of the course made good along a ground line

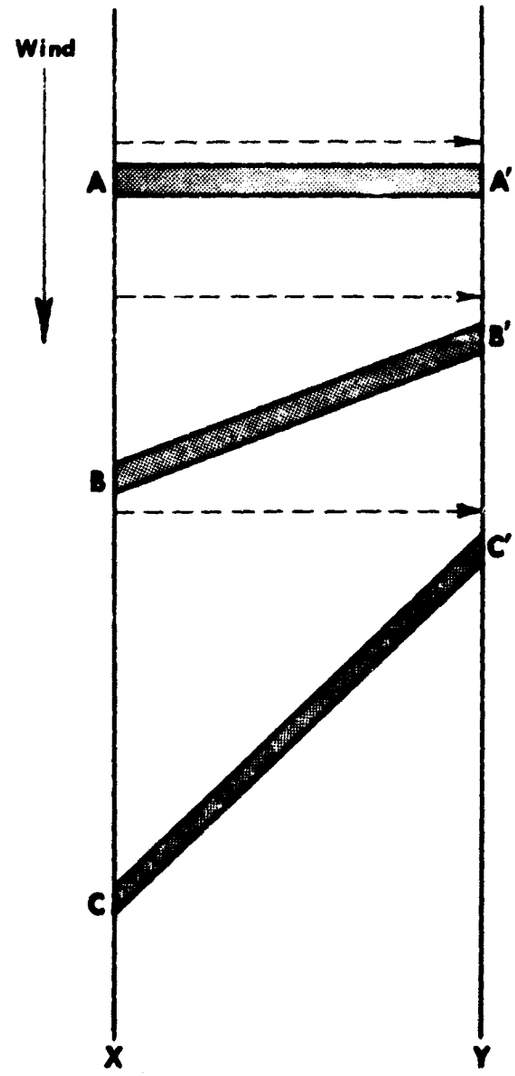

Fig. 1—Cloud orientations for three different ratios of disseminating vehicle's speed to wind speed for the case when the wind is directly across the vehicle's course.

provided the wind direction does not change. The effect of a change in wind direction is discussed in the next section

Figures 2 and 3 show the effect on the orientation of the cloud caused by winds not perpendicular to the vehicle's ground course; in Figure 2, there is a partial headwind as the vehicle moves from left to right and, in Figure 3, a partial tailwind as the vehicle moves right to left

Again, the particle flux through a vertical plane of unit crosswind width will be the same for all orientations provided that the wind does not change However, for the same amount of material disseminated along the dashed lines, the particle flux will be greater for the situations shown in Figures 2 and 3 than those shown in Figure 1. This increase is a result of the greater crosswind source strength, i.e. a fixed distance along a dashed line has a shorter crosswind dimension in Figures 2 and 3 than in Figure 1. The crosswind distance (the perpendicular distance between X and Y) is a function of the difference in the orientations of the wind direction and the vehicle's course Thus, the true source strength per unit crosswind distance is the source strength per unit distance of vehicular course divided by the sine of the angle between the wind direction and the vehicle's course

Thus far, this discussion of flux calculations has been kept simple by not considering the situation where the wind direction changes between the time of the cloud's dissemination and the time it reaches the sampling position The effect of such a change in direction is examined in the next section

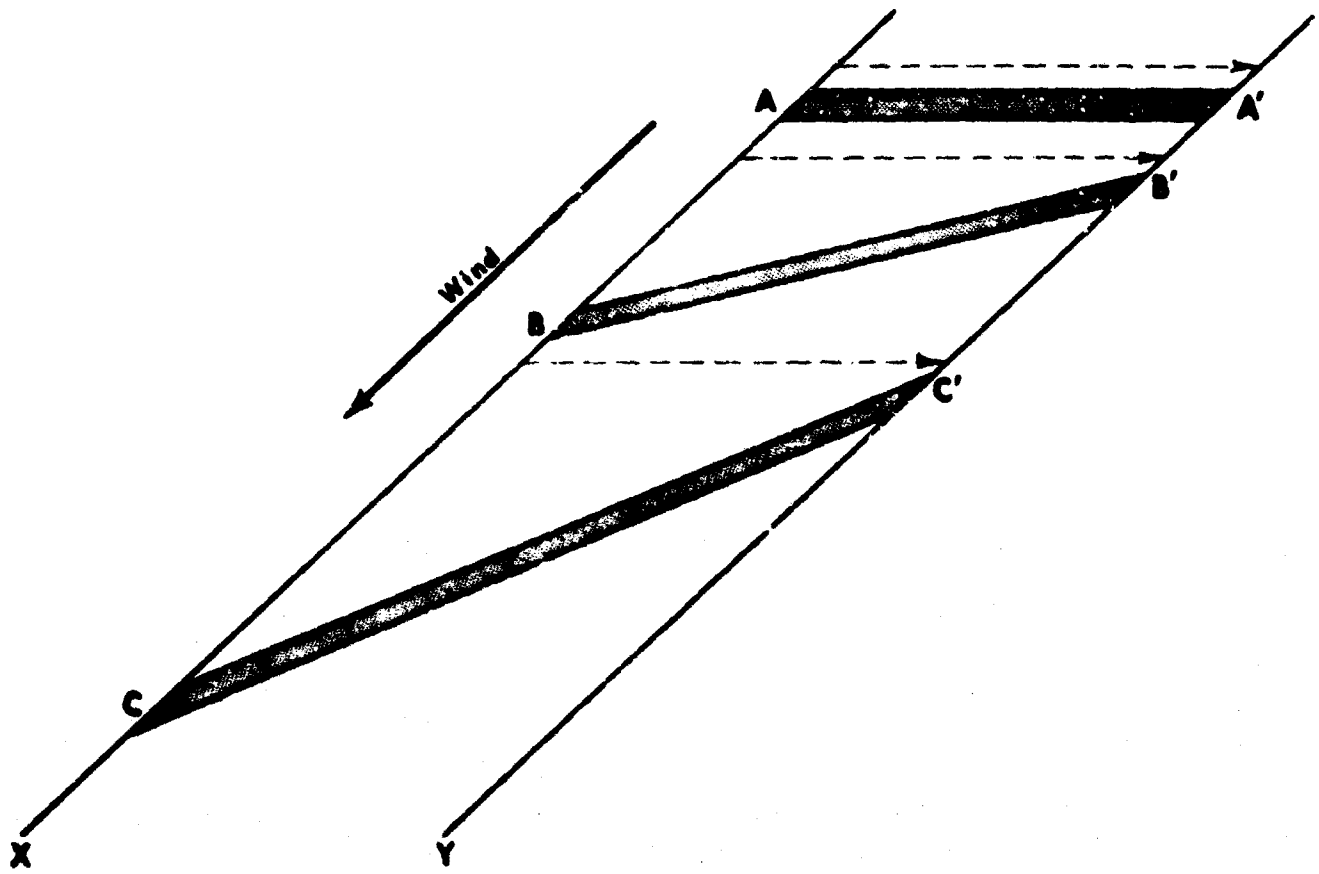

Fig. [illegible] orientations for three different ratios of crosswind to vehicle's speed to wind speed for the case of a wind of [illegible] partially head wind and partially crosswind.

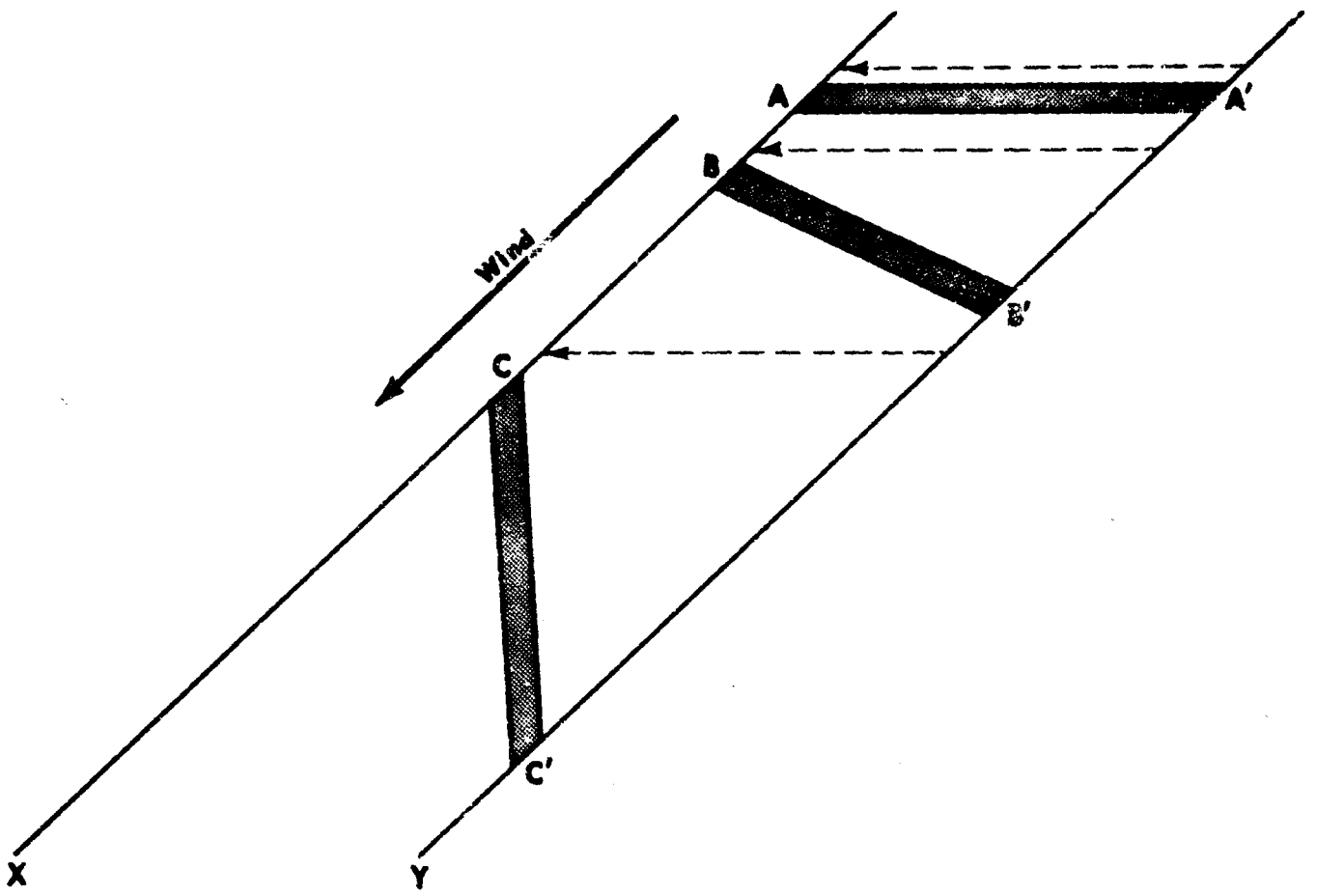

Fig. 3--Cloud orientations for three different ratios of disseminating vehicle's speed to wind speed for the case of a wind which is partially tail wind and partially crosswind.

III EFFECT OF CHANGES IN WIND DIRECTION ON CALCULATED FLUX VALUES

The magnitudes of changes in wind direction depend upon the existing eddy structure. In general, eddies can be classed in three size groups insofar as importance to the flux calculation is concerned.

First, eddies with diameters much smaller than the downwind dimension of the disseminated cloud as it arrives at the sampling position are of no particular importance to the flux calculation since they alone do little toward causing the cloud to become irregular or to change its orientation. If many small whirls exist between the leading edge and the trailing edge of the cloud, they tend in series to give a net effect of zero or no whirl at all. Thus, no allowance need be made for them in the flux calculation which is fortunate since obtaining the information required for making the allowance is probably not possible with equipment presently available.

Second, eddies with diameters of the order of the downwind dimension of the cloud undoubtedly have a marked effect on the sampling recoveries obtained. The effect from these eddies is not due alone to the changes in wind direction or the resulting irregularity in the cloud but also to the variable wind speed associated with the eddies. The net wind speed at the sampling position includes both the speed of turning of the eddy and the speed with which the eddy is being translated. Thus, the wind speed experienced will have a value in a possible range of twice the rotational speed of the eddy. The errors introduced into the calculated flux values by eddies of this dimension appear to be unavoidable with present instrumentation and hence must be accepted as part of the experimental uncertainty inherent in the method used. Whereas the small eddies tend to cancel each other out, the effects from these larger eddies will tend to cancel out only by averaging the results obtained from several trials.

Finally, much larger eddies which are associated with simultaneous wind direction changes over a large area are eddies for which allowance may be made in the flux calculations. With eddies of this dimension, any pair of paired points, AA', BB' and CC' in Figures 1, 2 and 3 would continue to remain a constant distance apart with constant bearings on each other regardless of the change in wind direction. Thus, there is no tendency for one point to rotate about the other or, at least, the net tendency is zero.

The effect of such a wind shift on the source strength value per unit of crosswind distance is shown graphically in Figure 4. The figure shows each of the three initial lines, AA', BB' and CC', and the changes in crosswind distance they undergo due to shifts in wind direction. In each case, the line segment maintains a constant length and orientation at each of the four positions shown. It is readily seen that as these remain constant the crosswind distance between the two

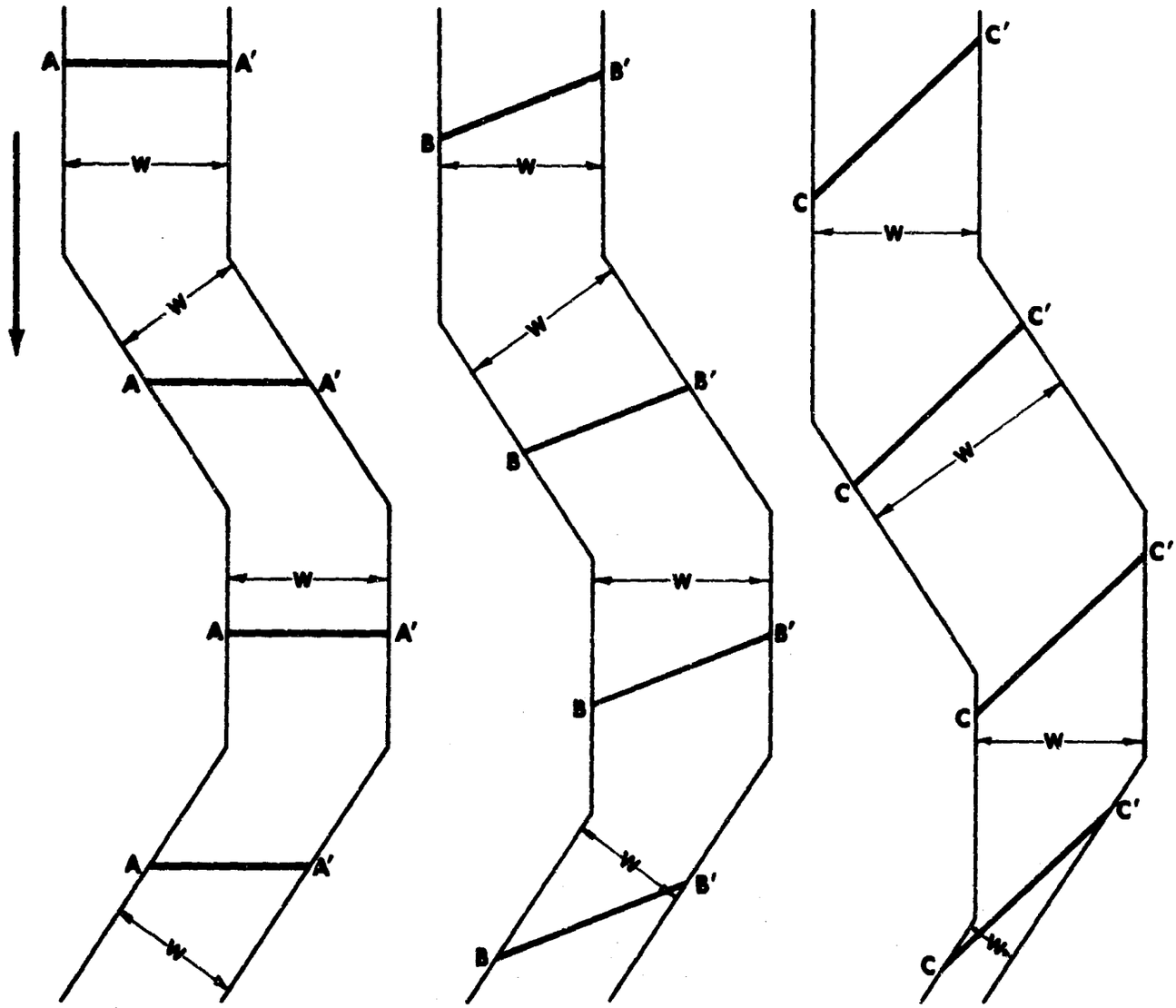

Fig. 4--Effect of initial cloud orientation on the change in crosswind dimensions of a cloud as the wind direction changes, shown for three initial cloud orientations with the same crosswind dimensions.

points bounding the segment varies appreciably with changes in wind direction. It follows, that the source strength per unit crosswind distance also changes appreciably with changes in wind direction Moreover, in the cases of BB' and CC', a given amount of change has a different effect when the change is to the left rather than to the right

The crosswind distances are indicated by the letter W in Figure 4 After making an approximate 35° turn the crosswind distance between A and A' has decreased and hence the source strength has increased (per unit crosswind distance); after the first turn, the crosswind distance between B and B' remains virtually unchanged. In the case of CC', the crosswind distance increases, thus decreasing the source strength. A second turn equal to the first but opposite in direction returns to the original situation. A third turn equal to the second has a very different effect on the crosswind distances for BB' and CC' than did the first turn from the original conditions Now, the value of W is sharply reduced, particularly in the case of CC'. Here the crosswind distance is less than 1/4 that after the first change in wind direction. Admittedly, this is an extreme example since the wind speed is equal to the vehicular speed and hence probably not an operational situation unless a slow-moving ground vehicle were used. However, even a moderate-speed ground vehicle might become involved in a situation shown by BB' Here the longest value of W is 1.6 times that of the shortest value.

As mentioned earlier, the effective number of particles per gram may be calculated by dividing the integrated flux value by the crosswind source strength at the time the cloud transits the sampling array. Referring to Figure 5 to help clarify the concepts involved

1. A vehicle travels from J to B' in unit time and encounters a wind the direction of which is D_o with a speed equal to the distance from J to B per unit time.

2 The weight of material disseminated along JB' will, when the vehicle reaches B', be distributed along the line BB'.

3. If at this time the wind shifts from a direction of D_o to D and maintains this new direction until the cloud has passed the sampling position, the crosswind distance between B and B' at the time of sampling is equal to the length of the line KB', thus the source strength per unit crosswind distance is the weight of material disseminated between J and B' divided by the distance between K and B'

In practice, the source strength value is likely to be reported as the weight disseminated per unit distance of vehicular travel This value must be multiplied by the ratio of the distance from J to B' and from K to B' to give the source strength per unit crosswind distance. This ratio is

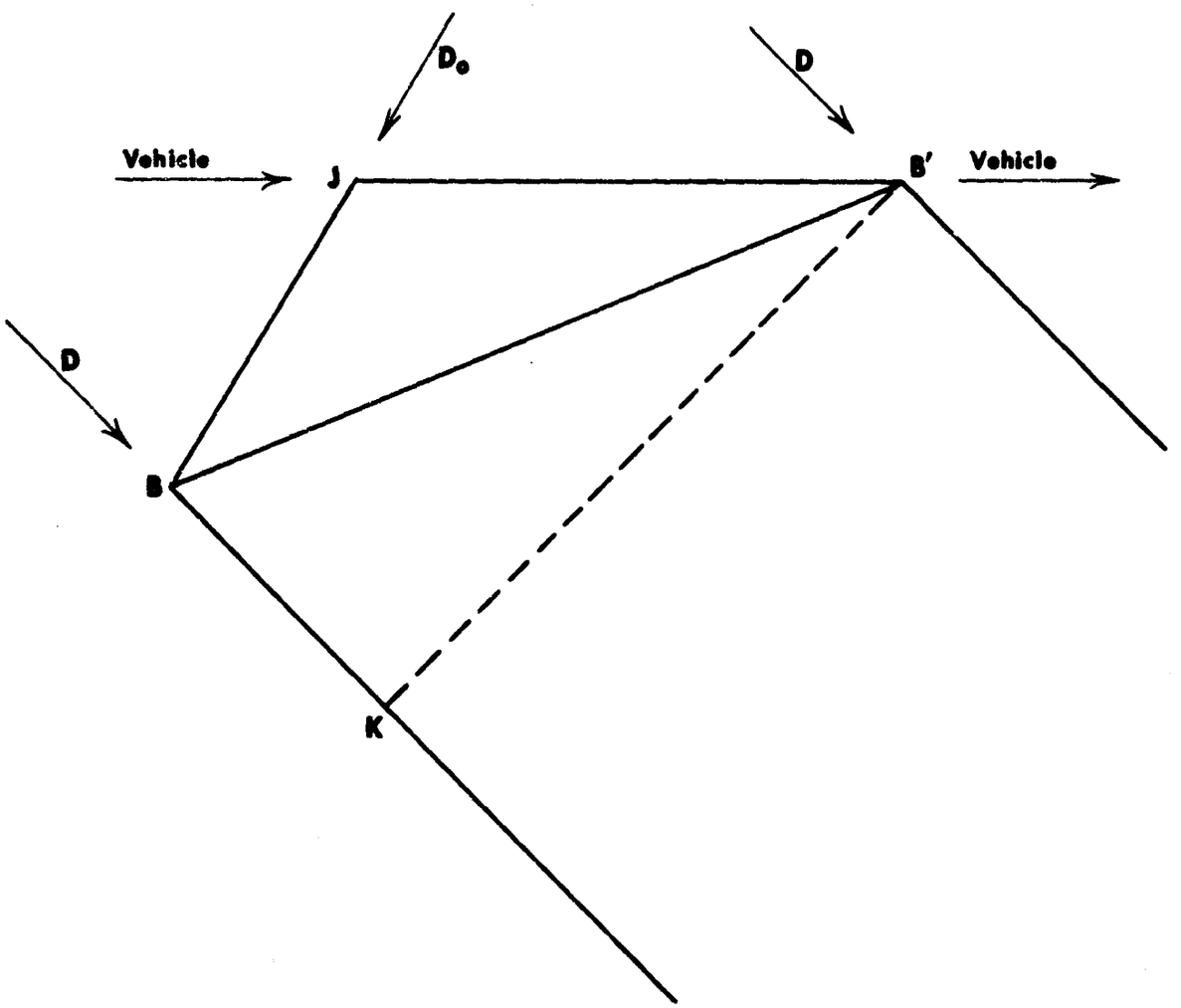

Fig. 5--Graphical representation of the adjustment required to obtain the correct value of source strength per unit crosswind distance from the value of source strength output per unit distance of vehicular course. The adjustment factor is the ratio between the distances from J to B' and from K to B'.

$$\frac{V}{W} = \frac{1}{\sin (D-R) + (u_o/V) \sin (D_o-D)} \qquad (1)$$

where

V = vehicular speed

W = crosswind distance between points in cloud disseminated unit time apart

u_o = wind speed at time of dissemination

D_o = wind direction at time of dissemination

D = wind direction at time of sampling

R = true bearing of vehicle's course

For the purposes of Eq (1), the wind directions are taken to be the direction toward which the air is moving in order that the air motion and the orientation of the vehicular course may be considered in the same sense with both motions identified by their headings.

The discussion thus far has been in terms of two wind directions only, the directions at the time of dissemination and at the time of sampling. Actually, to the extent that the assumption is valid that the points B and B' will maintain a constant separation and orientation other wind directions may occur between the time of dissemination and sampling without affecting the ratio between V and W.

Thus far, no mention has been made of the wind speed at the time of sampling. The reason for this is that the wind speed at the time of sampling has no effect on the crosswind source strength nor, by the same reasoning, on the flux through a vertical plane of unit crosswind width. Admittedly, with higher winds a smaller proportion of the flux is recovered by samplers and adjustments must be made accordingly to the recovery values for the purpose of estimating the flux. The actual flux calculation is discussed in the next section.

IV. CALCULATION OF NUMBER OF PARTICLES PER UNIT WEIGHT OF MATERIAL

The flux through a vertical plane with a width of unit crosswind distance is given by

$$N = \int_0^\infty \int_0^\infty u\, c\, dt\, dz \qquad (2)$$

where

N = total number of particles through a vertical plane with a width of unit crosswind distance

u = wind speed at time, t, at height, z

c = particle concentration at time, t, at height, z

It is impractical to have continuous sampling in the vertical; therefore, the integration with respect to height is substituted for by the product of the summation of the total dosage -- wind speed products obtained at uniformly spaced heights and the spacing between samplers. These total dosages are the values of the time integral of the concentration at each position and are obtained by dividing the particle recovery at the position by the volume sampling rate. Thus,

$$N = \Delta Z \sum u_z\, P_z / F_z \qquad (3)$$

where

ΔZ = vertical spacing between samplers

u_z = wind speed at height, z

P_z = number of particles recovered at height, z

F_z = volume sampled per unit time

The transition from Eq. (2) to Eq. (3) implies that u has now become $\bar{u}$, i.e., the wind speed value used is the average speed during the time of cloud passage. The effect on the calculated efficiency values caused by the way this value of u is chosen is discussed in the next section.

The number of particles effectively aerosolized per unit weight of material by a disseminating device is

$$n = \frac{N}{m} \qquad (4)$$

where

n = number of particles aerosolized per unit weight

N = total number of particles through a vertical plane with a width of unit crosswind distance

m = weight of material disseminated per unit crosswind distance

The value of m, as mentioned in the preceding section, is

$$m = \frac{M}{L} \times \frac{V}{W} \tag{5}$$

where

M = total weight of material disseminated,

L = ground distance traveled by vehicle while disseminating M,

and V/W is defined by Eq. (1).

Substituting from Eqs. (1), (3) and (5) in Eq. (4) gives

$$n = \frac{L\Delta Z}{M} \sum \left\{ \frac{u_z P_z}{F_z} \left[\sin (D-R) + \frac{u_o}{V} \sin (D_o - D) \right] \right\} \tag{6}$$

where

n = number of particles aerosolized per unit weight of material

ΔZ = vertical spacing between samplers

L = length of ground path traveled by disseminating vehicle while disseminating

M = total weight of material disseminated

u_z = wind speed at height, z

P_z = number of particles recovered at height, z

F_z = volume of air sampled per unit time

D = direction toward which wind is blowing at time of sampling

D_o = direction toward which wind was blowing at time of dissemination

R = direction of ground source of disseminating vehicle

V = speed of vehicle

Note that the expression for V/W must be included within the summation since D is a function of height.

Uncertainties about the correct values for the parameters in the right hand side of Eq. (6) combine (not additvely) to produce a total undertainty as to the correct value of n. The probable magnitude of these uncertainties is discussed in the next section.

V. DISCUSSION

The variables which affect the calculated value of n, the number of particles aerosolized per unit weight of material, include:

1. Vertical spacing between samplers. This generally is constant and, within the framework of field trial uncertainties, is precisely known. An exception to the constant spacing occurs at the top and bottom of the sampling array; above the top sampler the spacing is infinite while below the bottom sampler the spacing is zero to the boundary if there is a sampler at ground level. Generally, there is no sampler at ground level which is usually unimportant in the case of disseminations from aircraft; for ground vehicle disseminations, the assumptions used in extrapolating the concentration values from the lowest sampler to the ground may have a marked effect on the calculated value of n.

2. Length of dissemination line. This distance should be accurately known for a ground vehicle and somewhat less accurately known for an aircraft. The percentage error for either type of vehicle is probably small.

3. Total weight of material disseminated. The weight disseminated is generally accurately known.

4. Volume of air sampled per unit time. The sampling rate is accurately known if everything works right, the correct pressure drop is maintained, the critical orifice controlling the flow rate doesn't become wholly or partially obstructed, etc.

5. Wind speed. The accuracy of the wind speed measurements depends on the characteristics of the instrumentation used. Percentage errors tend to be large at low wind speeds, particularly, near the anemometer's starting speed. Even when measured accurately, the wind speed value used is almost certainly in error since it usually is an average speed taken over a considerably longer time span than required for the cloud to pass the sampling tower. Generally, the major portion of the particle cloud traverses the sampling tower after 300 ft of travel within vertical limits of 50-60 ft. If the cloud is cylindrical, a major portion of the cloud is included within the same downwind dimension. At 10 mph, this major portion of the cloud would transit the sampling position in approximately four seconds. Since it generally is not known exactly which four-second period is involved, an average speed over a considerably longer period is generally used in calculating the value of n. This practice rarely gives the correct value but entails less risk of a gross error which might possibly result from the use of the wrong short-term average. This wind speed error must be accepted as part of the experimental uncertainty inherent in the system until the time when the time of cloud passage is known with greater precision. If the cloud's passage could be observed visually, greater re-

liance could be put in a short-term average wind speed value. The wind speed at the time of dissemination also affects the calculated value of n but only, as will be seen below, when the wind speed is a substantial fraction of the disseminating vehicle's speed.

6. Number of particles recovered The number of particles recovered at a particular position is generally estimated by examining a portion of the sample and multiplying the number of particles observed by an appropriate factor. If the number recovered is small, the total sample is usually examined completely but such samples normally do not contribute substantially to the total summation of recoveries at all positions. Hence, an uncertainty exists with respect to the reliability of the estimated total recovery at a given position. However, in adding the recoveries at several positions the relative uncertainty tends to decrease because of the tendency of the errors to cancel each other. A far greater error associated with recovery values is invoked by assuming that the observed value and the average value over the space, ΔZ, are identical. These uncertainties, again, are inherent in the system and cannot be avoided. They can be decreased by making ΔZ as small as possible.

7. Ground course of the disseminating vehicle. The value of this parameter is usually accurately known.

8. Wind direction. Much of the comment on wind speed is applicable to wind direction as well. An average direction taken over a period of time considerably longer than the time of cloud passage almost inevitably entails some error in the value used but ensures that the error generally is moderate. Examination of Figures 6-11 leads to an estimate of the error probably associated with wind direction. Looking first at Figure 6, the value of V/W^* may be found as a function of the difference in the direction of air flow and the disseminating vehicle's course (D-R) and as a function of the change in wind direction between the time of dissemination and the time of sampling (D_o-D) Figure 6 shows the relation for a particular value of the ratio between vehicular and wind speeds of 32. Here, it may be seen that the value of V/W is little affected by even large values of (D_o-D). Hence, it is obvious that this parameter may justifiably be ignored when a jet aircraft is used as the disseminating vehicle.

The relationship among the various parameters when the vehicular speed is 16 times the wind speed is shown in Figure 7. This ratio of 16 is one that has frequently been encountered at least approximately during field calibration trials of disseminating devices. An aircraft traveling at 180 mph with the wind speed

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*The bracketed portion of Eq. (6).

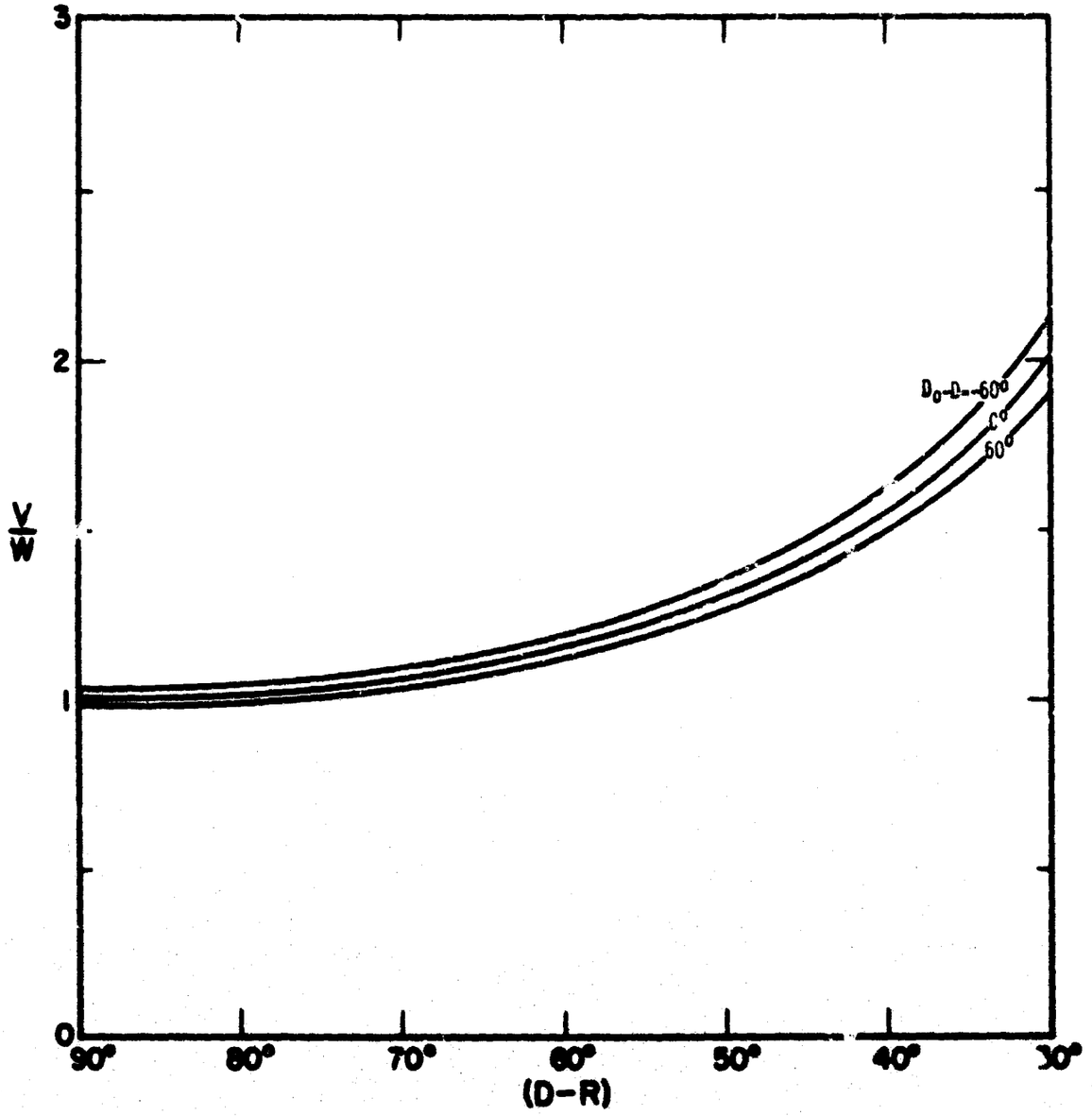

Fig. 6—Values of V/W, the ratio between the distance the vehicle travels in unit time and the crosswind distance between two points in the cloud disseminated unit time apart, as a function of the difference between the sampling time wind direction and the vehicle's course and of the change in wind direction between dissemination and sampling times for the case where the vehicle's speed is 32 times the wind speed.

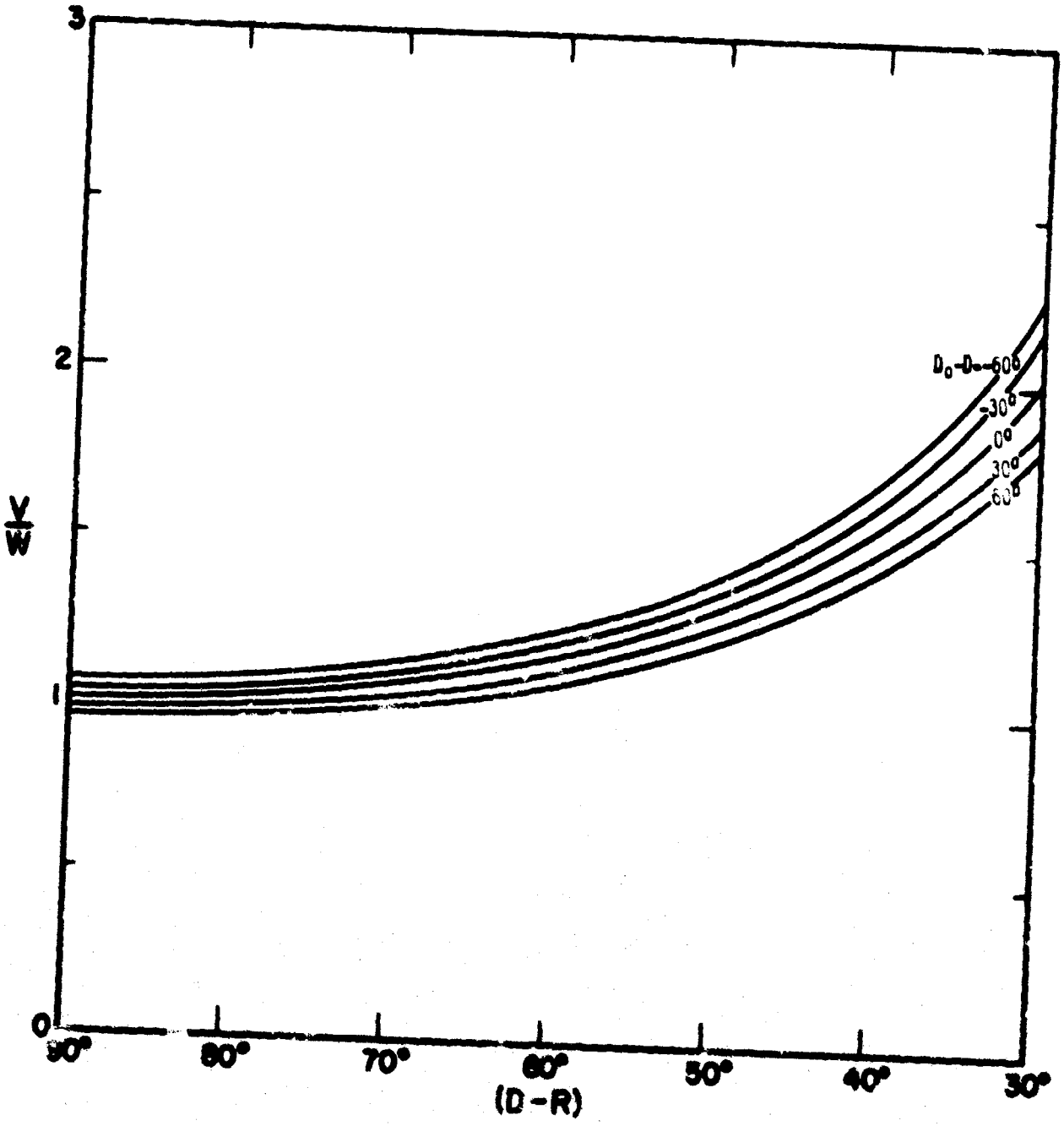

Fig. 7—Values of V/W, the ratio between the distance the vehicle travels in unit time and the crosswind distance between two points in the cloud disseminated unit time apart, as a function of the difference between the sampling time wind direction and the vehicle's course and of the change in wind direction between dissemination and sampling times for the case where the vehicle's speed is six times the wind speed.

ranging from 10 to 15 mph gives a value of the ratio ranging from 18 to 12. Although changes in wind direction between dissemination and sampling times have a greater effect than for the high speed aircraft, the error introduced by ignoring this parameter is generally small compared to that caused by the use of the wrong value of (D-R). A 10° error in the value of (D-R) leads to a greater error in V/W than does ignoring a 30° shift in wind direction between dissemination and sampling times. Thus, dropping the (u_o/V) sin (D_o-D) term from Eq. (6) is probably justified

A rule-of-thumb was adopted after the results of many of these calibration trials had been analyzed which specified that the results from trials for which the value of (D-R) was less than 45° would not be used for the purpose of arriving at an average calibrated value or efficiency value. It can be seen in Figure 7 that appreciable errors in the value of V/W will result for errors of 10-15° in the value of (D-R) when the latter is smaller than 45°. [Ignoring the effect of (D_o-D) is equivalent to assuming it equal to 0; hence, the $(D_o-D = 0)$ curve applies in this case.] These errors are of the order of 15-20%. Using errors of this magnitude as a criterion of unacceptability, it can be seen by examining Figures 8-11 that ignoring the fact that (D_o-D) may not actually equal zero becomes increasingly unacceptable as the ratio between vehicular and wind speeds decreases. For example, consider Figure 10 for the case when the true value of (D-R) is 50° and the true value of (D_o-D) is -10° and the values used are 60° and 0° respectively. The true value of V/W is 1.48 and the value used is 1.16. Thus, the value used will introduce an error into the calculated flux values of 22%. For the slow aircraft (Figure 7), the error would be 12% and for the high-speed aircraft (Figure 6), also 12%, with the error in V/W attributable almost entirely to the 10° error in the value of (D-R) in the latter two cases.

By this time, it is obvious that calculation of flux values involving slow-moving disseminators with the effect of change of wind direction ignored will almost certainly lead to extremely erratic results. Moreover, when the parameter is not ignored the error in estimating its value is still important to the accuracy of the flux calculation. Thus, the use of the "drive-by" method of calibrating an aerosol generator must necessarily entail considerable variability in the flux calculations and hence in the calibrated values of the disseminator's output. If the drive-by method is used, many repetitions of the calibration trial are required if confidence is to be placed in the mean (or median) value as being representative of the true value of the device.

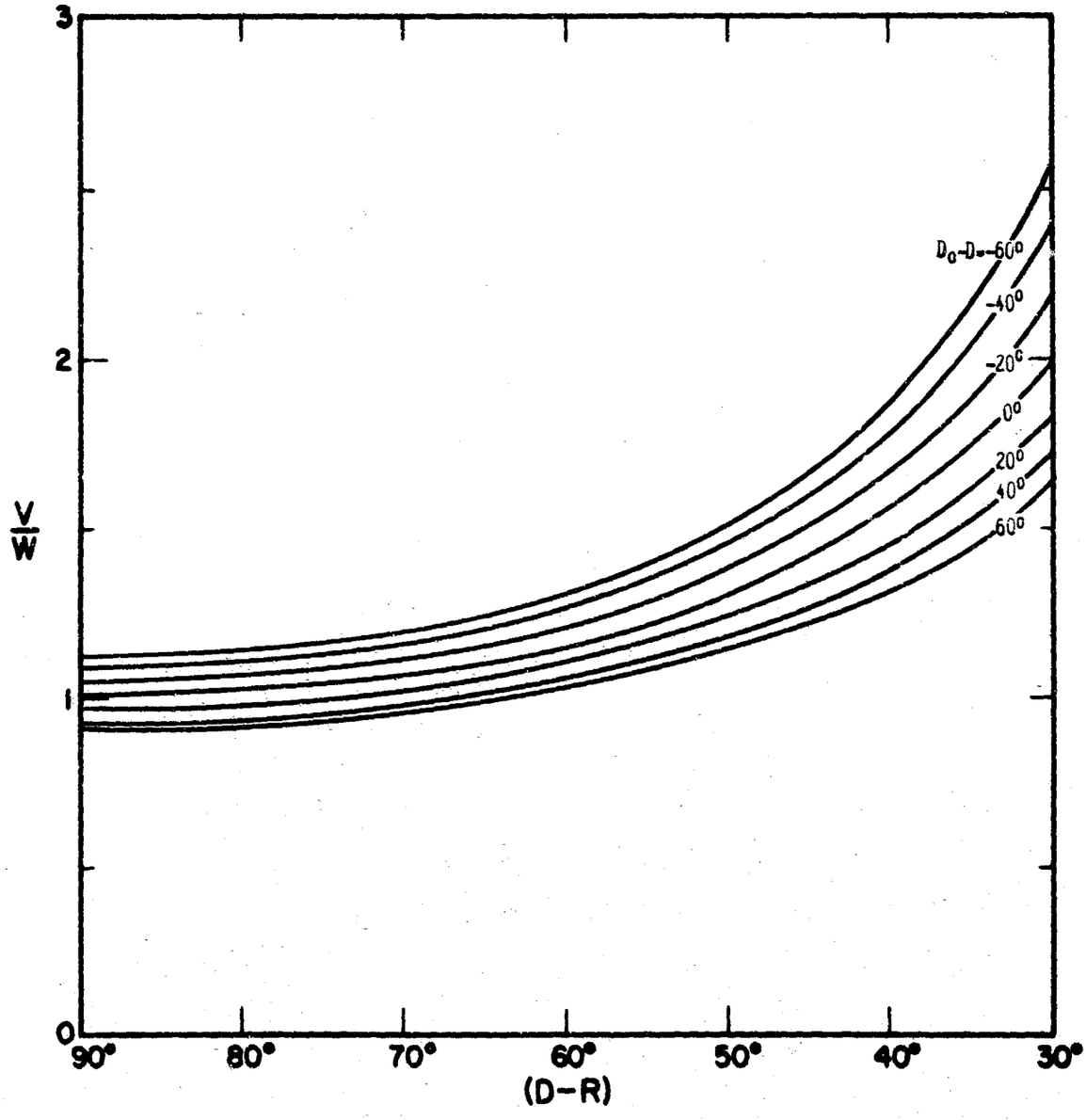

Fig. 8--Values of V/W, the ratio between the distance the vehicle travels in unit time and the crosswind distance between two points in the cloud disseminated unit time apart, as a function of the difference between the sampling time wind direction and the vehicle's course and of the change in wind direction between dissemination and sampling times for the case where the vehicle's speed is eight times the wind speed.

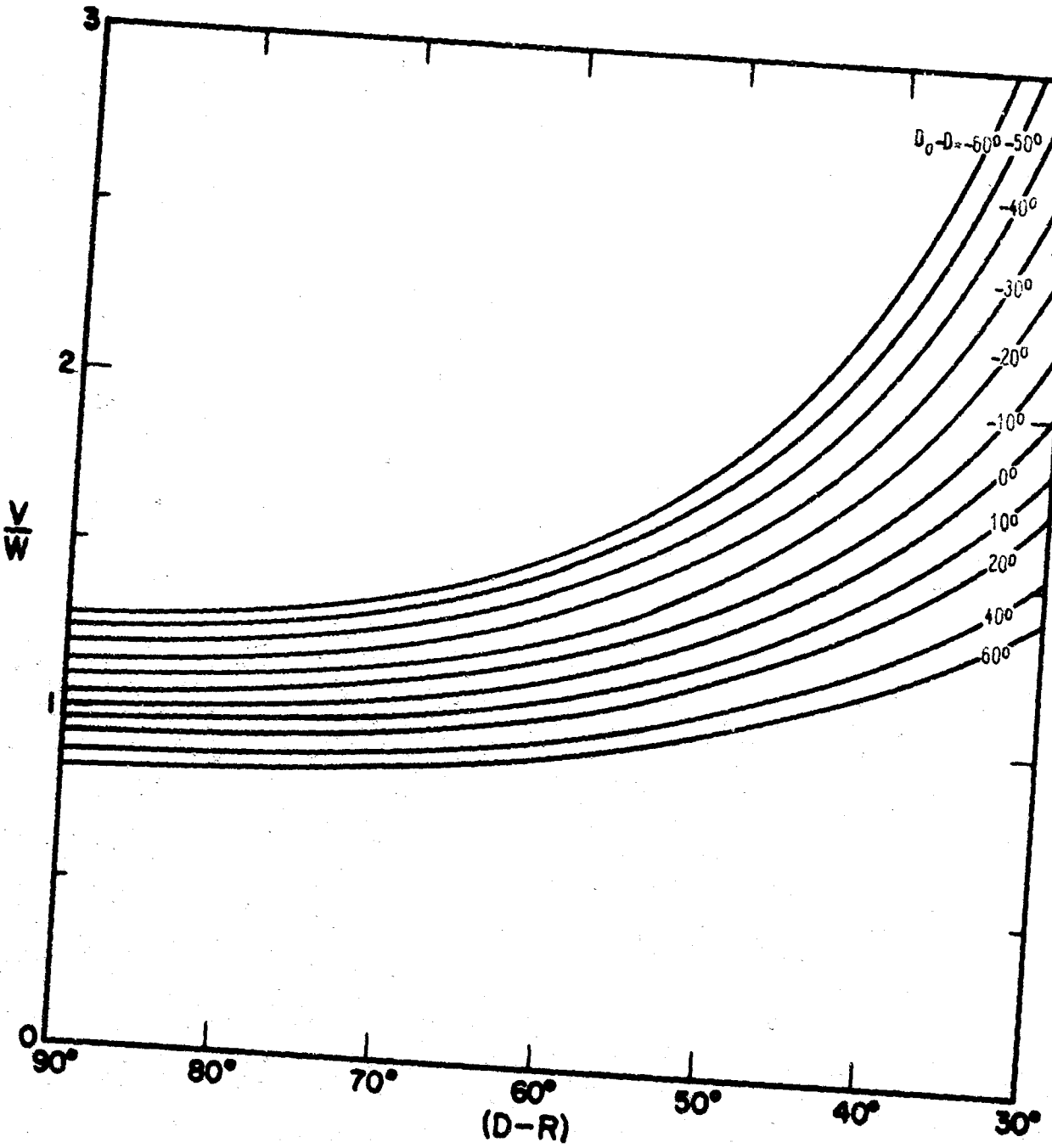

Fig. 9--Values of V/W, the ratio between the distance the vehicle travels in unit time and the crosswind distance between two points in the cloud disseminated unit time apart, as a function of the difference between the sampling time wind direction and the vehicle's course and of the change in wind direction between dissemination and sampling times for the case where the vehicle's speed is four times the wind speed.

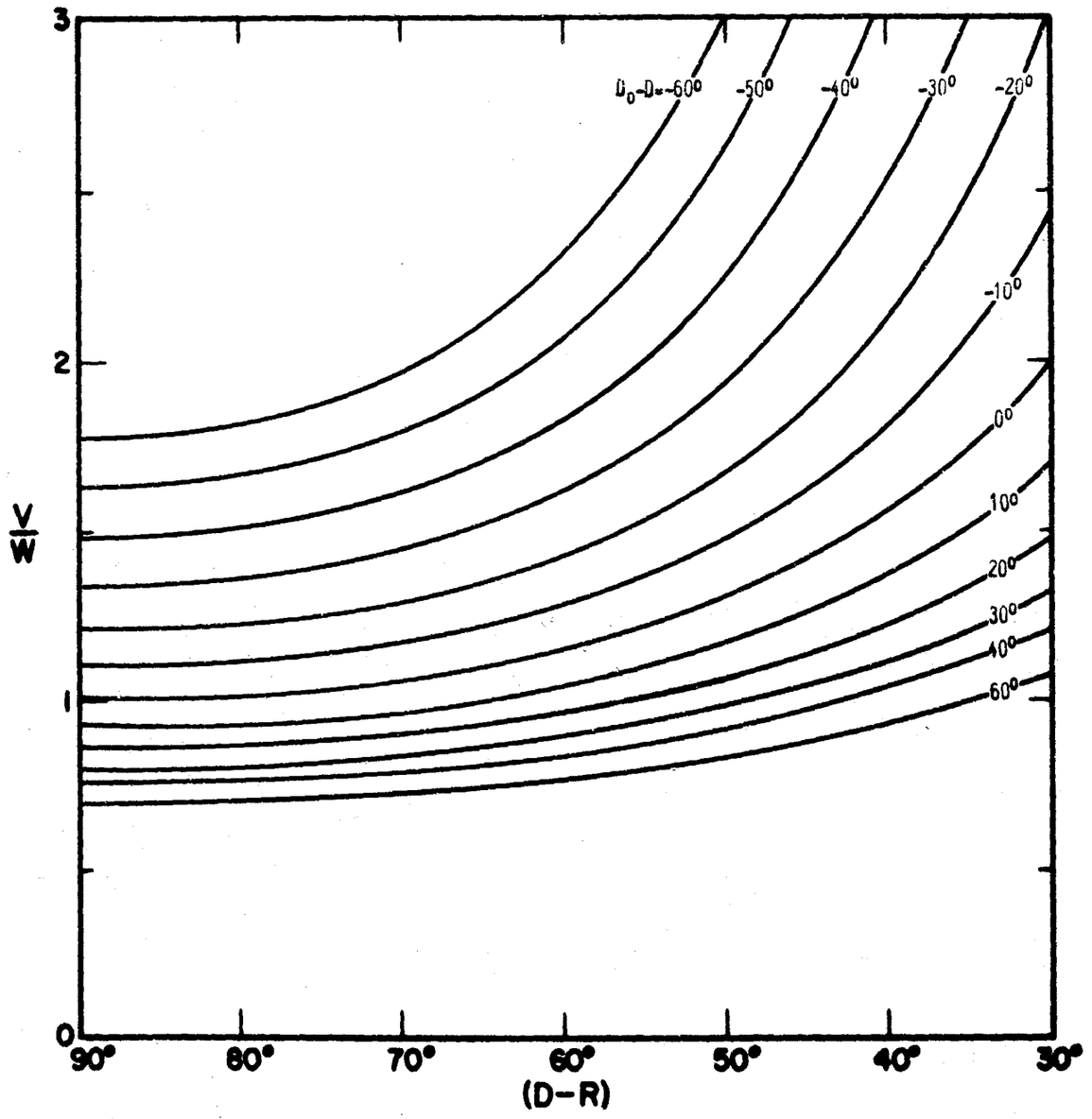

Fig. 10—Values of V/W, the ratio between the distance the vehicle travels in unit time and the crosswind distance between two points in the cloud disseminated unit time apart, as a function of the difference between the sampling time wind direction and the vehicle's course and of the change in wind direction between dissemination and sampling times for the case where the vehicle's speed is twice the wind speed.

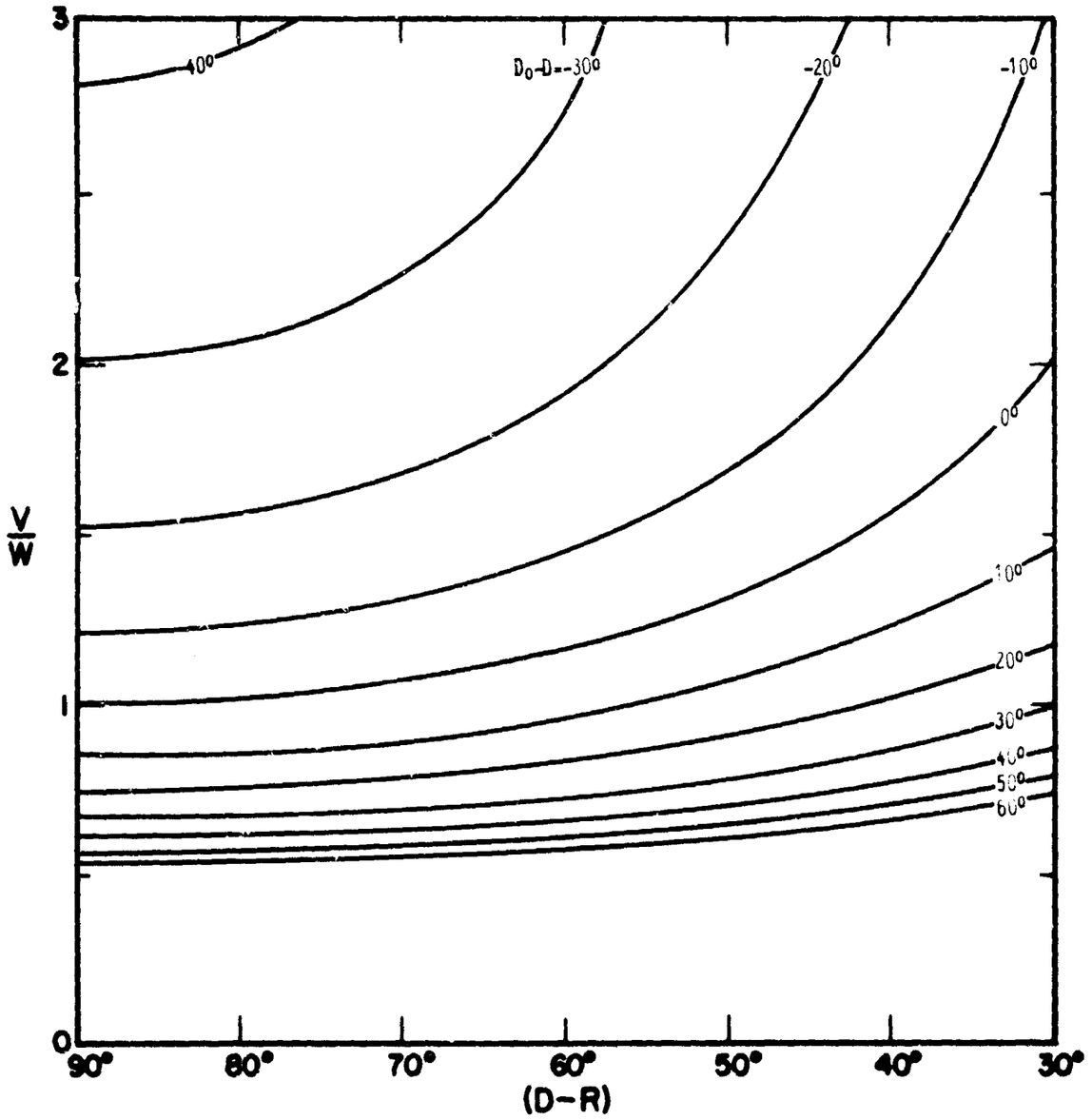

Fig. 11—Values of V/W, the ratio between the distance the vehicle travels in unit time and the crosswind distance between two points in the cloud disseminated unit time apart, as a function of the difference between the sampling time wind direction and the vehicle's course and of the change in wind direction between dissemination and sampling times for the case where the vehicle's speed is the same as the wind speed.