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Technical Report

**A HANDBOOK TO ESTIMATE
CLIMATOLOGICAL CONCENTRATION,
DEPOSITION AND HORIZONTAL
FLUXES OF POLLUTANTS ON
A REGIONAL SCALE**

Monitoring and Assessment Research Centre
Chelsea College, University of London

With the support of
United Nations Environment Programme and
The Rockefeller Foundation

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**A HANDBOOK TO ESTIMATE CLIMATOLOGICAL CONCENTRATION,
DEPOSITION AND HORIZONTAL FLUXES OF POLLUTANTS ON A
REGIONAL SCALE**

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A Technical Report (1979)

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1.0 Introduction

It is now recognized that the air transport of pollutants to distances outside of urban and local industrial areas must be considered for a number of environmental problems. Two general types of problems arise. In the first, the concentration, deposition rate, or horizontal flux (flux through a vertical plane) is required for a specific time: a given hour, day, year, etc. For the resolution of such problems the weather data for that time must be used. In the second type, the average or typical concentration, deposition rate or horizontal flux is required. In this case, average climatic conditions should be used. The present handbook provides calculation procedures only for the second or the climatological properties of pollution after travel to distances of about 100 to 1,000 kilometres (km).

The handbook provides tables and charts to estimate the following items from a continuous source of pollutants emitted from a point or small area:

- (i) Seasonal average ground-level air concentration, \bar{C} .
- (ii) Seasonal average deposition rate, \bar{D} .
- (iii) Seasonal average horizontal flux, \bar{F} (e.g. transport through a vertical plane).
- (iv) An instantaneous centreline or 'peak' ground-level air concentration, C_C , and a measure of its probability of occurrence.
- (v) An instantaneous centreline or 'peak' deposition rate, D_C , and a measure of its probability of occurrence.

By averaging four seasonal values, the average annual concentration may be computed.

The user of this workbook can minimize uncertainties and avoid errors by seeking the advice of air pollution meteorologists available in virtually all national weather services and elsewhere.

2.0 General theory

The calculations for the climatological items, \bar{C} , \bar{D} and \bar{F} are based on dilution of pollutants into sectors radiating from the pollutant source. The probability of pollutants being carried by winds of differing speeds and in different sectors is given by a wind rose, a diagram of the probability or frequency of occurrence of winds according to their speeds and directions. Since wind roses are not normally available for the average heights above the ground at which the pollutant is transported (wind roses are commonly prepared for ground-level winds), the probability statistics are obtained from a vector mean wind speed and direction and vector standard deviations, a measure of the wind variability. The dispersion of pollutants out of the sector or along the wind direction is neglected since, on average, losses are approximately balanced by gains from adjacent plumes. Vertical diffusion occurs and is described by a model using vertical eddy diffusion. Pollutant losses can take place through chemical reactions, radioactive decay, dry deposition and deposition with precipitation.

The calculations for the centreline or 'peak' items, C_C and D_C , include both crosswind and vertical diffusion. The rate of crosswind spreading of the pollutant is based on experience. The removal processes are the same as those listed above.

It is suggested that the appendices be studied prior to performing the calculations on the worksheets and in order to appreciate the assumptions and limitations of the results.

The climatological items \bar{C} and \bar{F} are probably more reliably predicted than \bar{D} but errors of a factor of two or more are possible in each of the items. The centreline or 'peak' items, C_C and D_C , are more uncertain than the climatological values.

3.0 Applications

Air pollutant concentrations, depositions, and horizontal fluxes at distances of 100 to 1,000 km from a continuous point or small area source are useful for a number of purposes as noted below:

- (i) To estimate the average seasonal or annual air concentration and/or deposition rate in the absence of monitoring data, in order to assess risk or the need for monitoring.
- (ii) To estimate a likely maximum short-term or instantaneous concentration or deposition rate and their relative probability of occurrence, in order to assess potential risk or monitoring needs.
- (iii) To estimate the amount of pollutant, on average, crossing national borders in a given time interval.
- (iv) To estimate approximate upper limits for source strength from observations of long-term average air concentration or deposition.
- (v) To apportion the fractions of measured air concentration or deposition rates attributable to selected sources.

4.0 Worksheets

The information requirements and the arithmetic steps to compute the properties \bar{C} , \bar{D} , \bar{F} , C_C and D_C and a measure of the probability of occurrence of C_C and D_C are given in the following worksheets. Notice that all values are converted to fundamental units of grams (g), centimetres (cm), and seconds (s). Wherever local information is considered superior to the estimates used in the worksheets, tables or figures, they should replace the latter.

INPUT INFORMATION

Line	Property	Symbol	Where to find	Value (with units)	Conversion to fundamental units	Fundamental units
1	Source location ^(a)	.....	Locally available map	— Latitude — Longitude		
2	Point at which calculation is desired	.....	Locally available map	— Latitude — Longitude		
3	Distance from source to point given in line 2 ^(b)	S	Locally available map	—	1 statute mile = 1.609×10^5 cm 1 nautical mile = 1.852×10^5 cm 1 km = 10^5 cm	— cm
3a	If source is an area source, is the largest linear dimension less than 0.1S? If answer is "yes", continue. If answer is "no", subdivide the original area into smaller areas until largest linear dimension becomes less than 0.1S. Separate calculations must be performed for each of the smaller areas.					
4	Direction, source towards point given in line 2	θ	Locally available map	— degrees	Measured clockwise from true north	— °
5	Average altitude over travel distance	.....	Locally available topographical map	—	Units may be left in either ft or km	—
6	Season (If annual value is required, obtain average for the four seasons)	.....	.....	—
7	Source strength	Q	Local information	—	(c)	— s ⁻¹

WIND INFORMATION

8	Vector mean wind speed	\bar{V}	Line 5, Table 1, Figure 12	— knots	1 knot = 51.44 cm s ⁻¹	— cm s ⁻¹
9	Vector mean wind direction	$\theta_{\bar{V}}$	Line 5, Table 1, Figure 12	— degrees	.....	— °
10	Vector standard deviation	σ	Line 5, Table 1, Figure 12	— knots	1 knot = 51.44 cm s ⁻¹	— cm s ⁻¹
11	Deposition velocity	V_d	Table 2 or other information	— cm s ⁻¹	.....	— cm s ⁻¹
12	Precipitation rate	\bar{r}	Line 6, Figure 11	— in mo ⁻¹	1 in mo ⁻¹ = 9.81×10^{-7} cm s ⁻¹	— cm s ⁻¹
12a	Precipitation rate anomaly ^(d)	r_a	Line 2, Figure 11 or local weather information	— in mo ⁻¹	1 in mo ⁻¹ = 9.81×10^{-7} cm s ⁻¹	— cm s ⁻¹
12b	Wind direction-precipitation relationship ^(e)					
13	Chemical or radioactive half life	$T_{\frac{1}{2}}$	Table 3 or other source	—	See footnote (c) for time conversion	— s

FOR FLUX THROUGH VERTICAL PLANE

14	Horizontal length of plane	W	Locally available map	See footnote (b)	1 nautical mile = 1/60 degree of latitude = 1.852×10^5 cm; 1 statute mile = 1.609×10^5 cm	— cm
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(a) For an area source, use the centre or area-weighted centre of gravity as the source location. If emissions are markedly uneven over area, use emission-weighted centre of gravity for the source location.

(b) Calculations become progressively less reliable as $S > 1000$ km; other methods to compute concentration, deposition rate, or flux may be superior to this workbook when $S < 100$ km. For flux through a vertical plane, S is the distance to the centre of the plane rather than the point given in line 2.

(c) Pollutant may be in units of grams, lbs (1 lb = 454 grams), tonnes (1 tonne = 10^6 grams), curies, number of atoms, molecules, particles, etc. The concentration will be given in the same units as the source strength. The unit of time (e.g. grams/second) may be second, hour (1 hour = 3.6×10^3 seconds), day (1 day = 8.64×10^4 seconds), month (30-day month = 2.59×10^6 seconds) or year (365-day year = 3.154×10^7 seconds).

(d) If precipitation rate at point given in line 2 exceeds the value selected for line 12 by 25 per cent (e.g. $> 1.25\bar{r}$), use line 12a.

(e) This entry is the factor by which the precipitation rate in line 12 should be multiplied to provide the precipitation rate in the direction of line 4. If no information is available for a wind-direction precipitation relationship, assume a value of 1.0; that is, precipitation rate independent of wind direction.

INTERMEDIATE CALCULATIONS

Line	Quantity sought	Operation	Results
15	Adjusted distance, $1.5S$	Multiply line 3 by 1.5	— cm
16	$\Delta\theta = |\theta - \theta_{\bar{v}}|$	Subtract line 9 from line 4, change negative to positive sign if present	— °
16a	$\cos\Delta\theta$	Using $\Delta\theta$ from line 16 as abscissa, read off value from ordinate from Figure 6	—
16b	$\sin\Delta\theta$	Using $\Delta\theta$ from line 16 as abscissa, read off value from ordinate from Figure 6	—
17	$\bar{v} \cos\Delta\theta$	Multiply line 8 by line 16a	— cm s^{-1}
17a	$\bar{v} \sin\Delta\theta$	Multiply line 8 by line 16b	— cm s^{-1}
18	$\bar{v} \sin\Delta\theta/\sigma$	Divide line 17a by line 10	—
19	$(\bar{v} \sin\Delta\theta/\sigma)^2$	Multiply line 18 by itself	—
20	$1/t_m = \frac{\bar{v} \cos\Delta\theta}{1.5S}$	Divide line 17 by line 15	— s^{-1}
21	$t_\sigma = \frac{1.5S}{\sigma}$	Divide line 15 by line 10	— s
22	σ^2	Multiply line 10 by itself	— cm^2s^{-2}
22a	$1/\sigma^2$	Divide 1 by line 22	— s^2cm^{-2}
22b	$\frac{1}{\pi} e^{-(\bar{v} \sin\Delta\theta/\sigma)^2}$	Enter line 18 as the abscissa of Figure 4 and read value of ordinate	—
22c	$\frac{1}{\pi\sigma^2} e^{-(\bar{v} \sin\Delta\theta/\sigma)^2}$	Multiply line 22b by line 22a	— s^2cm^{-2}
23	\bar{r} (adjusted)	Multiply line 12 by line 12b. If 12b is blank, enter line 12	— cm s^{-1}

INTERMEDIATE CALCULATIONS FOR FLUX THROUGH PLANE

24	$\frac{W}{1.5S}$	Divide line 14 by line 15	—
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INTERMEDIATE CALCULATIONS FOR CENTRELINE CONCENTRATION AND DEPOSITION RATE

25	$\frac{1}{\sqrt{2\pi a S}} = 7.979 \times 10^{-3}/S$	Divide 7.979×10^{-3} by line 3	— s cm^{-2}
25a ^(f)	$\frac{1}{\sqrt{2\pi a S}} (E/H)r = 9.256 \times 10^{-6}/S$	Divide 9.256×10^{-6} by line 3	— cm^{-2}
26	$\frac{V - \bar{v} \cos\Delta\theta}{\sigma}$	Enter acceptable probability as ordinate of Figure 10. Read the abscissa at the intersection of the probability horizontal line and the curve.	—
26a	$V - \bar{v} \cos\Delta\theta$	Multiply line 26 by line 10	— cm s^{-1}
26b	$V = V - \bar{v} \cos\Delta\theta + \bar{v} \cos\Delta\theta$	Add line 26a to line 17; change negative sign to positive sign, if present.	—
26c	$t = \frac{S}{V}$	Divide line 3 by line 26b	— s
26d	r/\bar{r}	Divide an estimated high rainfall by average seasonal rainfall, line 12; ensure that units are identical.	—
26e	Relative probability of rainfall rate, r	Enter line 26d as abscissa of Figure 5 and read relative probability as ordinate	—

FINAL CALCULATIONS

CLIMATOLOGICAL CONCENTRATIONS

27	Integral	Select from Figure 13 the chart corresponding to V_d , line 11; \bar{r} , line 23; and $T_{\frac{1}{2}}$, line 13. Enter value from line 20 as abscissa and line 21 for the curves in the body (see Figure legend for letter identification) and read ordinate (note correction for exponent described in Figure legend). Interpolation may be needed.	— $(\text{cm s})^{-1}$
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^(f) Assumes an arbitrarily high precipitation rate of 10 cm d^{-1} and a value of $E/H = 10 \text{ cm}^{-1}$ rather than 1.02 cm^{-1} in an effort to maximize deposition rates.

Line	Quantity sought	Operation	Results
28	Concentration per unit emission rate	Multiply line 27 by line 22c	— s cm^{-3}
29	Concentration, C(S)	Multiply line 28 by line 7	— cm^{-3}
CLIMATOLOGICAL DEPOSITION RATE			
30	Integral	Select from Figure 13, the one chart corresponding to V_d , line 11 ; \bar{r} , line 23 ; and $T_{\frac{1}{2}}$, line 13. Enter value from line 20 as abscissa and line 21 for curves in the body (see Figure legend for letter identification) and read ordinate (note correction for exponent described in Figure legend). Interpolation may be needed.	— s^{-2}
31	Deposition rate per unit emission rate	Multiply line 30 by line 22c	— cm^{-2}
32	Local precipitation rate anomaly factor	Divide line 12a by line 12. If no entry in line 12a, e.g. no precipitation rate anomaly, enter 1.0	—
32a	Adjustment for local precipitation rate anomaly	Multiply line 31 by line 32	— cm^{-2}
33	Deposition rate	Multiply line 32a by line 7	— $(\text{cm}^2\text{s})^{-1}$
HORIZONTAL FLUX THROUGH A VERTICAL PLANE			
34	Integral	Select from among Figure 13 the one corresponding to the deposition velocity, V_d , line 11 ; the precipitation rate, r , line 23 ; and the half-life, $T_{\frac{1}{2}}$, line 13. Enter value from line 20 as abscissa and line 21 for curves in the body (see Figure legend for letter identification) and read ordinate (note correction for exponent described in Figure legend). Interpolation may be needed.	— cm s^{-2}
35	Flux per unit emission rate per unit length	Multiply line 34 by line 22c	— cm^{-1}
36	Flux per unit emission	Multiply line 24 by line 14	—
37	Flux across vertical plane	Multiply line 36 by line 7	— s^{-1}
CENTRELINE OR 'PEAK' GROUND-LEVEL CONCENTRATION			
38	Vertical diffusion factor	Select curve from Figure 7 corresponding to the deposition velocity, V_d , line 11. Enter t from line 26c as abscissa and read vertical diffusion factor as ordinate from curve. Interpolation may be needed.	— cm^{-1}
39	Half-life factor	Select line from Figure 9 corresponding to the half-life, $T_{\frac{1}{2}}$, line 13. Enter t , line 26c, as abscissa and read half-life from straight line. Interpolation may be needed. If pollutant is stable, $T_{\frac{1}{2}} = \text{infinity}$ and factor is 1.0.	—
40	Product of vertical diffusion and half-life factors	Multiply line 38 by line 39	— cm^{-1}
41	Centreline concentration per unit emission rate	Multiply line 40 by line 25	— s cm^{-3}
42	Centreline concentration	Multiply line 41 by line 7	— cm^{-3}
CENTRELINE OR 'PEAK' DEPOSITION RATE			
43	Dry deposition factor	Select curve from Figure 8 corresponding to the deposition velocity V_d , line 11. Enter t from line 26c as abscissa and read dry deposition factor as ordinate from curve. Interpolation may be needed.	—
44	Product of dry deposition and half-life factors	Multiply line 43 by line 39	—
45	Centreline deposition per unit emission rate	Multiply line 44 by line 25a	— cm^{-2}
46	Centreline deposition	Multiply line 45 by line 7	— $(\text{cm}^2\text{s})^{-1}$

Appendix A – Theory

I Climatological average ground air concentration

The instantaneous ground-level air concentration, C , at a distance, S , and direction, θ , from a continuous point source can be given by :

$$C = \frac{Q}{V S \delta \theta} R(t) \quad \dots (1)$$

where V is the wind speed, $\delta \theta$ is a small sector centred on the direction θ and $R(t)$ is a term which accounts for vertical atmospheric dispersion, t is the time of transit from pollution source to a distance, S , and Q is the rate of emission of the pollutant. In the time interval over which the average concentration is determined, the wind speed (and direction) can vary. Usually this statistical variability is given by a wind rose which provides the probability or frequency of wind occurrence in sectors and within wind speed intervals.

The pollutant material is assumed to be transported by winds either at 850 millibars (mbar) pressure altitude or about 1.5 km (5,000 ft) above mean sea level (amsl), or at 700 mbar, about 3 km (10,000 ft) amsl, depending on terrain elevation as given in Table 1. Wind roses are not normally available for these altitudes. Instead, the vector mean wind speed, \bar{v} , and direction, $\theta_{\bar{v}}$, and the vector standard deviation, σ , have been mapped globally and used as a substitute for wind roses. Figure 1 shows an example of a vector mean wind blowing from the north-west with a circle of radius σ , the vector standard deviation, drawn around its endpoint. Given \bar{v} , $\theta_{\bar{v}}$, and σ , the probability density of winds from various directions and speeds may be found at any point.

The probability per unit wind speed (e.g. the probability of a wind speed between V and $V + \delta V$) in the direction $\theta \pm \frac{1}{2} \delta \theta$ can be written (Brooks *et al.* 1950) as :

$$\frac{1}{\pi \sigma^2} e^{-\frac{(\bar{v} \sin \Delta \theta)^2}{\sigma^2}} e^{-\frac{(V - \bar{v} \cos \Delta \theta)^2}{\sigma^2}} V \delta \theta \quad \dots (2)$$

where $\Delta \theta$ is the angle between the direction from source toward the point at which the concentration is desired and the vector mean wind direction, $\theta_{\bar{v}}$ (see Figure 1). The mean concentration over all wind speeds along the direction θ properly weighted by their probability of occurrence becomes :

$$\bar{c}(s) = \frac{Q}{\pi \sigma^2} e^{-\frac{(\bar{v} \sin \Delta \theta)^2}{\sigma^2}} \frac{1}{S} \int_0^{\infty} R(t) e^{-\frac{(V - \bar{v} \cos \Delta \theta)^2}{\sigma^2}} dv \quad \dots (3)$$

The integral can be converted to :

$$S \int_0^{\infty} R(t) e^{-\left(\frac{1}{t} - \frac{1}{t_m}\right)^2 t \sigma^2} \frac{1}{t^2} dt \quad \dots (4)$$

where $t_m = \frac{S}{V \cos \Delta \theta}$ and $t_\sigma = \frac{S}{\sigma}$. This latter integral has been evaluated with an electronic computer and its results provided as the graphs, Figure 13. The full form for the long-term average concentration is :

$$\bar{c} = \frac{Q}{\pi \sigma^2} e^{-\frac{(\bar{v} \sin \Delta \theta)^2}{\sigma^2}} \int_0^{\infty} R(t) e^{-\left(\frac{1}{t} - \frac{1}{t_m}\right)^2 t \sigma^2} \frac{1}{t^2} dt \quad \dots (5)$$

The same form for \bar{c} applies if there is dry and/or wet deposition except that $R(t)$ is different.

The values of $R(t)$ have been computed with an electronic computer using vertical diffusion and, as appropriate, wet and/or dry deposition (Draxler and Elliot 1977). The vertical diffusion obeys a law such that the vertical flux is proportional to the vertical gradient of concentration; the proportionality coefficient is called the coefficient of eddy diffusion. The values of this coefficient appear in Figure 2 (Draxler and Elliot 1977). The transfer of material is calculated only in the vertical direction as a function of time. The finite difference scheme employs boxes of unit horizontal area between 0 and 14 km, the vertical dimension of each successive box increases logarithmically upward with the bottom box 30 metres in depth. No material transfers through 14 km and there is no diffusion through the model bottom. Each time step in the iterative process is 120 seconds long to ensure computational stability. Air density decreases with altitude according to the U.S. Standard Atmosphere; the density of the ground level box is $1.223 \times 10^{-3} \text{ g cm}^{-3}$. A unit input, say one gram or one curie, is inserted during the first time step into the bottom box and thereafter no input occurs.

Dry deposition removes the pollutant material from the bottom box only; according to

$$\frac{1}{C} \frac{dC}{dt} = -V_d \quad \dots (6)$$

during every time step where C is the concentration in the bottom box at each time step and V_d is the dry deposition velocity. The loss to the column by dry deposition is felt at higher altitudes by vertical diffusion.

Wet deposition removes pollutant material from a pre-assigned thickness, a rain (or precipitation) bearing layer H, according to

$$\frac{1}{C_H} \frac{dC_H}{dt} = \frac{-Er}{H} \quad \dots (7)$$

during each time step. C_H is the average of concentrations in each box between O and H, and E is the ratio of pollutant concentration in deposited rainwater (or snow water) to average air concentration in the layer O to H; r is the intensity of precipitation. Again, adjustment to losses in the layer from the ground to H are felt at altitudes above H through vertical diffusion.

II Deposition

It can be shown that the average deposition rate due to dry and/or wet deposition, \bar{D} , can be computed from the formula

$$D = \frac{Q}{\pi\sigma^2} e^{-(\bar{V}\sin\Delta\theta)^2/\sigma^2} \int_0^{\infty} D^*(t) e^{-\left(\frac{1}{t} - \frac{1}{t_m}\right)^2 t \sigma^2} \frac{1}{t^2} dt \quad \dots (8)$$

which is analogous to that for air concentration with $D^*(t)$ replacing $R(t)$. $D^*(t)$ is calculated from the same assumptions described above for dry and wet deposition. It modifies $R(t)$ by the loss to the atmospheric column due to dry and/or wet deposition. The average deposition rate has the dimensions of an amount of material deposited per unit area per unit time at a distance S and direction θ from the continuous point source. To obtain the total deposition for a month, season, etc., \bar{D} must be multiplied by the number of seconds in the time interval (e.g. $30 \times 86,400$ seconds in a 30-day month).

III Transport through a Vertical Plane

Figure 3 exhibits the geometry (in plan view) for the case of transport through a vertical plane, AB, extending from the ground to the top of the atmosphere. The angle ϕ is presumed to be reasonably small so that the transport across arc A'B' approximates the transport across the plane AB. The transport, F, across A'B' can be shown to be equal to

$$F = \frac{Q}{\pi\sigma^2} e^{-(\bar{V}\sin\Delta\theta)^2/\sigma^2} \phi \int_0^{\infty} q(t) e^{-\left(\frac{1}{t} - \frac{1}{t_m}\right)^2 t \sigma^2} \frac{1}{t^3} dt$$

or

$$F = \frac{Q}{\pi\sigma^2} e^{-(\bar{V}\sin\Delta\theta)^2/\sigma^2} \frac{W}{S} \int_0^{\infty} q(t) e^{-\left(\frac{1}{t} - \frac{1}{t_m}\right)^2 t \sigma^2} \frac{1}{t^3} dt \quad \dots (9)$$

where $q(t)$ is the amount of pollutant material in the atmospheric column when it crosses the vertical plane (e.g. the initial one unit minus the losses up to the time, t) and has been obtained from the same model calculations as for the ground-level concentrations and deposition rate.

The transport has the dimensions of the amount of material per unit time crossing the infinitely tall vertical plane subtending an angle ϕ with the source point or having a width, W. To obtain transport across the plane in a month, season, etc., F must be multiplied by the number of seconds in the time interval (e.g. $30 \times 86,400$ seconds in a 30-day month).

IV Centreline or 'peak' concentration

The centreline or 'peak' concentration at ground level, C_C , from a continuous point source is

$$C_C = \frac{QR(t)}{\sqrt{2\pi}\sigma_h V} \quad \dots (10)$$

where σ_h is the standard deviation of the crosswind (horizontal) spread of a pollutant; other symbols have been defined earlier. Based on empirical experience (Heffter and Ferber 1975), we assume that on a scale of travel from about 100 to 1,000 km $\sigma_h = at$, where t is in seconds and $a = 50 \text{ cm s}^{-1}$. Further, since $t = S/V$

$$C_C = \frac{QR(t)}{\sqrt{2\pi} a S} \quad \dots (11)$$

The probability density at wind speed, V, and direction $\Delta\theta$ of the mean wind velocity is

$$\frac{1}{\pi\sigma^2} e^{-(\bar{V}\sin\Delta\theta)^2/\sigma^2} e^{-(V-\bar{V}\cos\Delta\theta)^2/\sigma^2} \quad \dots (12)$$

Given \bar{V} , σ , and $\Delta\theta$, the probability density at V and $\Delta\theta$, relative to that at \bar{V} and $\theta_{\bar{V}}$, may be calculated from Figure 4.

The maximum air concentration will occur when there is no wet deposition; hence precipitation is taken as zero. Further, the maximum will occur with no meander so that this factor, 1.5, described in Appendix C-2, is taken as unity. Finally, the values for $R(t)$ are based on smaller than average coefficients of vertical diffusion. The vertical distribution of coefficients of eddy diffusion appears in Figure 2 labelled as 'stable'.

V Centreline or 'peak' deposition

In contrast to the assumption in the above section, the 'peak' deposition will occur when the first (and heavy) rain occurs at the plume centreline over the point of interest with no prior wet deposition. If the amount of pollutant in a column is designated as $q(t)$ (the initial input less that deposited in dry deposition up to time, t), then the wet deposition at time, t is given by

$$D_c = \frac{Q q(t)}{\sqrt{2\pi} a S} (E/H)r \quad \dots (13)$$

The quantity, $q(t)$, represents the column content to the top of the model atmosphere (e.g. to 14 km rather than to the depth of the rain-bearing layer, 4.0 km). Except at very late times, most of the pollutant material lies below 4.0 km so that relatively minor errors are introduced in equation (13) by using $q(t)$ rather than the pollutant content to the height H (4.0 km). Use of $q(t)$ thus produces slightly too much deposition. To maximize the deposition further, (E/H) has been taken as 10 cm^{-1} rather than 1.02 cm^{-1} and r as 10 cm d^{-1} .

$$(E/H)r = 1.157 \times 10^{-3} \text{ s}^{-1}$$

Values of $\frac{1}{\sqrt{2\pi} a S}$ can be multiplied by $1.157 \times 10^{-3} \text{ s}^{-1}$ to yield the deposition ($\text{cm}^{-2} \text{ s}^{-1}$) for a unit emission rate. Other maximum rainfall rates and values for the parameter (E/H) or Λ (see Appendix A-4) can be substituted in the formula $(E/H)r$ if other values are deemed preferable.

The relative probability of high deposition rates depends both on the probability of maximizing wind speeds and the probability of precipitation scavenging. This latter probability should be found from proper local or regional rainfall statistics. In the absence of such statistics, one may use the rainfall probability distribution assumed in Appendix B-1 : $P(r) = e^{-r/\bar{r}}$. This relative probability distribution appears in Figure 5. The total relative probability is the product of the wind speed and rainfall probabilities assuming no correlation between wind speed (or direction) with rainfall distributions.

Appendix B – Precipitation scavenging

I Theory

A true mathematical representation of the physical processes of precipitation (the word rain will be substituted for precipitation hereafter) scavenging of air pollutants is either unavailable or too complex for practical application. Plausible but grossly simplified formulations are substituted for the correct ones. While a similar simplification of reality permeates the entire workbook, the case of rain scavenging is highlighted because the uncertainty of wet deposition measurement is particularly important.

At least two, more or less equivalent, formulations are often given. The first has been used in this workbook (Appendix A-1) as equation (7).

A second formulation refers to (E/H) as Λ , the wet deposition rate, with the dimensions of 1/amount of water (e.g. cm^{-1}). Values of Λ range, in general, from one to 10 cm^{-1} while the value of (E/H) used in this workbook is 1.02 cm^{-1} (Johnson *et al.* 1975).

From the maps discussed in the next section, one may obtain climatological monthly rainfall rates denoted by r . This monthly rain is composed of periods of no rain, rates less than r , and greater than or equal to r , each different rainfall rate yielding its own air concentration and deposition rate. To cope with this dependency upon rainfall rate, the model quantity $R(t)$, $D^*(t)$ or $q(t)$ must be weighted by a rainfall probability function. The latter is assumed to be of the form

$$P(r) = e^{-r/\bar{r}} \quad \dots (14)$$

The model values of $R(t)$ and $q(t)$ suggest that

$$\begin{matrix} R(t,r) \\ q(t,r) \end{matrix} = \begin{matrix} R(t,o) \\ q(t,o) \end{matrix} e^{-(E/H)\bar{r}t} \quad \dots (15)$$

provided r and t are not too large. For average rainfall rates, r , up to $10^{-5} \text{ cm s}^{-1}$ (about 1 cm d^{-1}) and travel times, t , up to about five days, the above exponential form reproduces the model values to within a few per cent. It becomes less reliable at greater rainfall rates and times.

It may be shown that with the two above assumed exponential forms, equations (14) and (15), the value of $R(t)$ or $q(t)$ to be used for climatological rainfall rate, r , becomes

$$\begin{matrix} R(t,r) \\ q(t,r) \end{matrix} = \begin{matrix} R(t,o) \\ q(t,o) \end{matrix} \frac{1}{(E/H)\bar{r}t + 1} \quad \dots (16)$$

The deposition rate is the sum of dry plus wet deposition rates. The dry deposition rates are computed simply by multiplying C by V_d , the dry deposition velocity. C can be found from Appendix A using the value for $R(t,r)$ from equation (15). The wet deposition rate at time t is approximated from the integral

$$\bar{D}_{\text{wet}}(t,\bar{r}) = (E/H) \frac{1}{\bar{r}} \int_0^{\infty} q(t,o) e^{-(E/H)rt} r e^{-r/\bar{r}} dr \quad \dots (17)$$

or

$$\bar{D}_{\text{wet}}(t,\bar{r}) = q(t,o) \frac{E \bar{r}}{H} \frac{1}{[(E/H)\bar{r}t + 1]^2} \quad \dots (18)$$

II Adjustment for a different scavenging efficiency

The value of $(E/H) = 1.02 \text{ cm}^{-1}$ may be considered to be in error (e.g. too small) by some experts. Since (E/H) and r always appear as a product, one can easily assume a value of (E/H) different from 1.02 cm^{-1} . Thus, for example, if the preferred value of (E/H) is 2.04 cm^{-1} rather than 1.02 cm^{-1} , one may use twice the actual rainfall rate to double the quantity E/H . The correction for new values of (E/H) is not exact because both diffusion and the probability distribution of rainfall rates depend on the average rainfall rate, \bar{r} . The sense of the correction for changes in the values of (E/H) will be right but the corrected air concentration and deposition rate may not have been modified by the proper factors.

III Precipitation maps

Maps of Northern Hemisphere rainfall for each month of the year over land areas have been given by Shaw (1936). From these, the central month of each season has been selected to be representative of the season, and these are shown in Figure 11.

It should be noted that the maps are not modern. The user is encouraged to obtain seasonal rainfall rates from local climatological data wherever possible.

IV Precipitation and wind direction correlation

The theory of this workbook assumes that rainfall is randomly distributed with respect to wind speed and direction. There are many areas of the world where studies have shown that rain occurs preferentially in certain wind direction sectors. Unfortunately, no general study of the correlation between rain and 850 or 700 mbar wind direction is available. When known from local information, however, the correction for a non-random rain distribution is easily applied. For example, if the observed annual rainfall rate is $40 \times 10^{-7} \text{ cm s}^{-1}$, but statistical analyses reveal only half as much rain when winds blow in the sector containing the direction from pollutant source to the point of interest (e.g. the direction θ in Figure 1), then one merely uses $20 \times 10^{-7} \text{ cm s}^{-1}$ rather than $40 \times 10^{-7} \text{ cm s}^{-1}$.

V Precipitation variability

Rainfall is highly dependent on orography. For example, the windward side of mountain ranges receives more than the average rainfall, the lee side generally less. The most important consequence of localized rainfall anomalies is the deposition rate within the locality itself. Air concentration farther downwind will, of course, be modified but this is less marked since the rainfall anomaly is limited to a comparatively short distance along the travel distance, S .

If the sampling point lies within an area of anomalously high rainfall, r_a , embedded within a broader area of rainfall, \bar{r} , then the deposition should be increased by $\frac{\bar{r}_a}{\bar{r}}$. This correction is only approximate.

The use of average rainfall along S should be adequate for normal geographic variability. As a second approximation, if there is a marked gradient along S , slightly greater weight should be given to that portion of the region near the source. The same rainfall near the source will remove more of the pollutant because the concentration is higher than in the region more remote from the source where the concentration is lower due to dry and wet deposition and vertical diffusion.

Appendix C—Wind data

I The charts

Visual or electronic tracking of balloons is made at least once per day at many weather stations over the globe. The winds at such stations may be used to compute the vector mean wind speeds and directions and vector standard deviations. Isolines drawn from station data appear on Figure 12.

The terrain altitude varies over the globe. Figure 12 provides wind statistics for 850 mbar or about 1,500 metres (5,000 ft) above mean sea level (amsl) and at about 700 mbar or about 3,000 metres (10,000 ft) amsl. It is felt that air motions about 1,500 metres above terrain may represent travel of ground source pollutants to distances of about 1,000 km. Table 1 suggests a scheme for selecting the 850 and 700 mbar charts.

Northern Hemisphere charts (Crutcher 1959) provide seasonal mean values of \bar{V} , $\theta\bar{v}$, and σ . The average values of the three statistical properties, \bar{V} , $\theta\bar{v}$, σ , may be averaged over the distance between the source of pollution and the point of interest rather than at either end of the line joining the two points.

II Meandering paths

Every statistical study of individual air trajectories on a regional scale reveals meander, in contrast to the assumption of flow in a straight line used in this workbook. To correct partially for the meander, a factor will be applied to the distance, S , which tries to allow for the average longer path than a straight line. Experience with actual regional-scale trajectories suggests that, on average, the travel distance should be 1.5 times greater than the straight line distance. This factor of 1.5 will be included in all the climatological calculations. However, its identity will be preserved so that other choices can be made if evidence or experience suggests a value other than 1.5.

III Orographic effects on air flow

Unfortunately, for air transport and dispersion, the irregularities of the earth's surface produce significant departures from the general air movements described by Figure 12. Topographic wind anomalies have been studied extensively in certain areas. A few general rules can be given but it is recommended, if possible, that local professional meteorological advice be sought if the terrain is not relatively flat.

Air tends to flow up or down valleys rather than across them. This tendency is normally more marked at night than during the day. The anomalies introduced by land-water interfaces depend on the relative temperature of the two surfaces. Superimposed on the overall prevailing air flow will be an additional wind component blowing from the colder towards the warmer surface.

Appendix D – Area and elevated sources

I Area source

The theory in Appendix A specifically designates the pollutant as originating continuously from a point source. But the calculations may also apply to area sources provided certain conditions are met. These conditions demand that the largest linear dimension of source area be small (<0.1) relative to the travel distance and that the emissions be relatively homogeneous over the source area. It is always possible to subdivide the original area and, by treating smaller ones, conform more closely to the above requirement.

The pollutant source strength (e.g. grams per second) will be the integrated value over the area. The imaginary point source which replaces the area emission will be taken at the approximate centre or centre of gravity of the area. Generally, the area-weighted centre of gravity can be selected by visual inspection. If there are significant inhomogeneities in the source strength over the area, weighting by emission rates should be used. If the ratio of area dimension to travel distance is small, the error in selecting the origin will have small effects on the calculations.

II Elevated source

Many pollutant sources are elevated due to the height of emission (e.g. a chimney) and/or the rise of the plume. Since the present document treats travel beyond about 100 km, the altitude of the plume is unimportant, except possibly for one case. Elevated sources have little or no early dry deposition; ground or near ground sources can deposit a sizeable fraction (~ 25 per cent) in the first hour of travel for $V_d = 1.0 \text{ cm s}^{-1}$. Part of this dry deposition will not, of course, occur from an elevated source.

Appendix E – Chemical or radioactivity losses

Many pollutants chemically transform into other substances while travelling through the atmosphere. Radioactive pollutants are lost by radioactive decay. These losses are readily treated provided they obey first-order kinetics: that is, the loss is proportional to the amount of the chemical present at any time. Mathematically, chemical changes obeying first-order kinetics are identical to those for radioactive decay. The rate-of-loss parameter is the half-life, $T_{\frac{1}{2}}$, the time taken to reduce the concentration by chemical reactions or radioactive decay to half of its original value.

The integrals of equation (5) and (8) can be replaced by

$$\frac{\bar{C}}{D} = \frac{Q}{\pi\sigma^2} e^{-(\bar{V}\sin\Delta\theta)^2/\sigma^2} \int_0^{\infty} e^{-\frac{0.693t}{T_{\frac{1}{2}}}} \left\{ \frac{R(t)}{D^*(t)} \right\} e^{-\left(\frac{1}{t} - \frac{1}{t_m}\right)^2 t \frac{1}{t_m^2}} dt \quad \dots (19)$$

The formula for the centreline or 'peak' concentration and deposition can be written as

$$C_c(S) = \frac{QR(t)}{\sqrt{2\pi}aS} e^{-0.693t/T_{\frac{1}{2}}} \quad \dots (20)$$

$$D_c(S) = (\text{Deposition given in Appendix A-V}) \cdot e^{-0.693t/T_{\frac{1}{2}}} \quad \dots (21)$$

The factor, $e^{-0.693t/T_{\frac{1}{2}}}$, can be determined in Figure 9 given the half-life, $T_{\frac{1}{2}}$, and the travel time t .

Acknowledgements

The author wishes to thank Professor Gordon Goodman for his invitation to work at the Monitoring and Assessment Research Centre under his directorship when this report was written.

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- (5) Shaw, N. 1936 *Manual of Meteorology*, vol. II: *Comparative Meteorology*. Cambridge: University Press.
- (6) Crutcher, H. L. 1959 Upper Wind Statistics Charts of the Northern Hemisphere (850, 700, and 500 mb levels). NAVAER 50-1C-535 vol. I. U.S. Navy.

Table 1 The Selection of the transport altitude

Average terrain height above mean sea level		Chart(s) to be used											
Metres	Feet	..	..	..	..	..	..	..	..	..	..	..	..
0–600	0–2000	..	..	..	..	..	..	..	..	..	..	..	850 mb
600–1500	2000–5000	..	..	..	..	..	..	..	..	..	..	..	Average of 850 and 700 mb
1500–2100	5000–7000	..	..	..	..	..	..	..	..	..	..	..	700 mb

Table 2 Deposition velocity*, V_d

													V_d $cm\ s^{-1}$
Gases													
Reactive gases (reactivity often depends on type of surface) Examples : sulphur dioxide, ozone, radioiodine													1.0
Non-reactive, relatively insoluble gases Examples : noble gases, chlorofluorocarbons													0.0
Particles													
Very large ($> 10\ \mu m$)													≥ 1.0
Large (5-10 μm)													0.3
Small ($< 5\ \mu m$)													
Forested areas													0.3
Most other types of surface													0.1

* Information on deposition velocities is imperfect. Differences in values occur between investigators. Values in table are subject to change. Deposition velocities often depend sensitively on type of surface (grass, water, forests, etc.), on wind speed and atmospheric stability.

Table 3 Chemical and radioactive half-life, $T_{1/2}$

Chemical half-lives*													$T_{1/2}$
Sulphur dioxide													
Highly polluted													1 hour
Ordinary (not unusually dry)													3 days
Clean or dry													10 days
Ozone (near ground)													3 hours
Nitric oxide (in sunlight)													3 hours
Nitrogen dioxide (in sunlight)													3 hours
Nitrous oxide													Infinite
Chlorofluorocarbons													Infinite
Radioactive													
Xenon-133													5.3 days
Iodine-131													8 days
Xenon-131													11.8 days
Tritium (H-3)													12.5 years
Strontium-90													28 years
Caesium-137													30 years
Plutonium radioisotopes													> 90 years
Carbon-14													5,730 years
Radon-222													3.8 days
Radon daughters													minutes to 22 years

*Chemical half-lives are highly uncertain and probably variable. The range of uncertainty due to ignorance of the chemical half-life may be estimated by calculating air concentration, flux, and/or deposition for plausible limits in the chemical half-life.

Figure 1. Graphical representation of symbols.

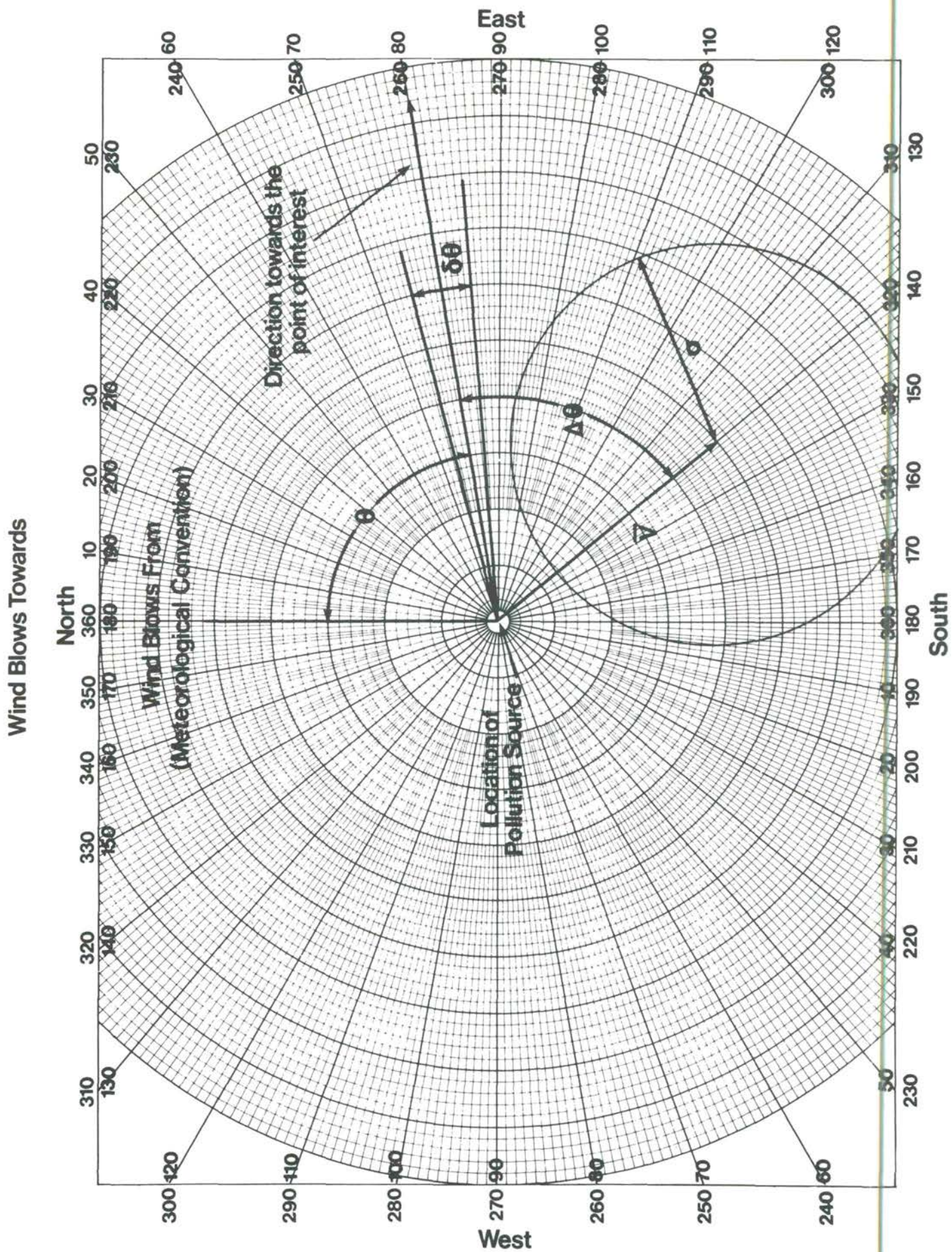


Figure 2. Vertical distribution of vertical eddy diffusion coefficient, K_z , for two types of atmospheric stability. The solid line applies to normal or average stability; the dashed line, which coincides with the solid line above 0.3 kilometres, deals with stable (small vertical mixing) conditions or slow diffusion. The tropopause caps the model at 12 kilometres, the top of the solid horizontal line. The neutral stability profile of K_z is used in all of the calculations except those maximizing ground level concentrations.

(Adapted from: Draxler, R. R. and Elliot, W. P. 1977. Long-range travel of airborne material subjected to dry deposition. *Atmospheric Environment* **11**, 35-40)

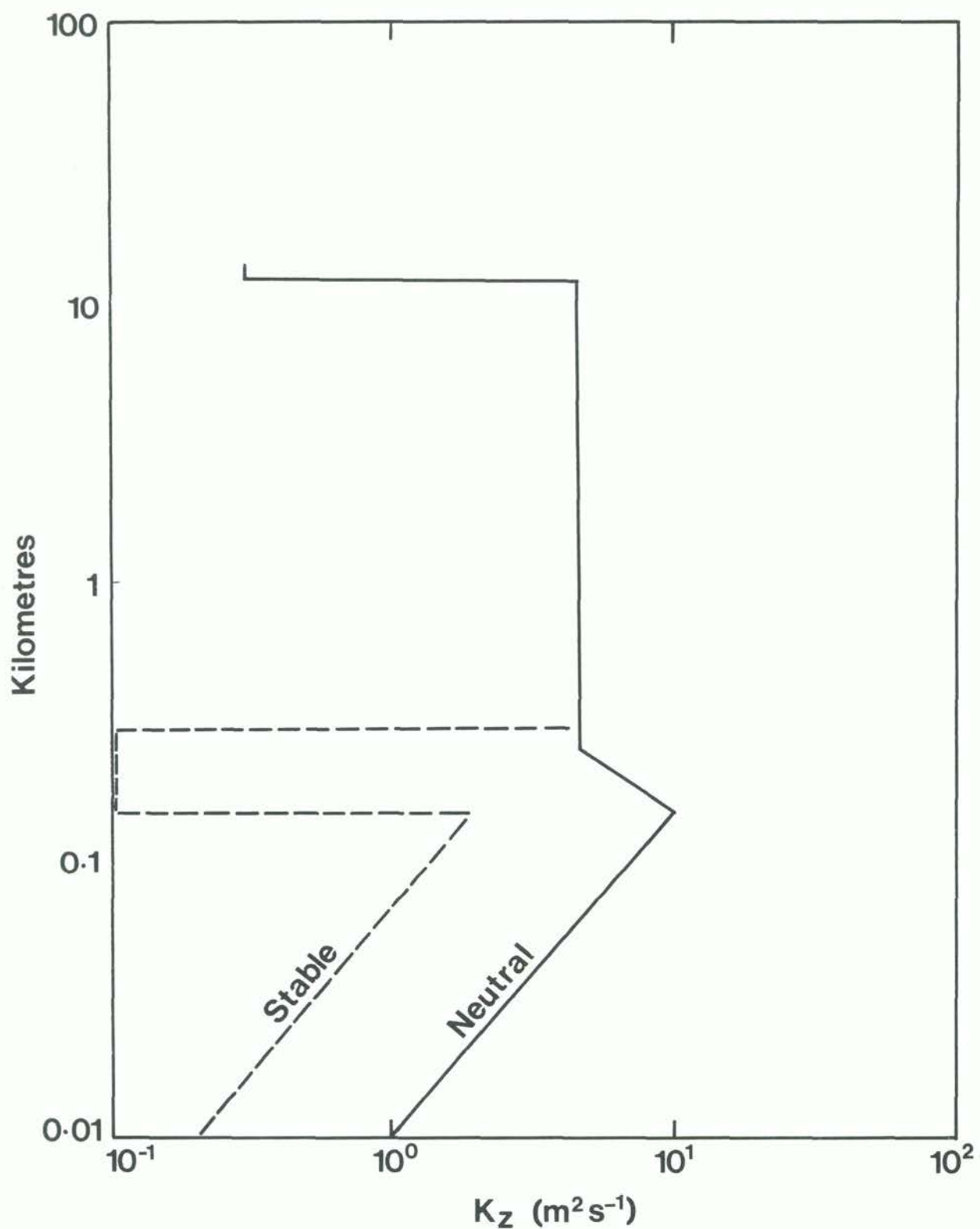


Figure 3. Graphical representation of symbols used for flux across vertical plane.

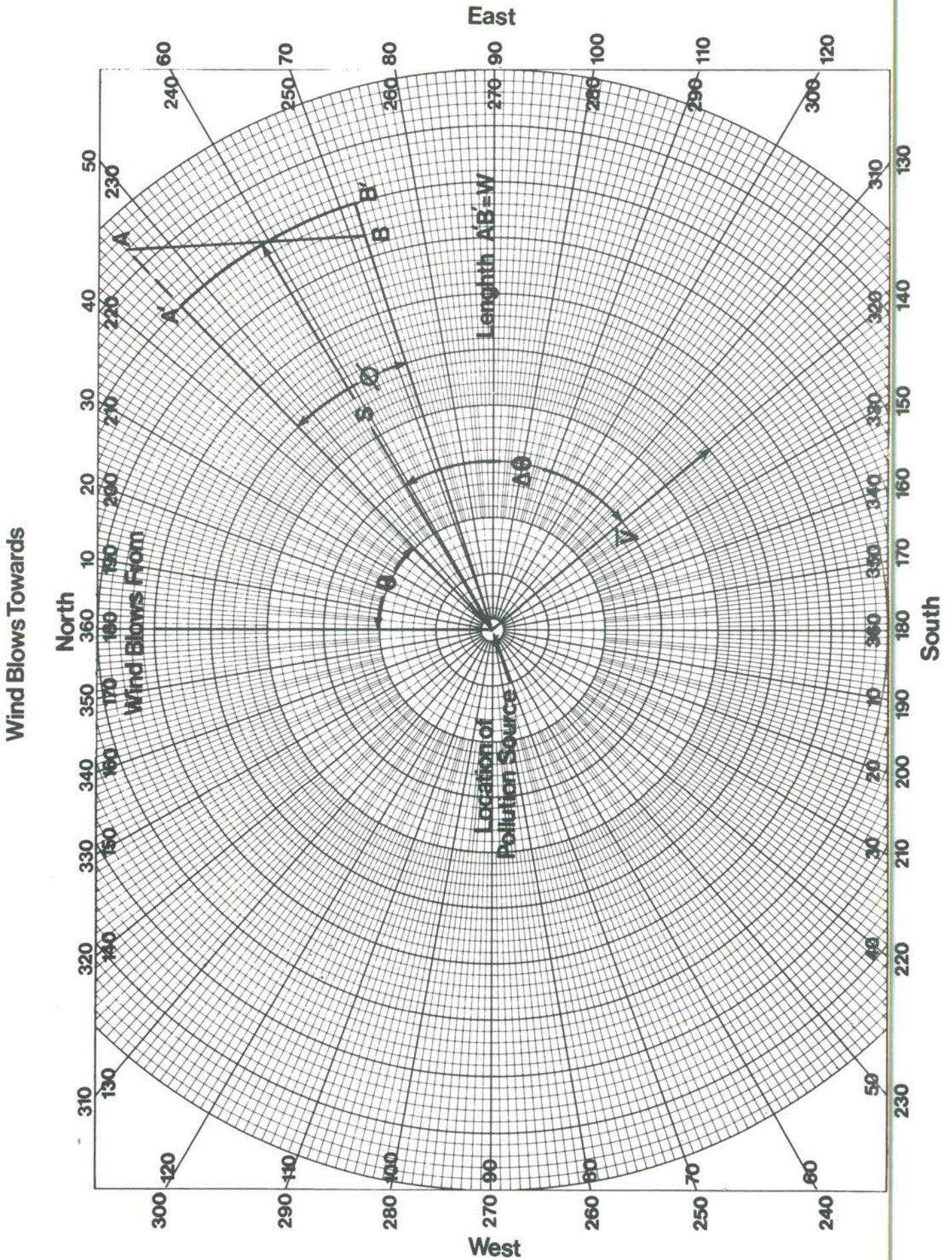


Figure 4. A graph to estimate values of probability from a Gaussian or normal probability curve. The abscissa (horizontal scale) depends on the wind speed and is normalized by the standard deviation of wind variability. The ordinate (vertical scale) is the probability.

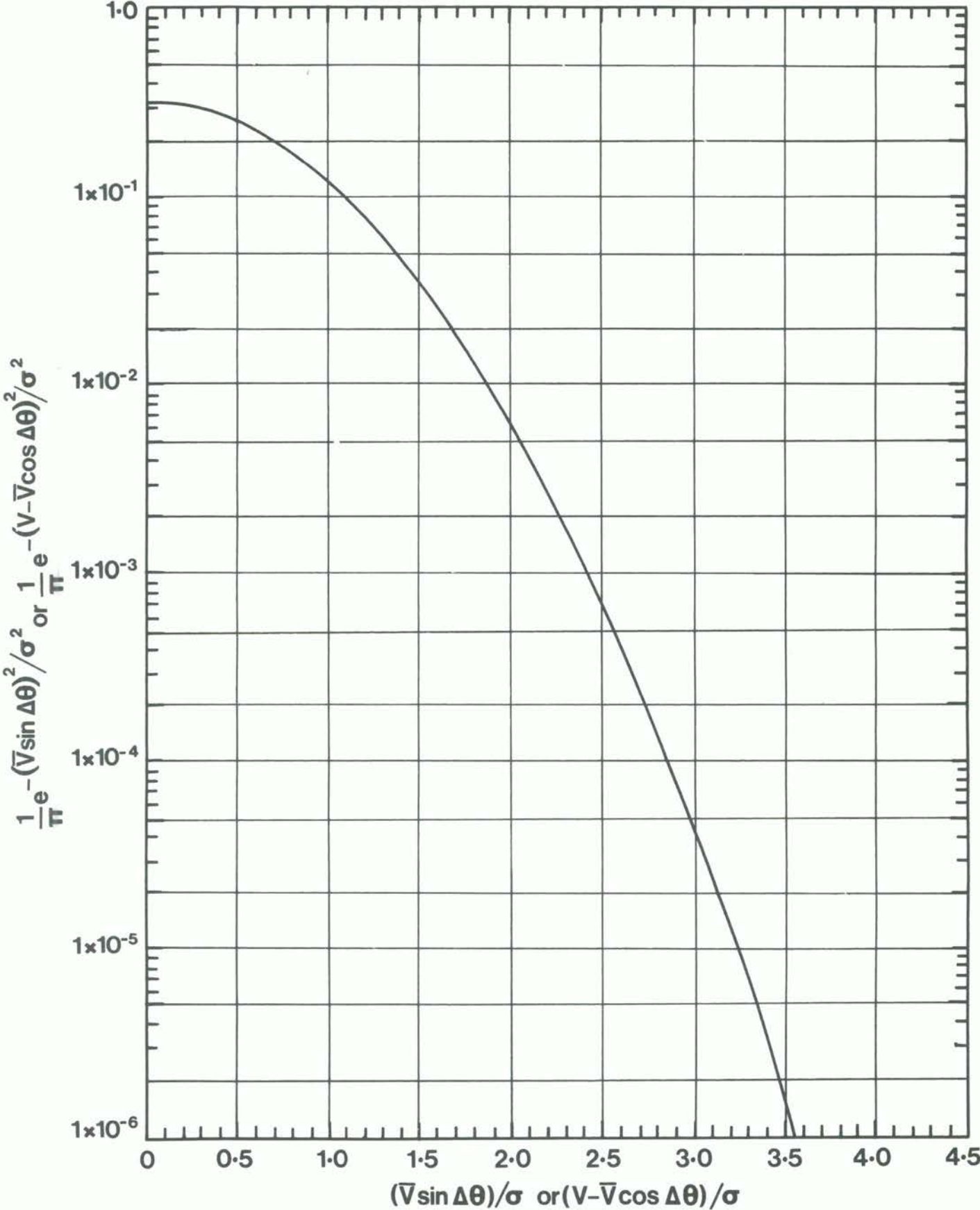


Figure 5. A graph to estimate the relative probability of a given rainfall rate, r , to the normal or average rainfall rate \bar{r} . The abscissa (horizontal scale) is the ratio of a given rainfall rate to its average value. The ordinate (vertical scale) provides the probability of occurrence of rainfall rate, r , assuming the probability to be given by $P(r) = e^{-r/\bar{r}}$. The graph is not applicable to value of $\frac{r}{\bar{r}} < 1$. If the abscissa exceeds 9, use the lower scale with the right hand straight line and multiply the ordinate by 10^{-4} or 0.0001.

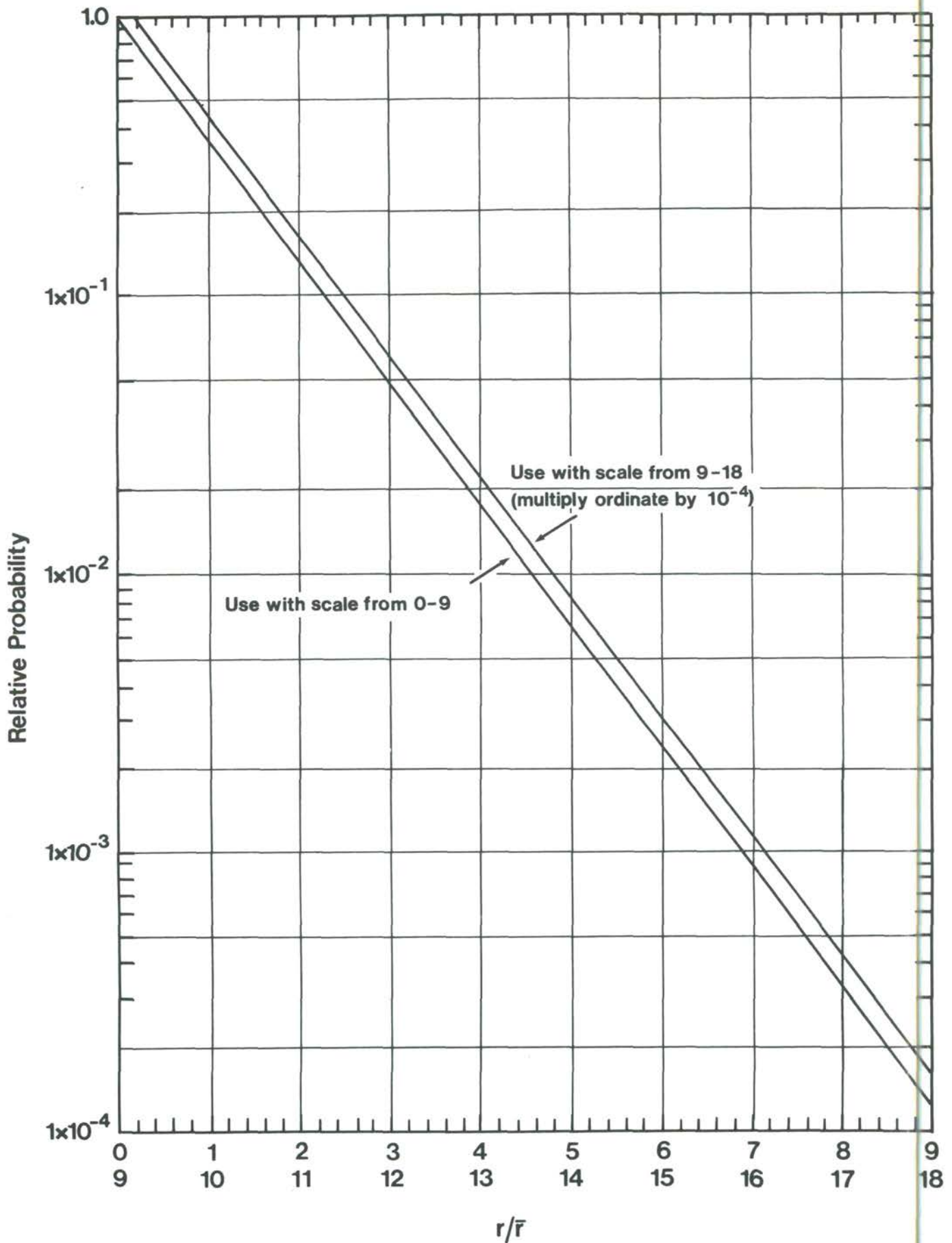


Figure 6. A graph to determine the sine and cosine of angle, $\Delta\theta$. Note the two sets of numbers in the abscissa (horizontal scale) and the need to reverse the sign for certain angles when determining the sine of those angles.

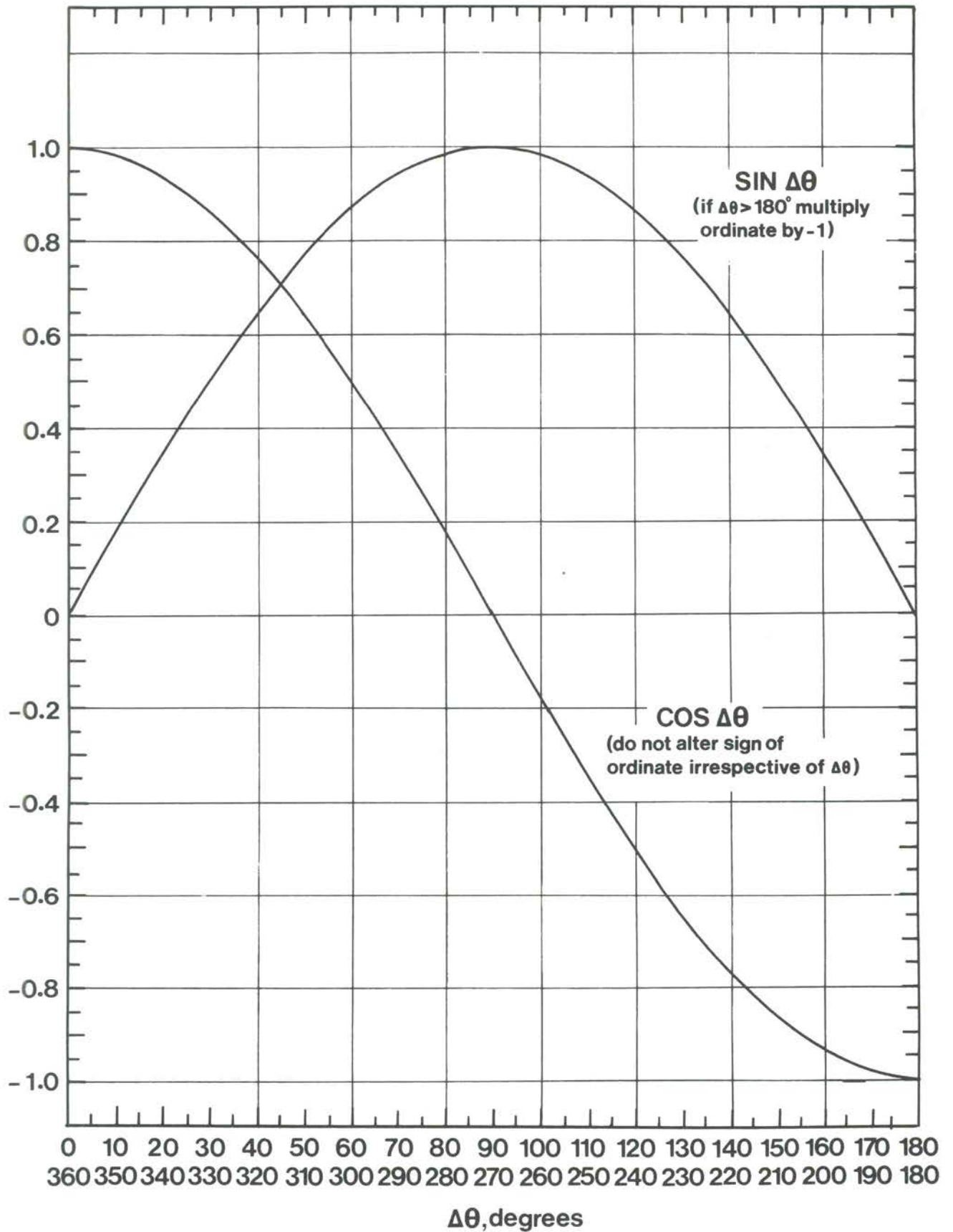


Figure 7. A graph to determine the value of $R(t)$ as a function of time for four deposition velocities and two diffusion rates. The abscissa (horizontal scale) is time; the values 5, 10, etc. should be multiplied by 10^4 (e.g. 5 reads 5×10^4 seconds). The ordinate (vertical scale) is the value of $R(t)$. Each of the numerical values 0.002, 0.005, etc. should be multiplied by 10^{-5} (e.g. 0.2 reads 0.2×10^{-5}). The inset in the lower left hand corner with a separate abscissa and ordinate scale provides information for that part of the main graph which is difficult to read. The solid lines are based on calculations using slow diffusion to maximize ground level concentration. However, at late times, the values of $R(t)$ are greater if average diffusion applies. This is because with slow diffusion so much material deposits in the early times that too little remains airborne at later times.

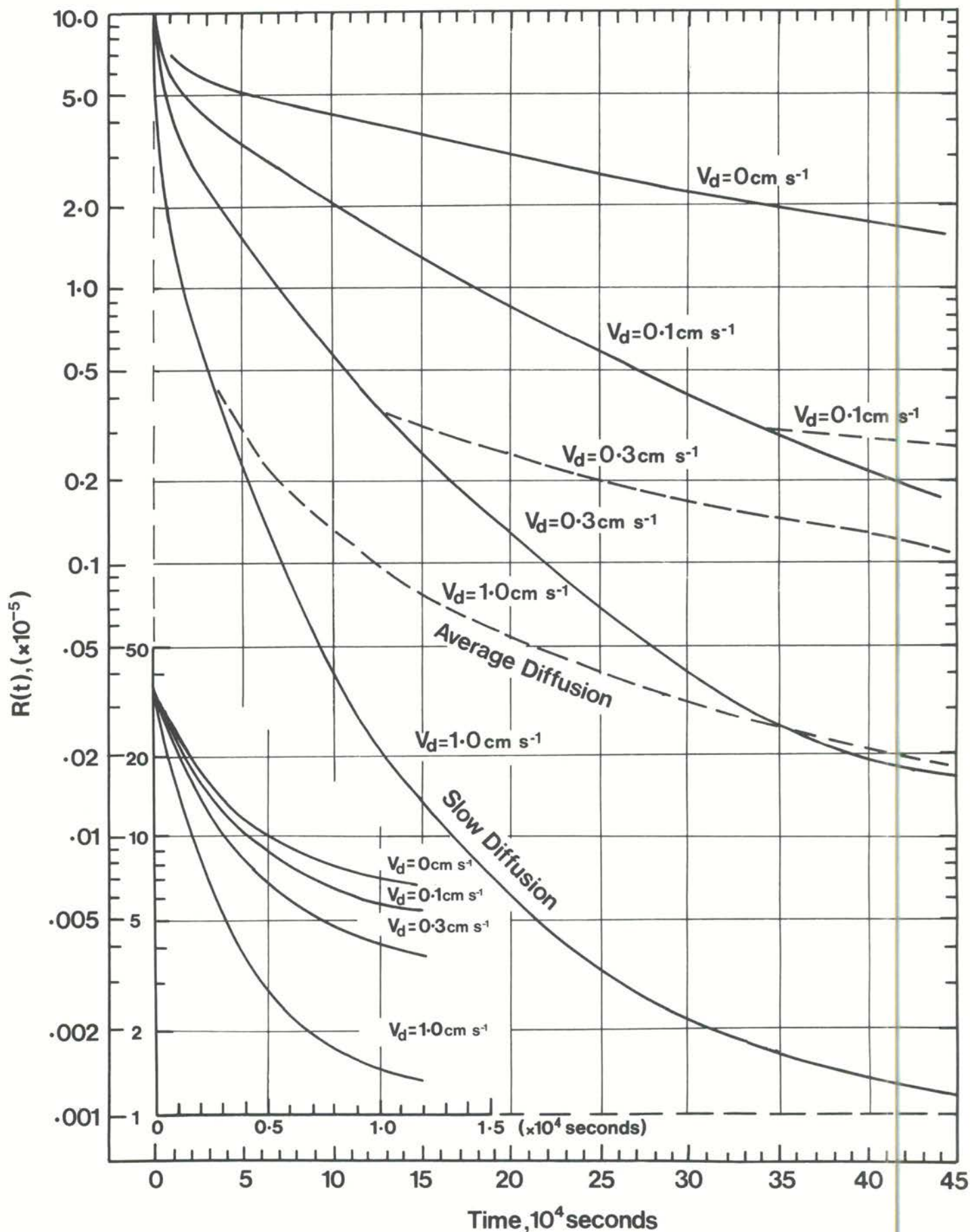


Figure 8. A graph of the residual content of a pollutant in a column after the column is depleted by dry deposition. The abscissa (horizontal scale) is time. The ordinate (vertical scale) represents the fraction of the initial pollutant content remaining in the column after time in the abscissa for three dry deposition velocities. Interpolation is necessary for dry deposition velocities other than 0, 0.3 and 1 cm s⁻¹.

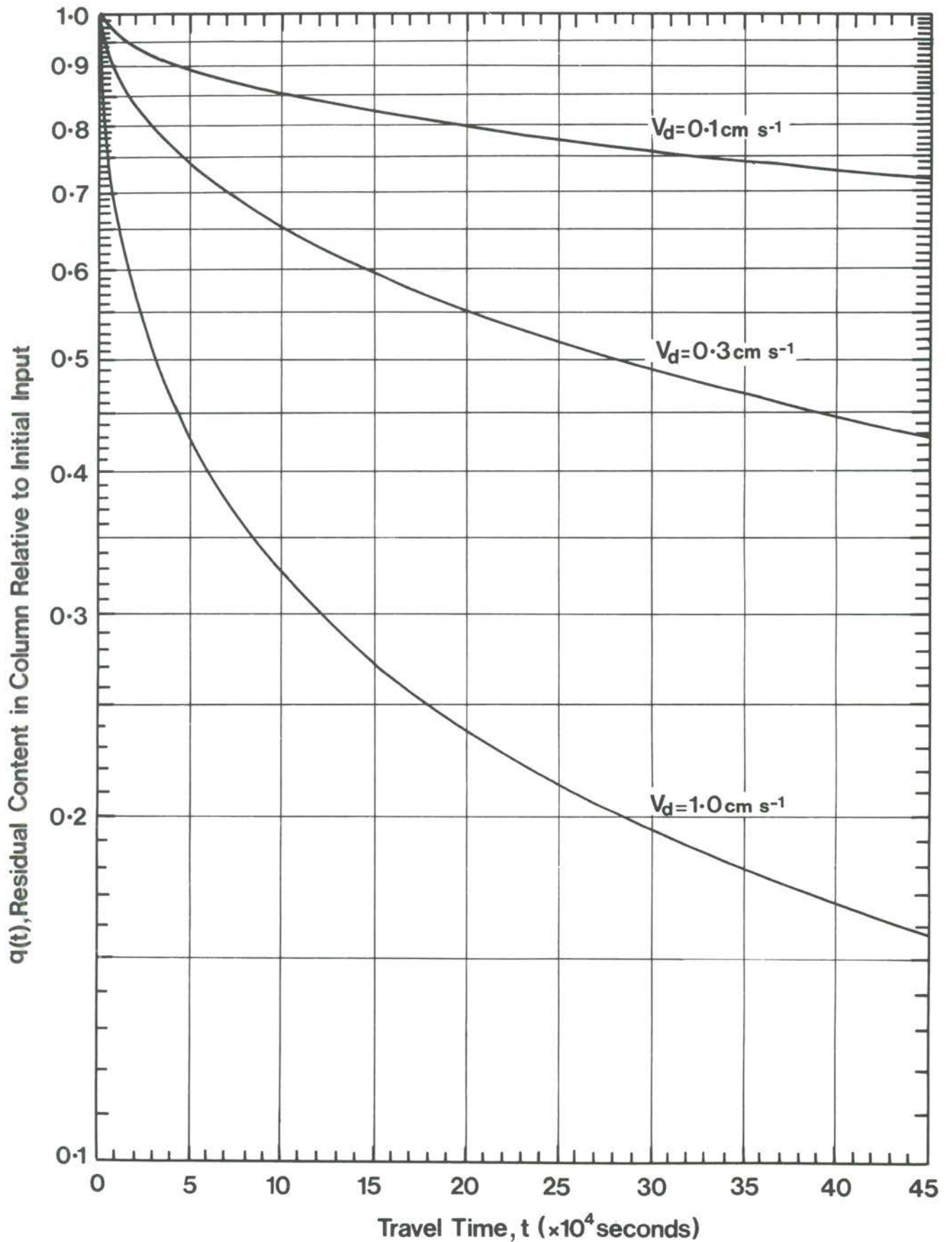


Figure 9. A graph of the residual content of a pollutant in a column after the decay due to radioactivity or due to chemical transformation. The abscissa (horizontal axis) is time. The ordinate (vertical scale) represents the fraction of the initial pollutant content remaining in the column after time in the abscissa for seven values of half life (radioactive or chemical). Interpolation is necessary for half-lives not shown on the graph.

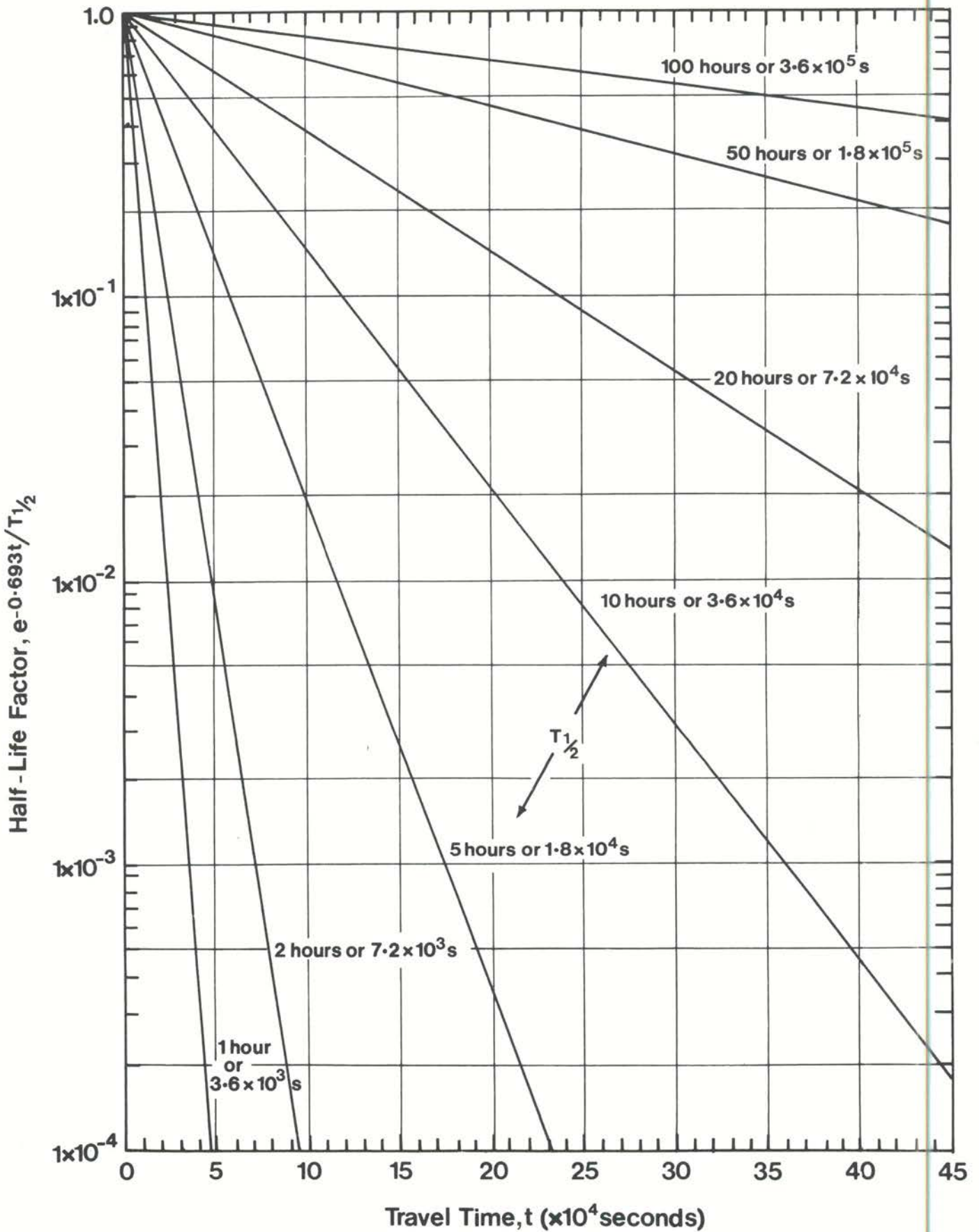


Figure 10. A graph of the probability of a wind speed greater or less than the average wind component blowing from the source of pollution to the sampling point. The abscissa (horizontal axis) is a normalized wind speed departure from a component (or directional) average. The ordinate (vertical scale), left side, provides the probability that a given wind speed is less than the component of the average wind in the direction from the source of pollution to the sampling point. The ordinate, right hand side, provides the similar probability for wind speeds greater than the component of the average wind in the direction from the source of pollution to the sampling point.

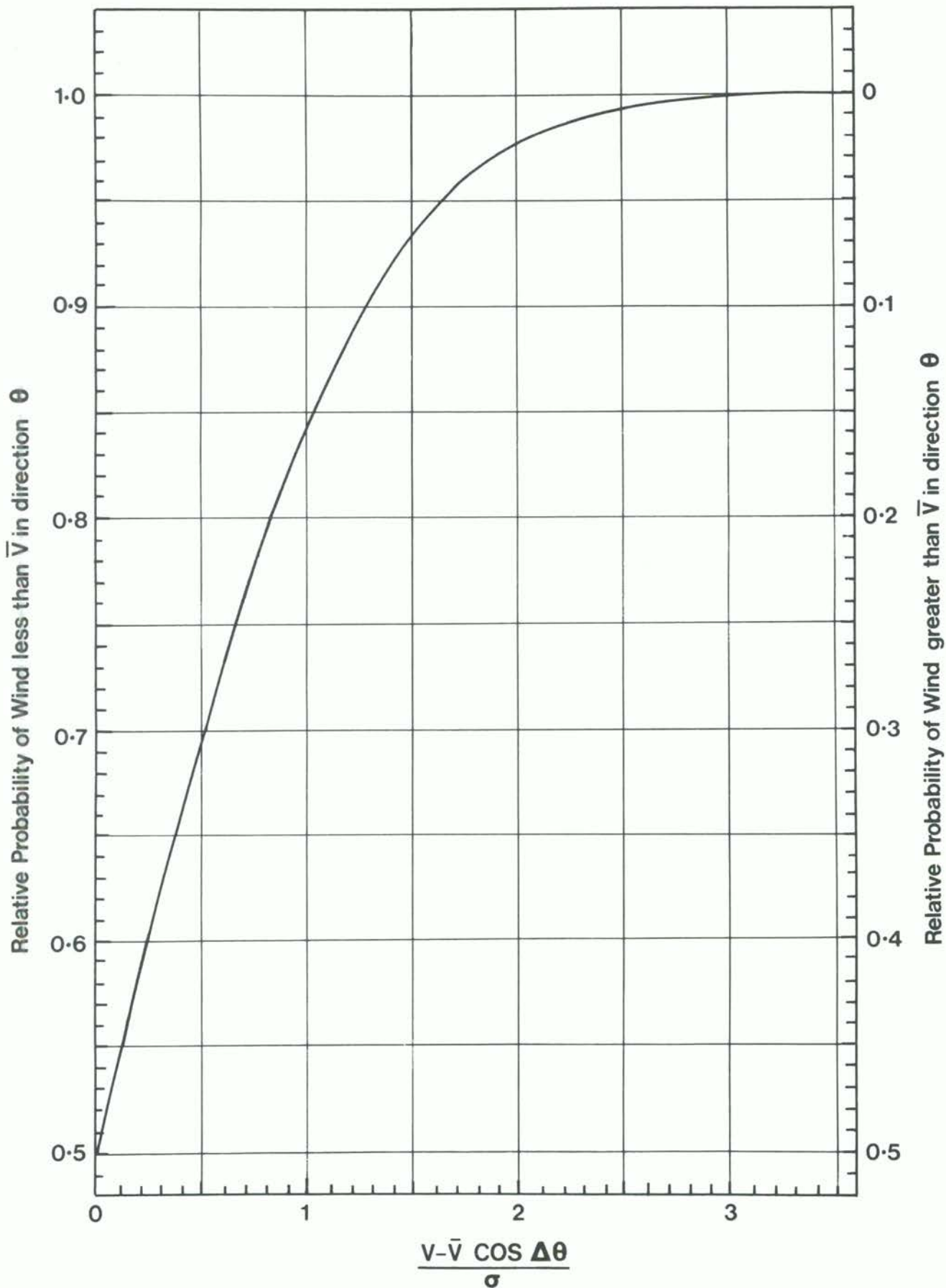
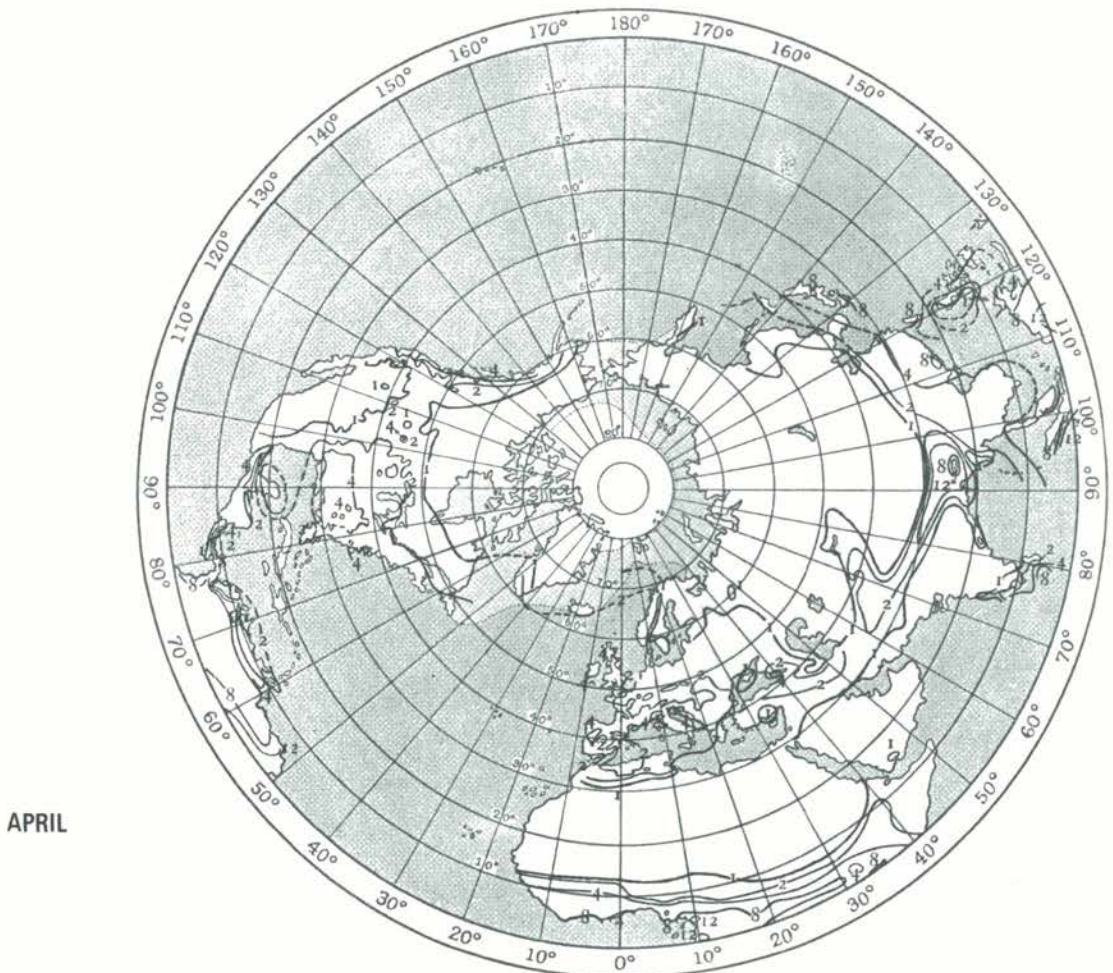
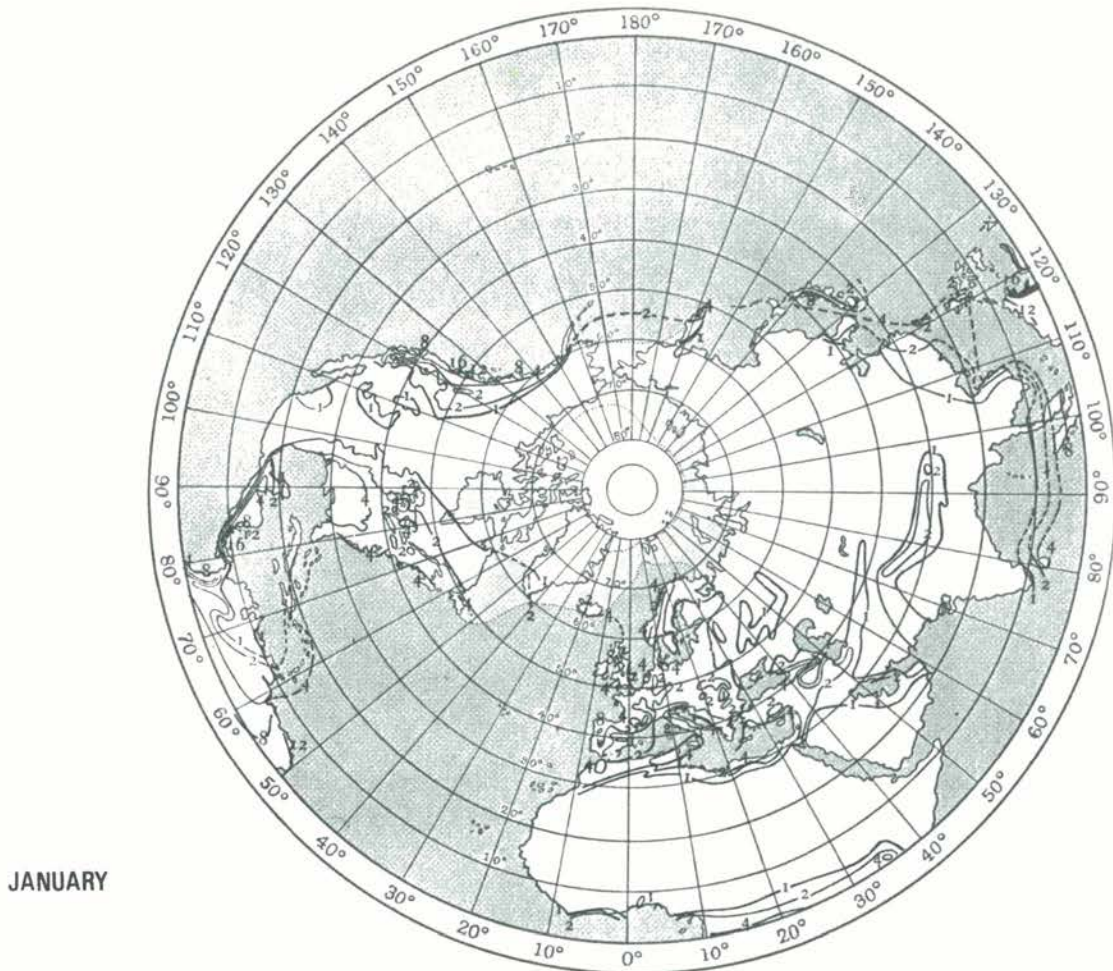
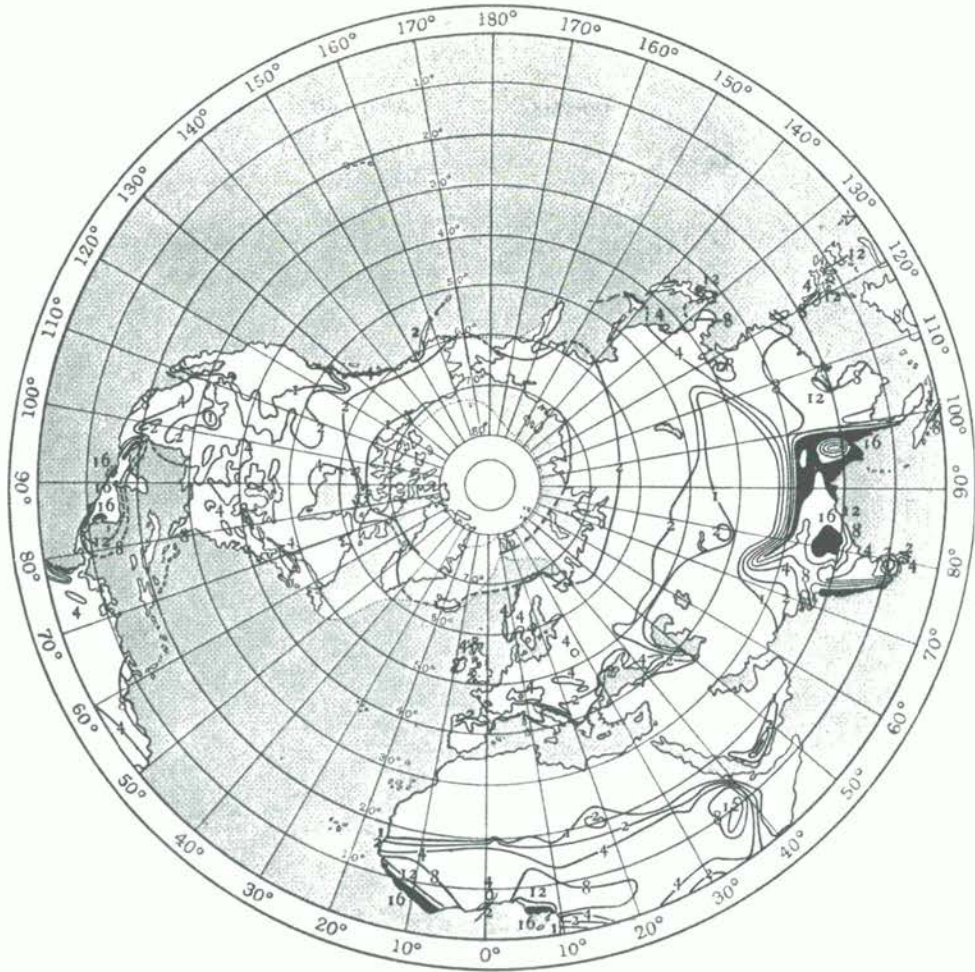
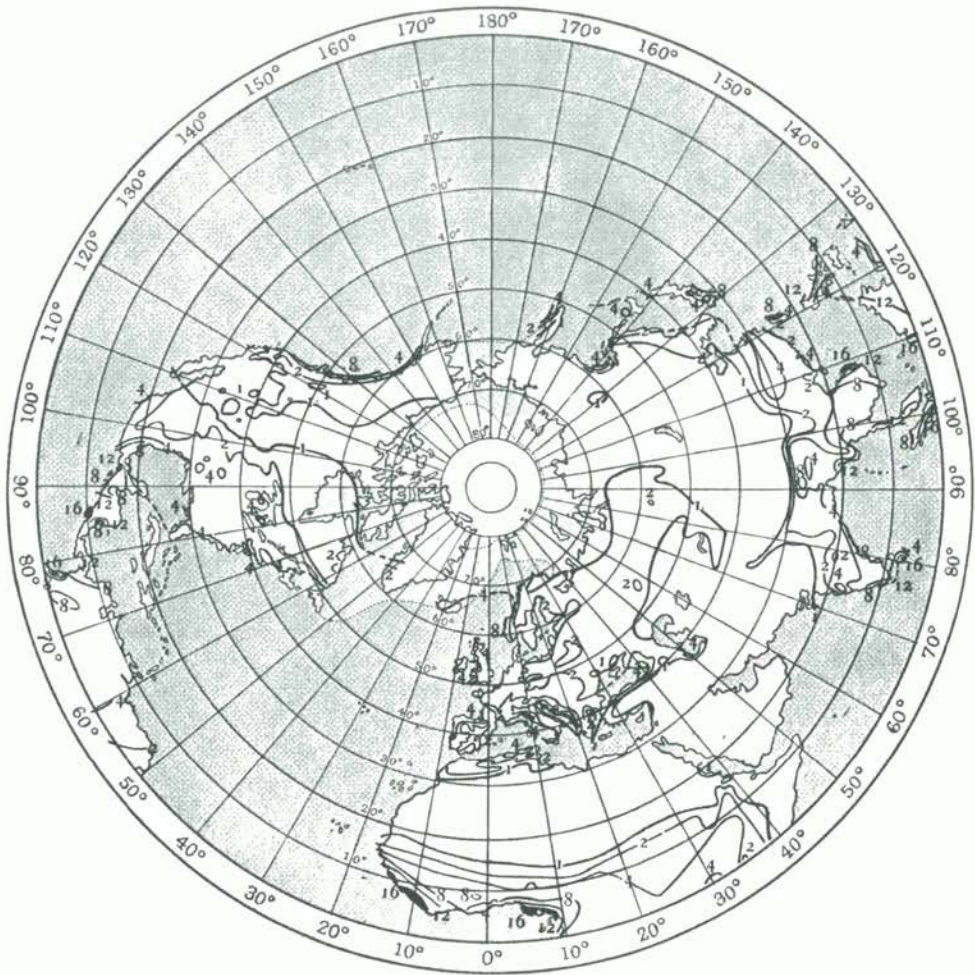


Figure 11. Maps of monthly normal or average precipitation. The isolines of equal precipitation are labelled in inches (1 inch = 2.54 cm). The dashed lines are uncertain. Preference should be given to local information of average precipitation if there is a disagreement between the various values of average precipitation. (Source: Shaw, N. 1938 Manual of Meteorology, Volume II Comparative Meteorology – Cambridge University Press).



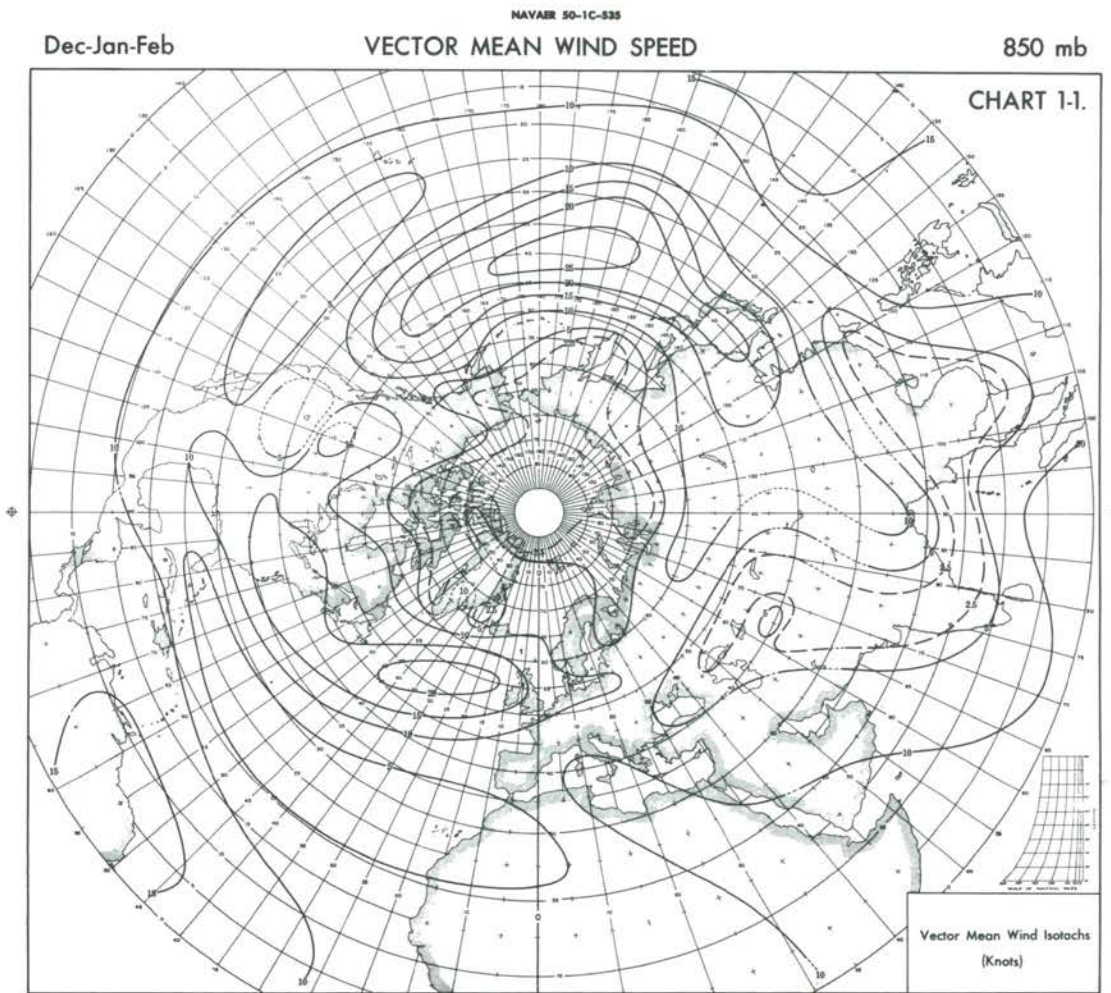


JULY



OCTOBER

Figure 12. Maps providing the average wind speeds and directions and the variability (vector standard deviation) of the winds at pressure altitudes of 850 and 700 millibars for each month of the year. The seasonal or three-month average winds are provided as vector mean wind speed, in knots ($1 \text{ knot} = 2 \text{ m s}^{-1}$), and vector mean wind direction on a 360° scale: $90^\circ =$ wind from the east; $240^\circ =$ wind from the south-west; $360^\circ =$ wind from the north, etc. The vector standard deviations are given in knots. (Source: Crutcher, H. L. 1959 Upper Wind Statistics Charts of the Northern Hemisphere (850, 700 and 500 mb levels). NAVAER 50-IC-535, vol. 1. Office of the Chief of Naval Operations, U.S. Navy).

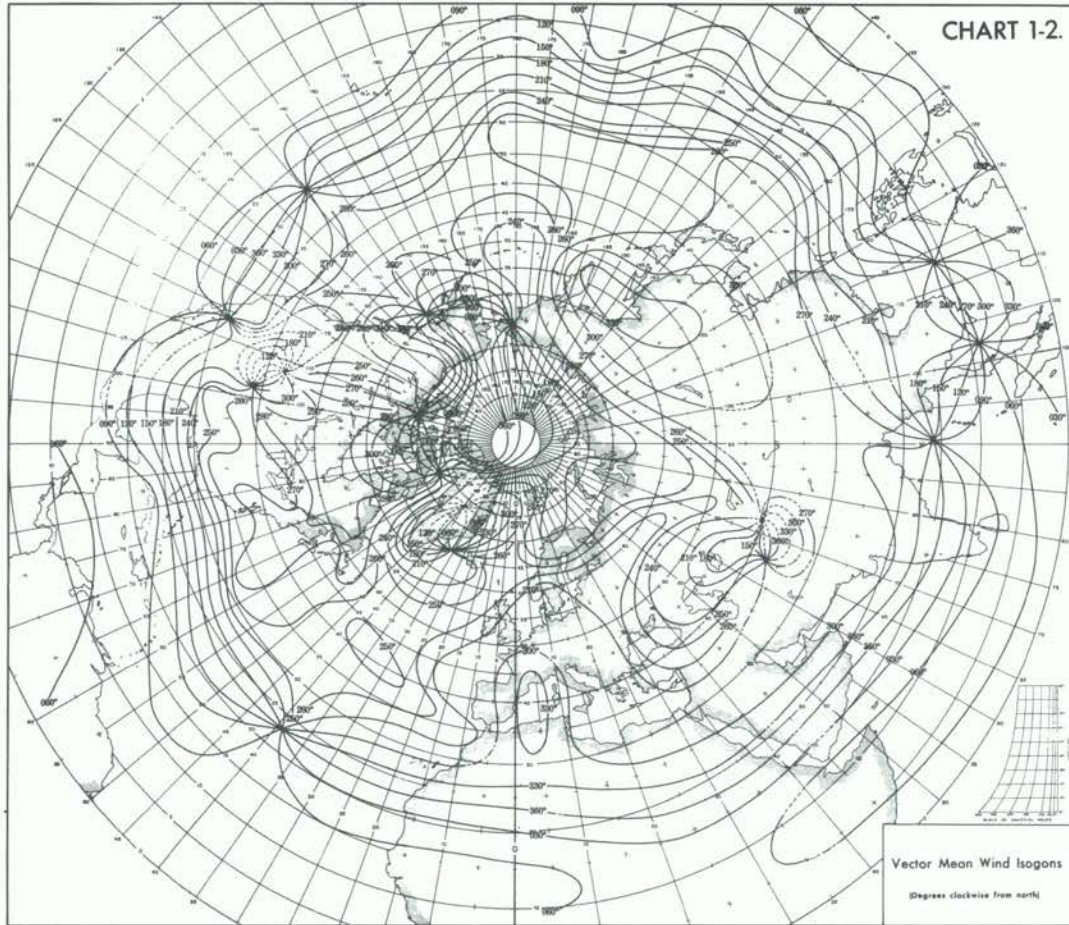


Dec-Jan-Feb

VECTOR MEAN WIND DIRECTION

850 mb

CHART 1-2.



Dec-Jan-Feb

VECTOR STANDARD DEVIATION

850 mb

CHART 1-3.

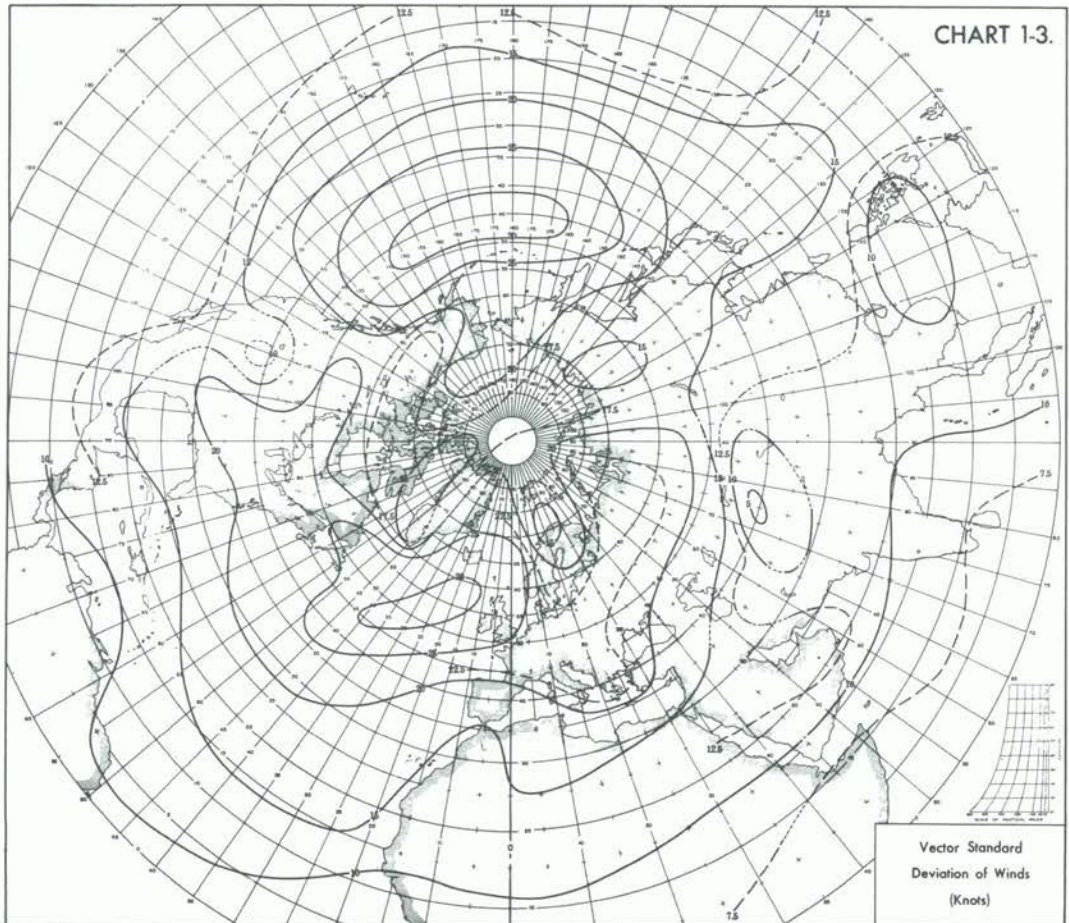
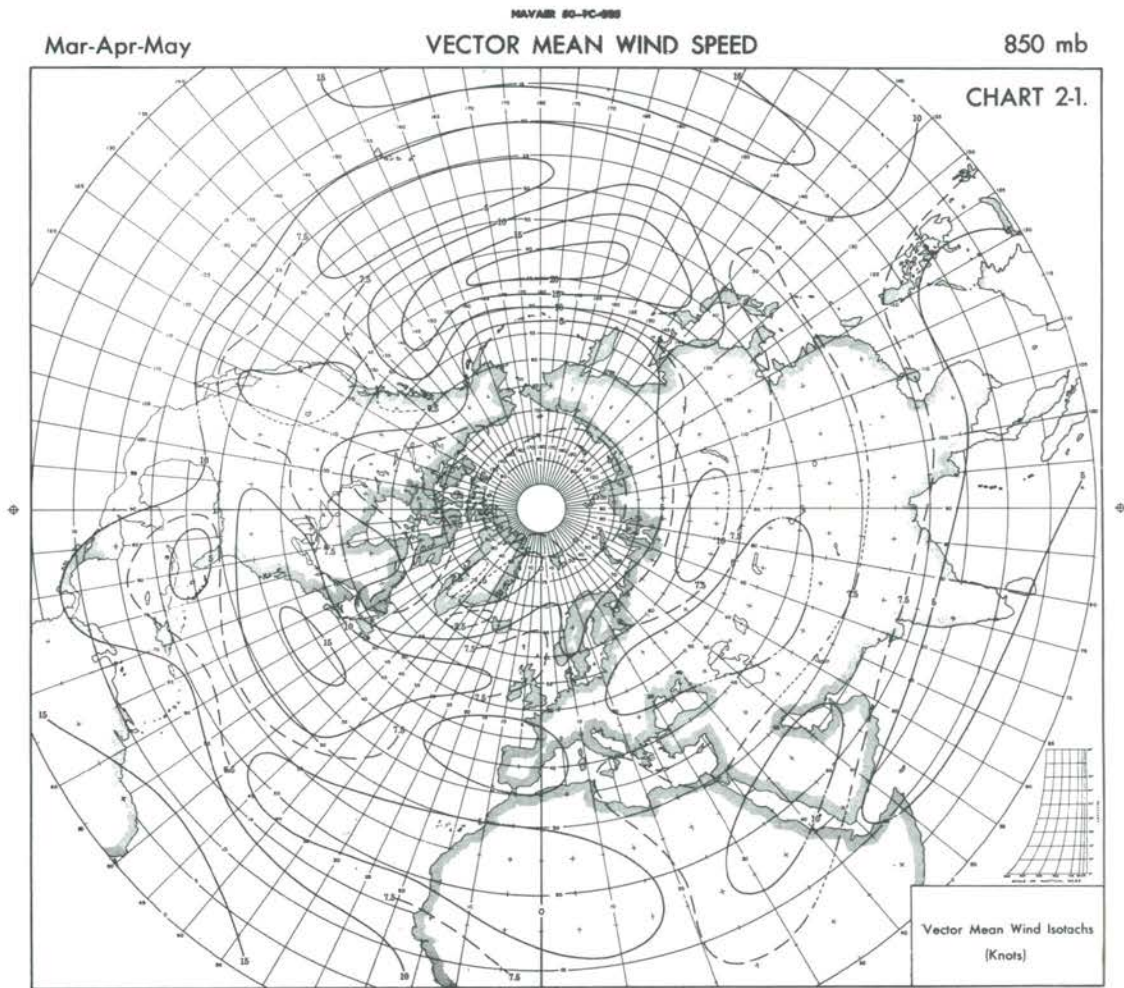


Fig. 12—cont.

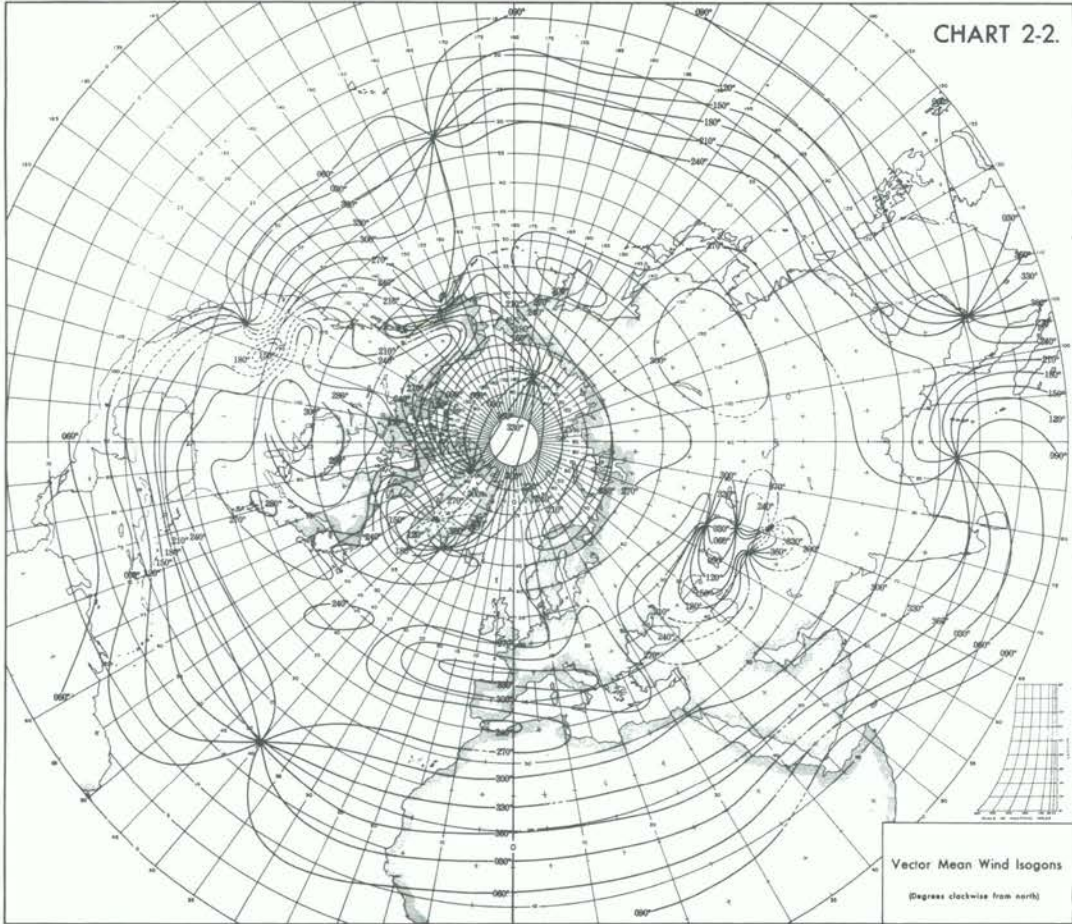


Mar-Apr-May

VECTOR MEAN WIND DIRECTION

850 mb

CHART 2-2.



Mar-Apr-May

VECTOR STANDARD DEVIATION

850 mb

CHART 2-3.

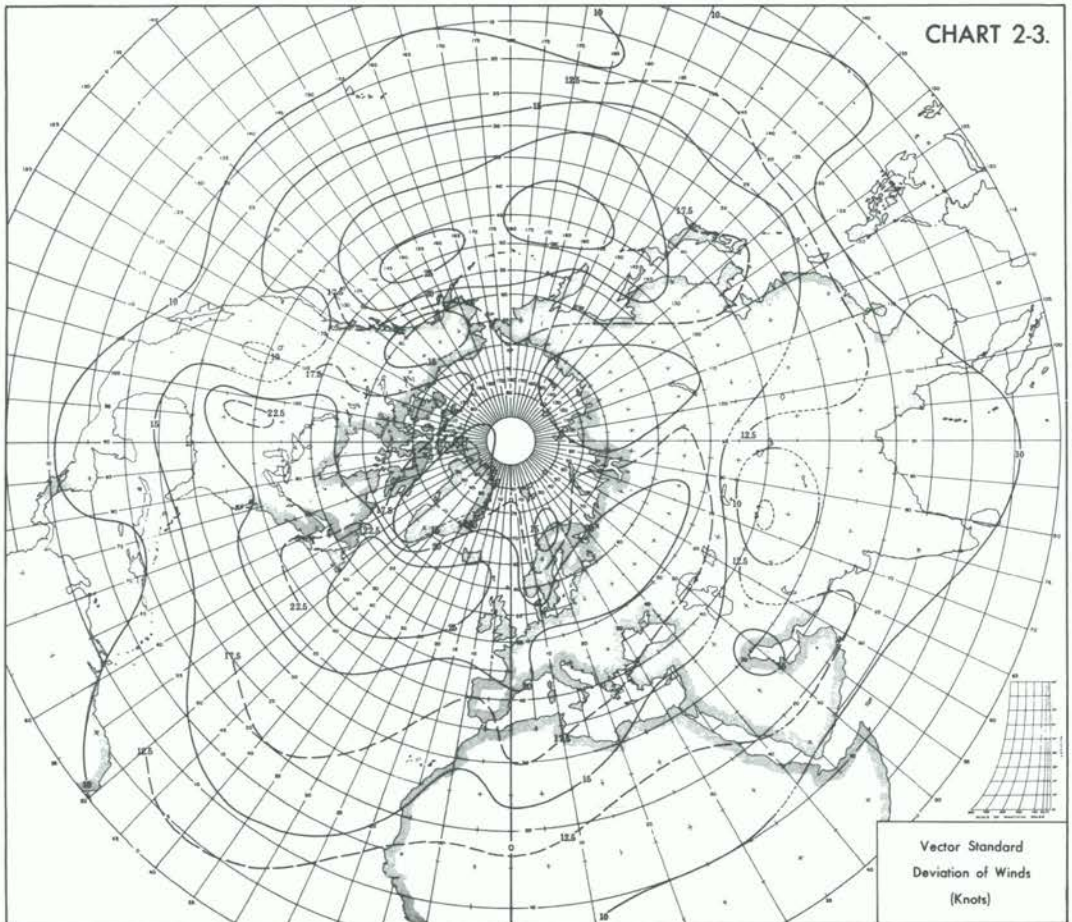
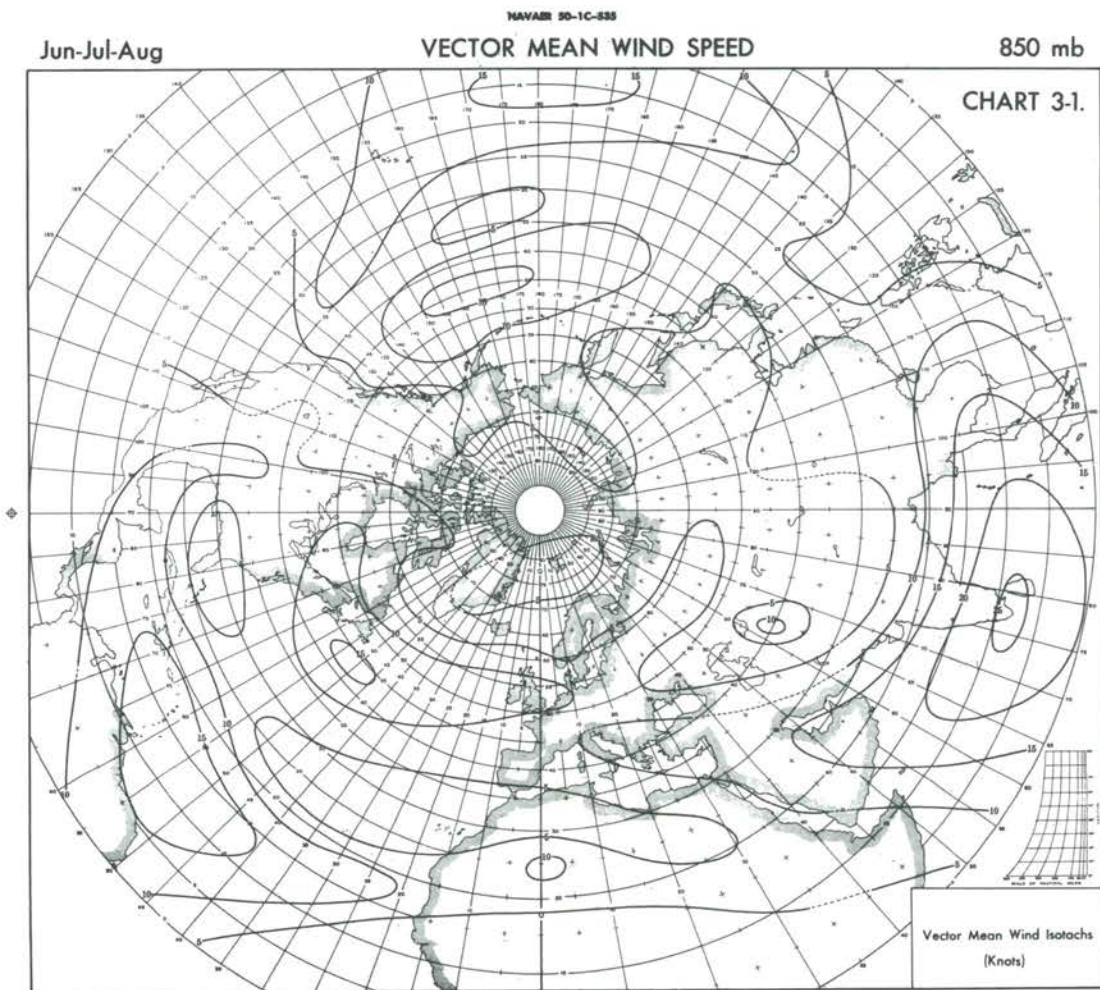


Fig. 12—cont.

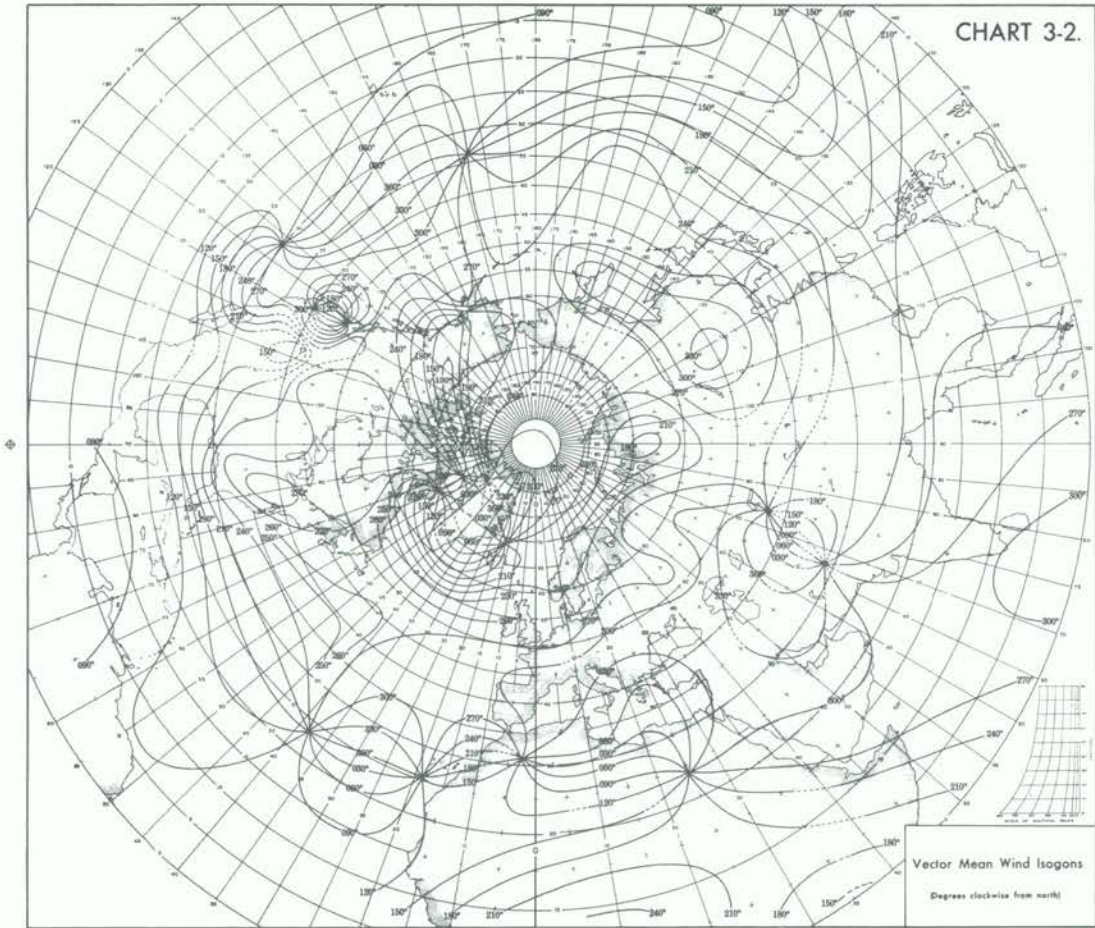


Jun-Jul-Aug

VECTOR MEAN WIND DIRECTION

850 mb

CHART 3-2.



Jun-Jul-Aug

VECTOR STANDARD DEVIATION

850 mb

CHART 3-3.

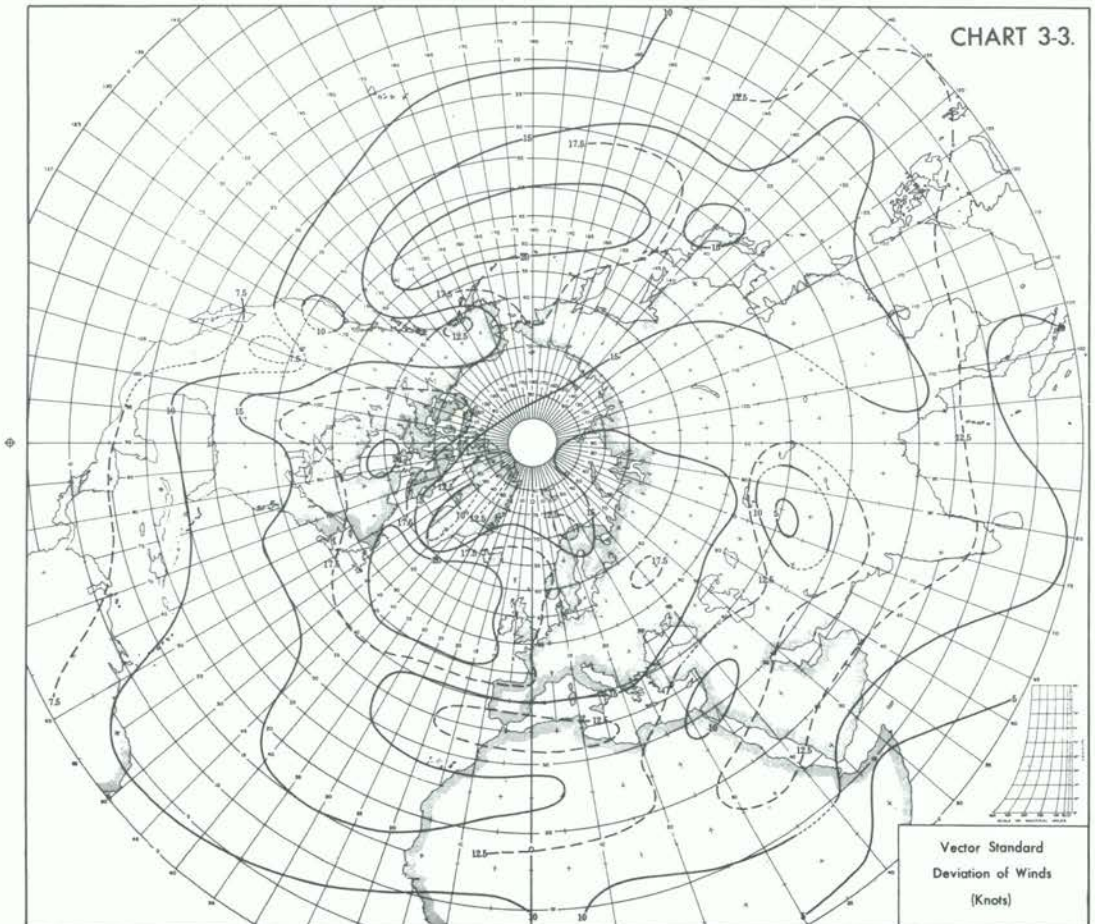
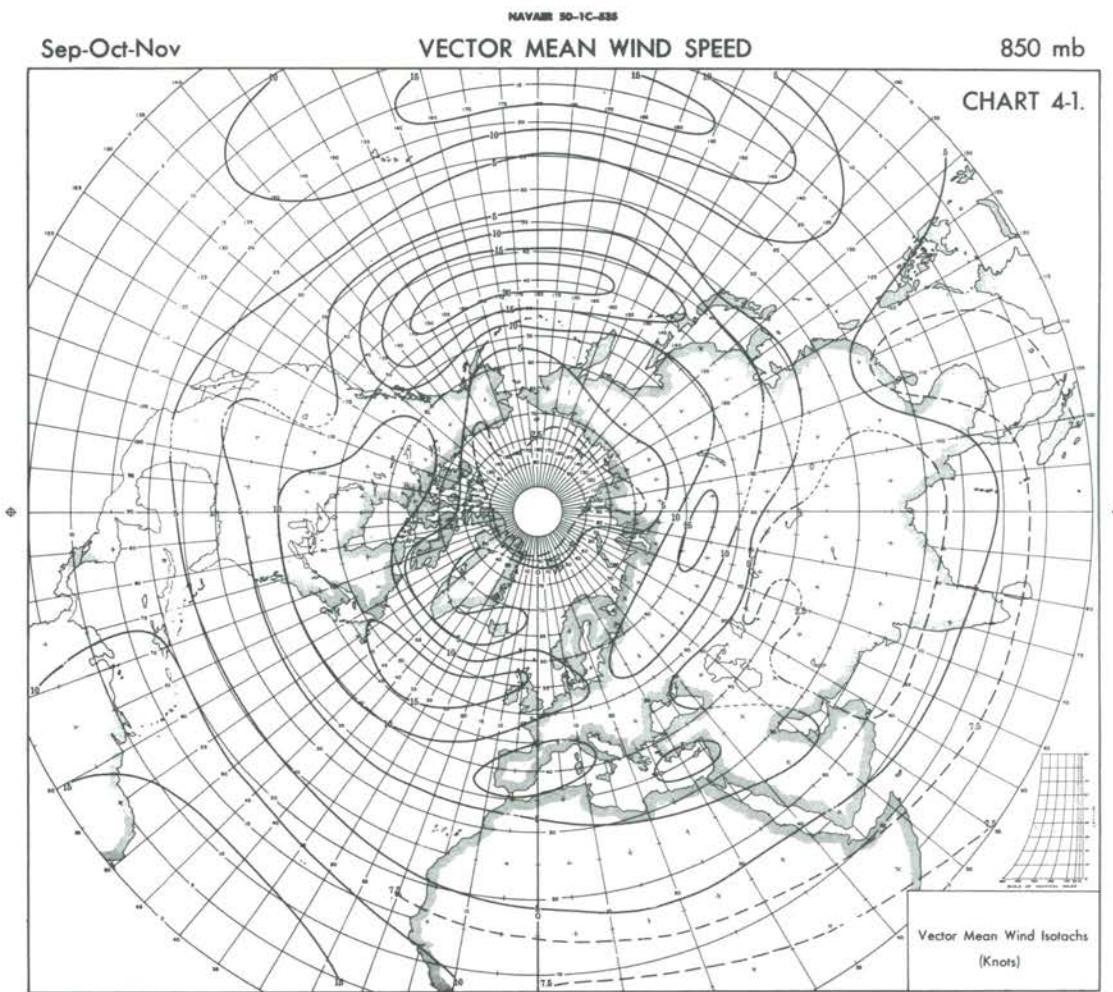


Fig. 12—cont.

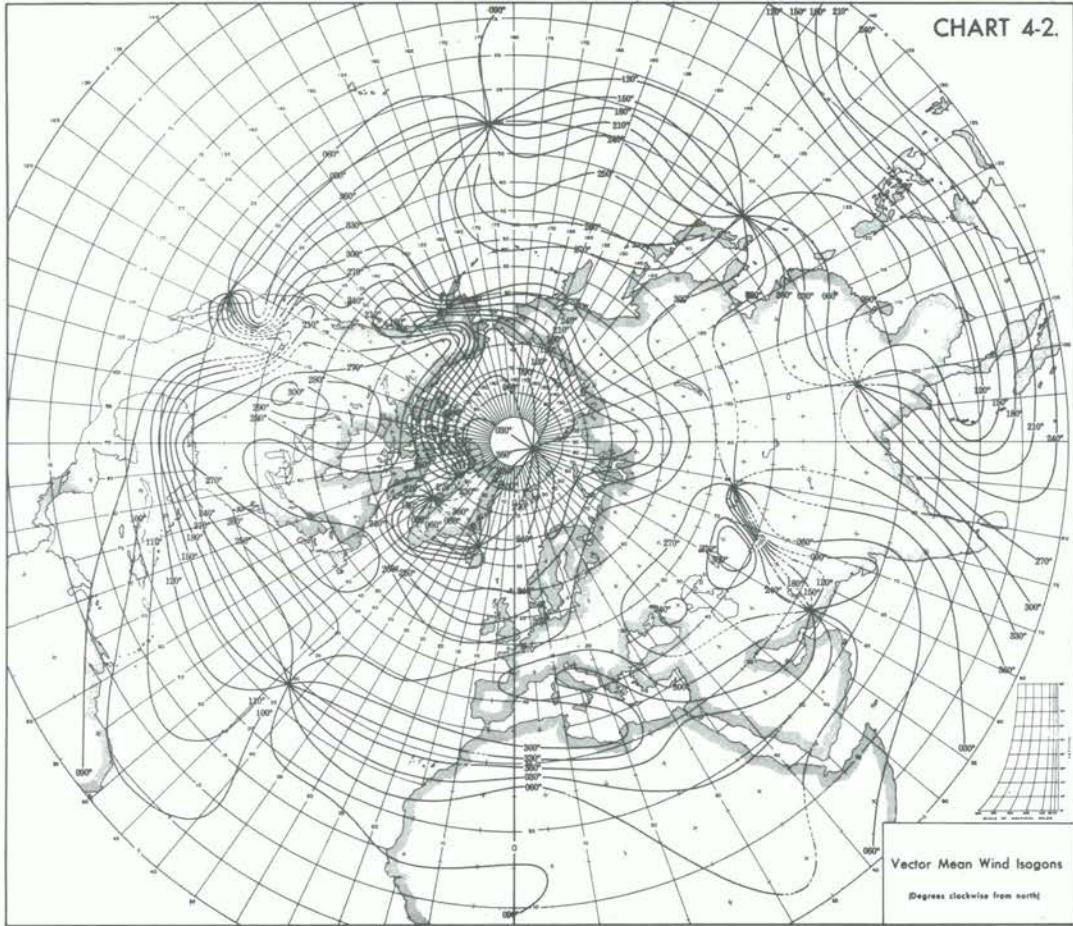


Sep-Oct-Nov

VECTOR MEAN WIND DIRECTION

850 mb

CHART 4-2.



Sep-Oct-Nov

VECTOR STANDARD DEVIATION

850 mb

CHART 4-3.

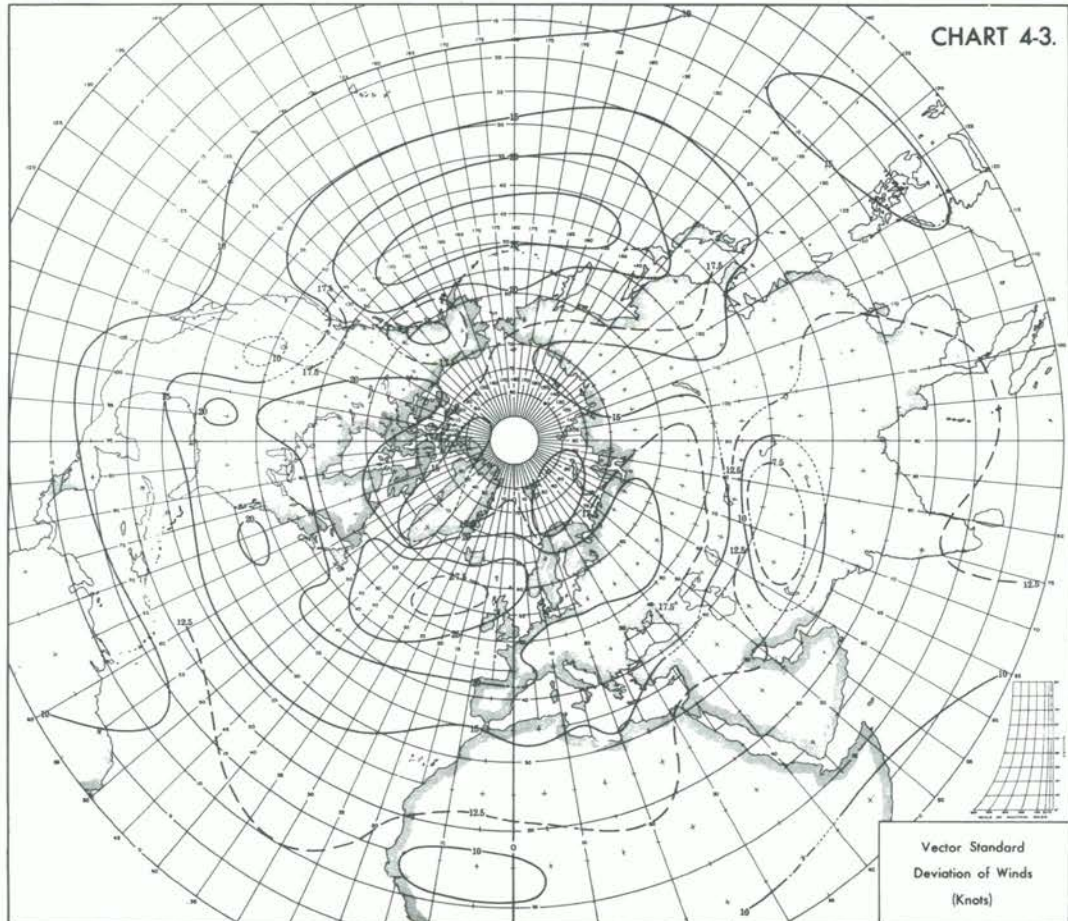
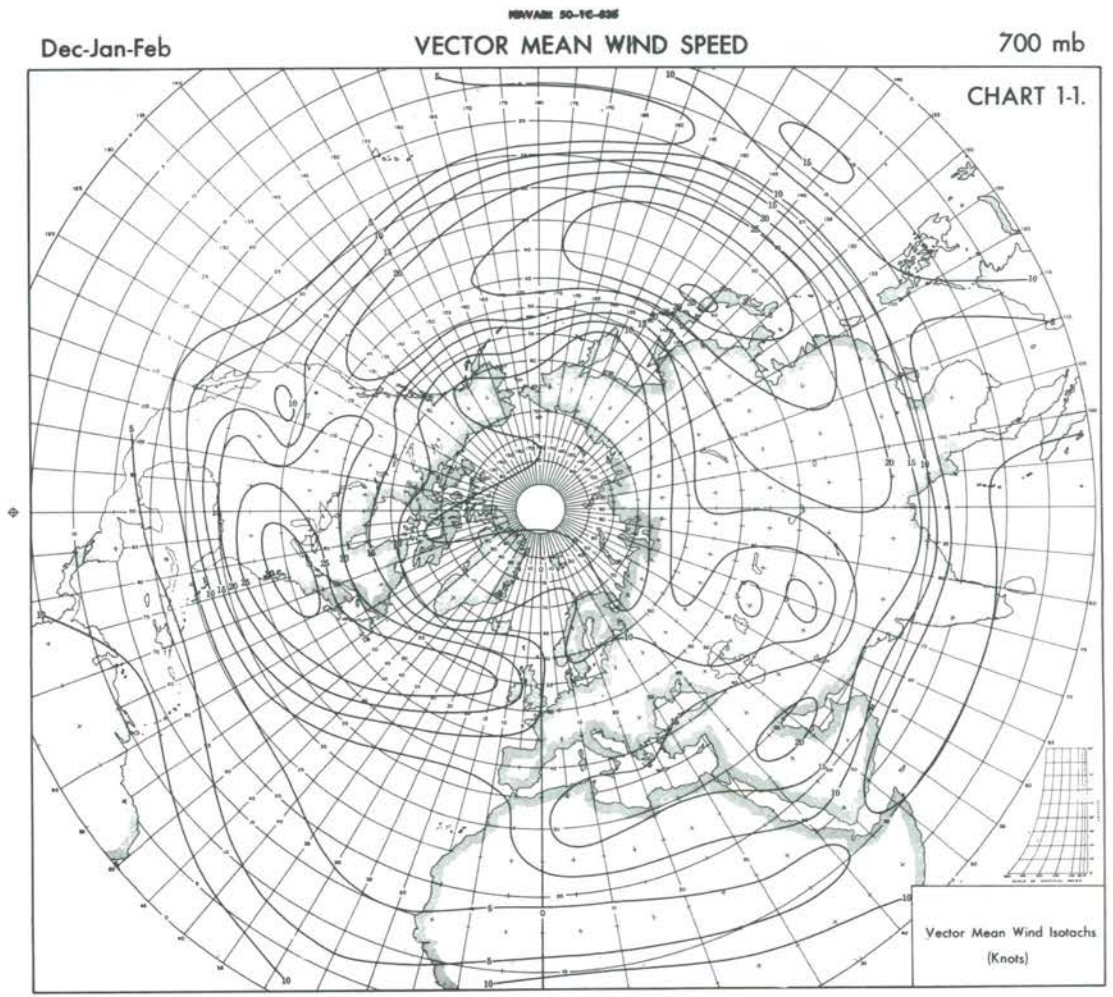


Fig. 12—cont.

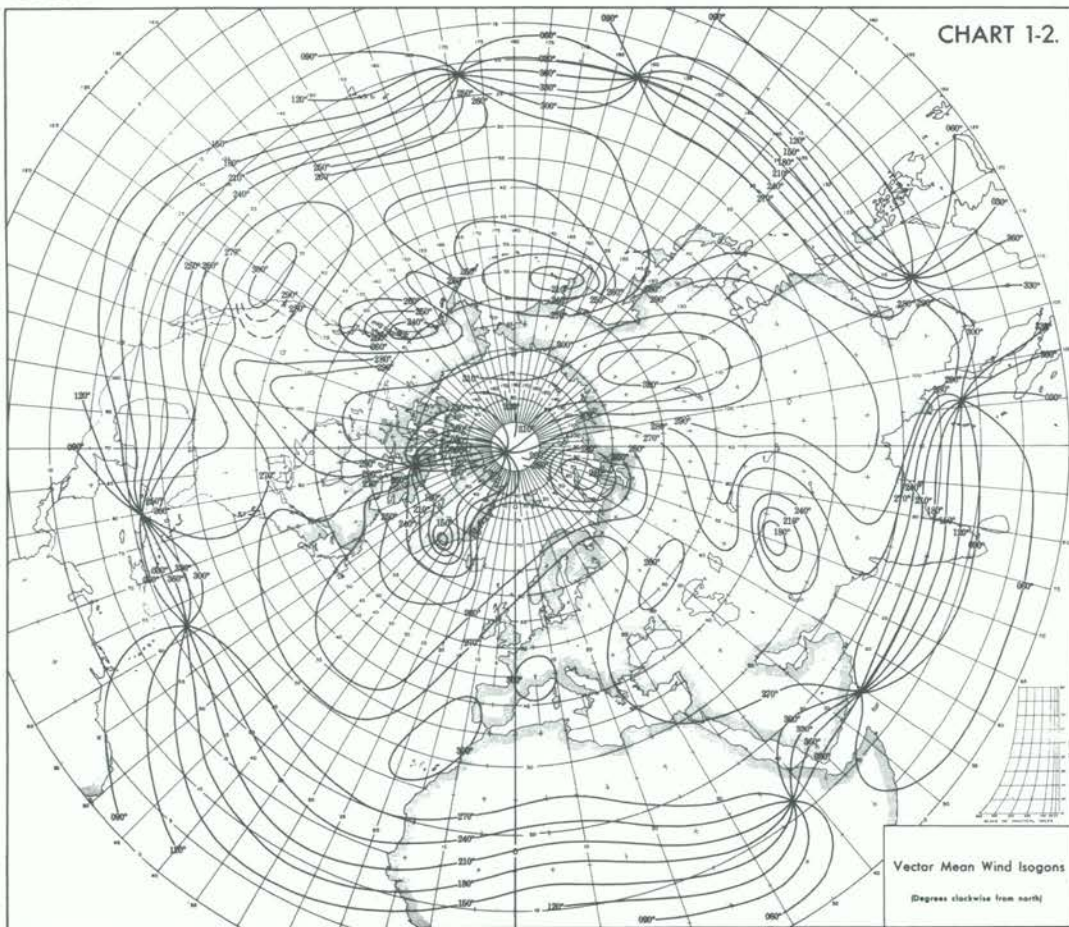


Dec-Jan-Feb

VECTOR MEAN WIND DIRECTION

700 mb

CHART 1-2.



Dec-Jan-Feb

VECTOR STANDARD DEVIATION

700 mb

CHART 1-3.

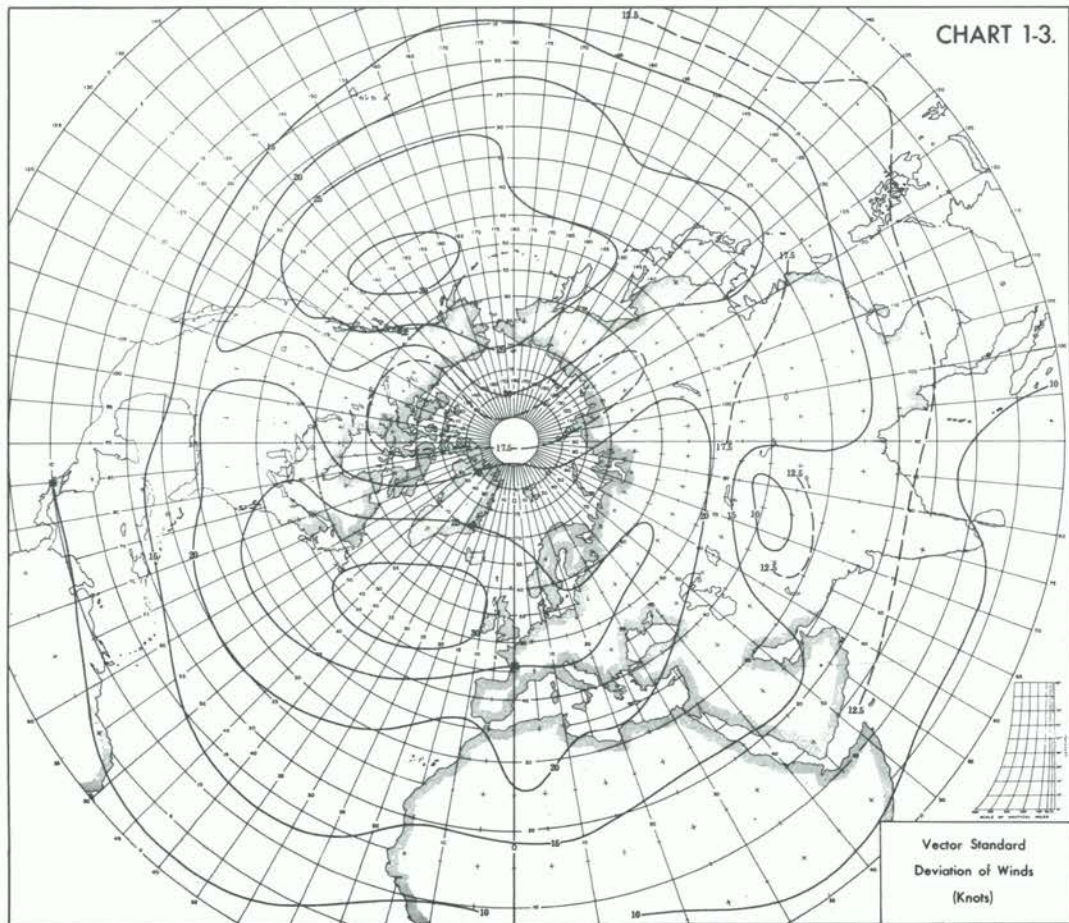
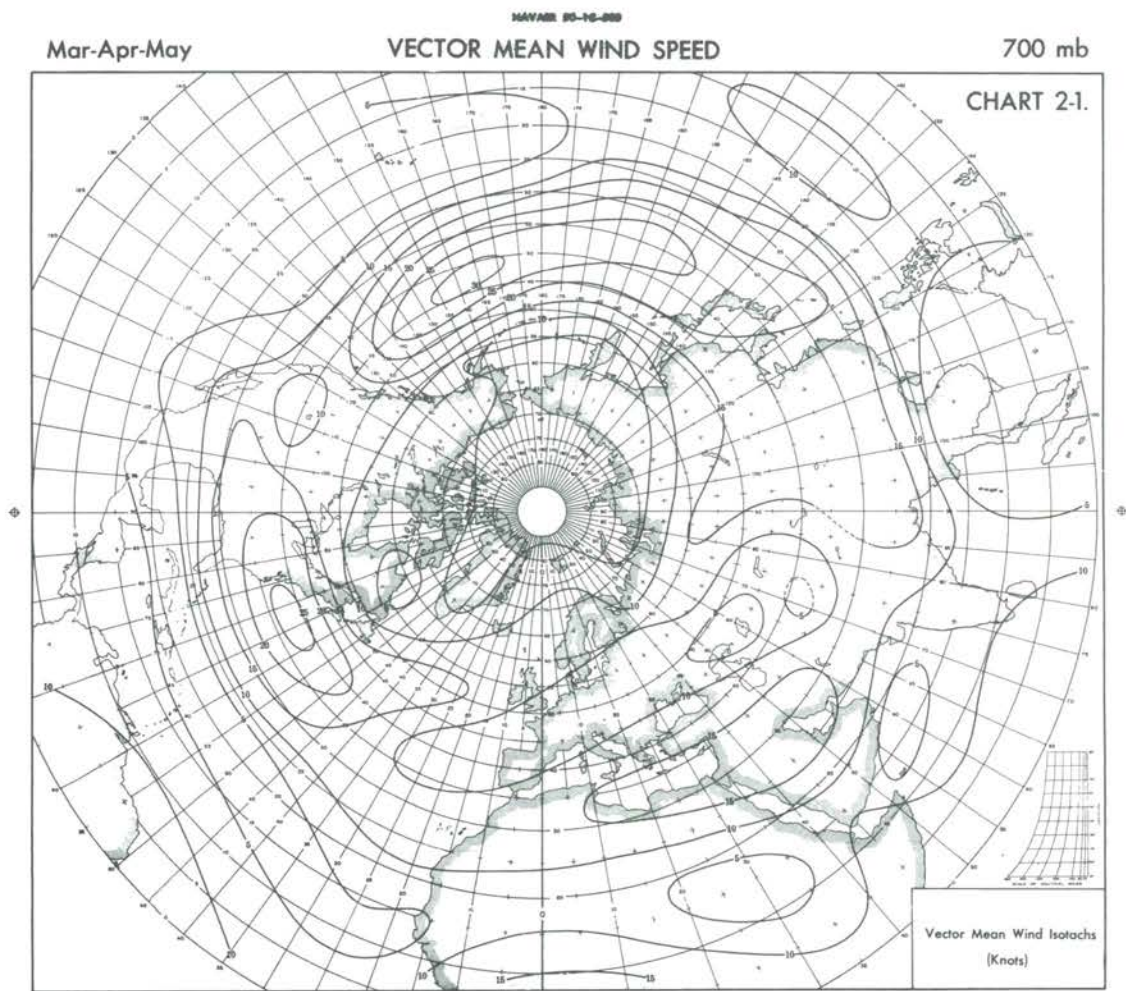


Fig. 12—cont.

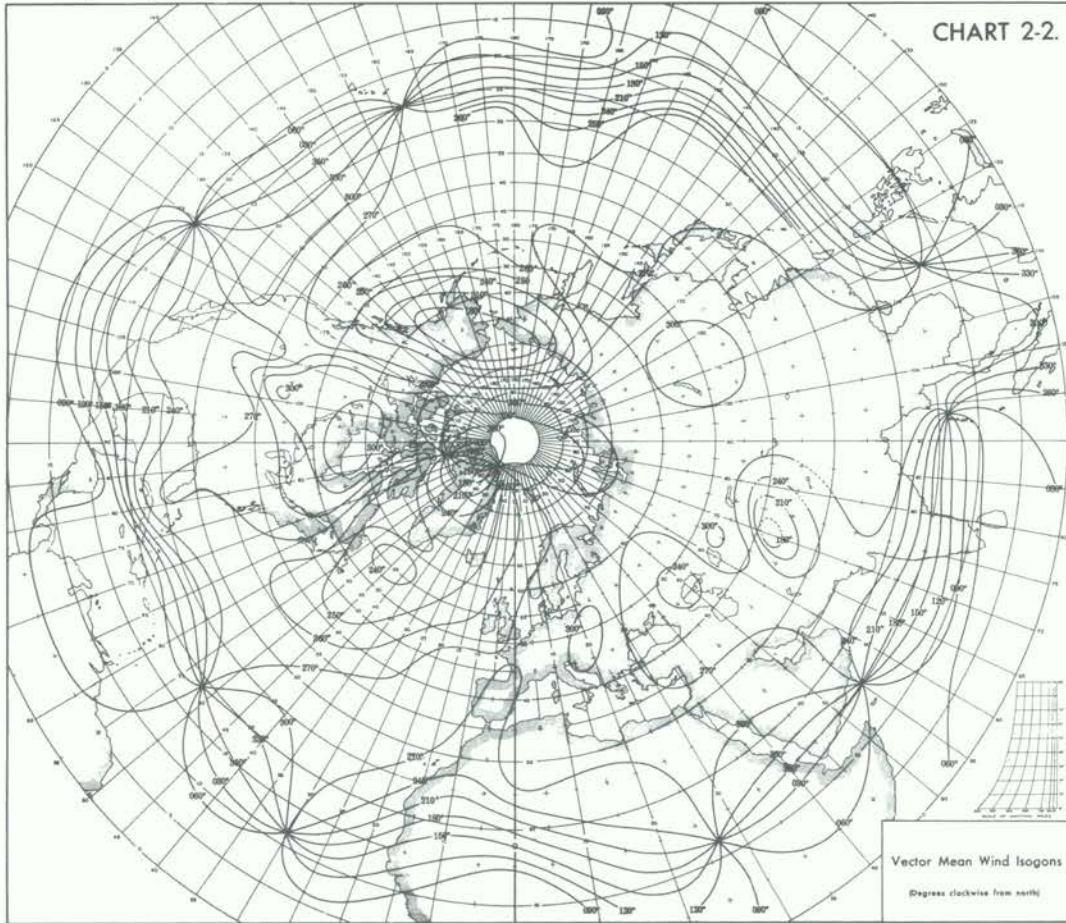


Mar-Apr-May

VECTOR MEAN WIND DIRECTION

700 mb

CHART 2-2.



Mar-Apr-May

VECTOR STANDARD DEVIATION

700 mb

CHART 2-3.

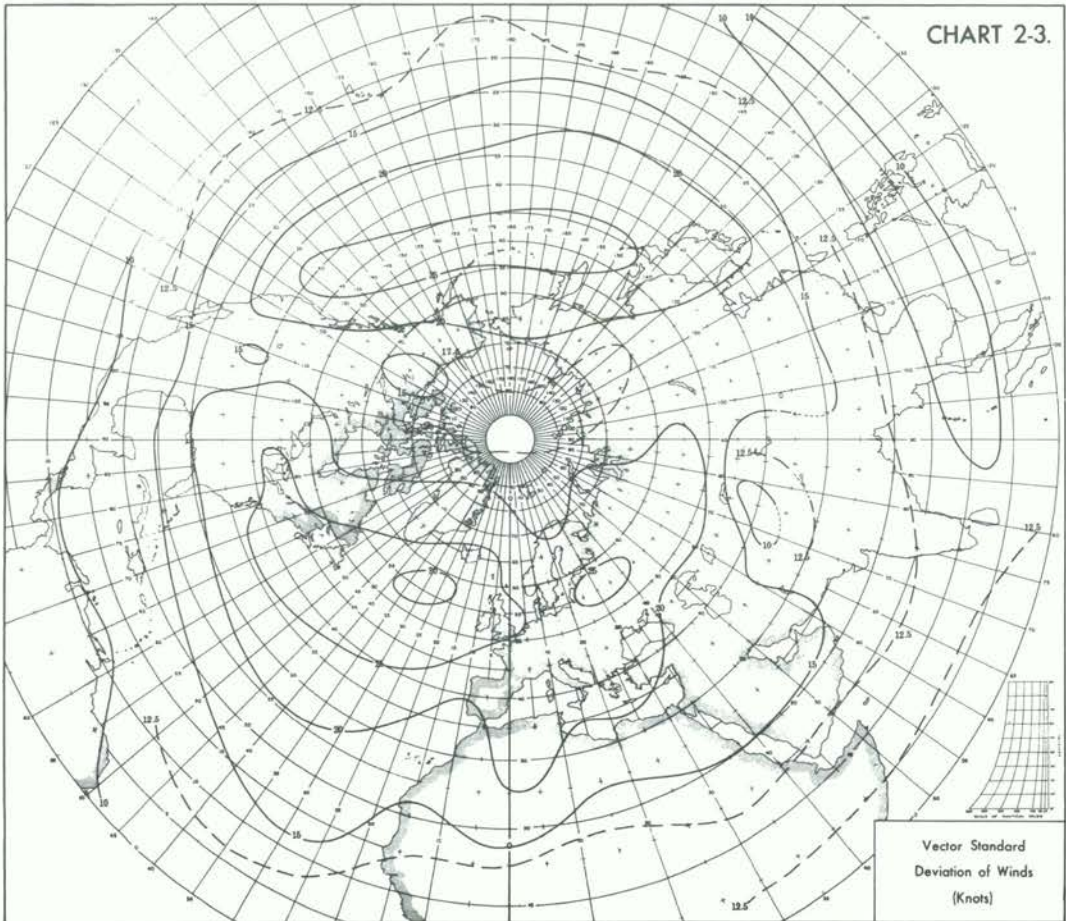
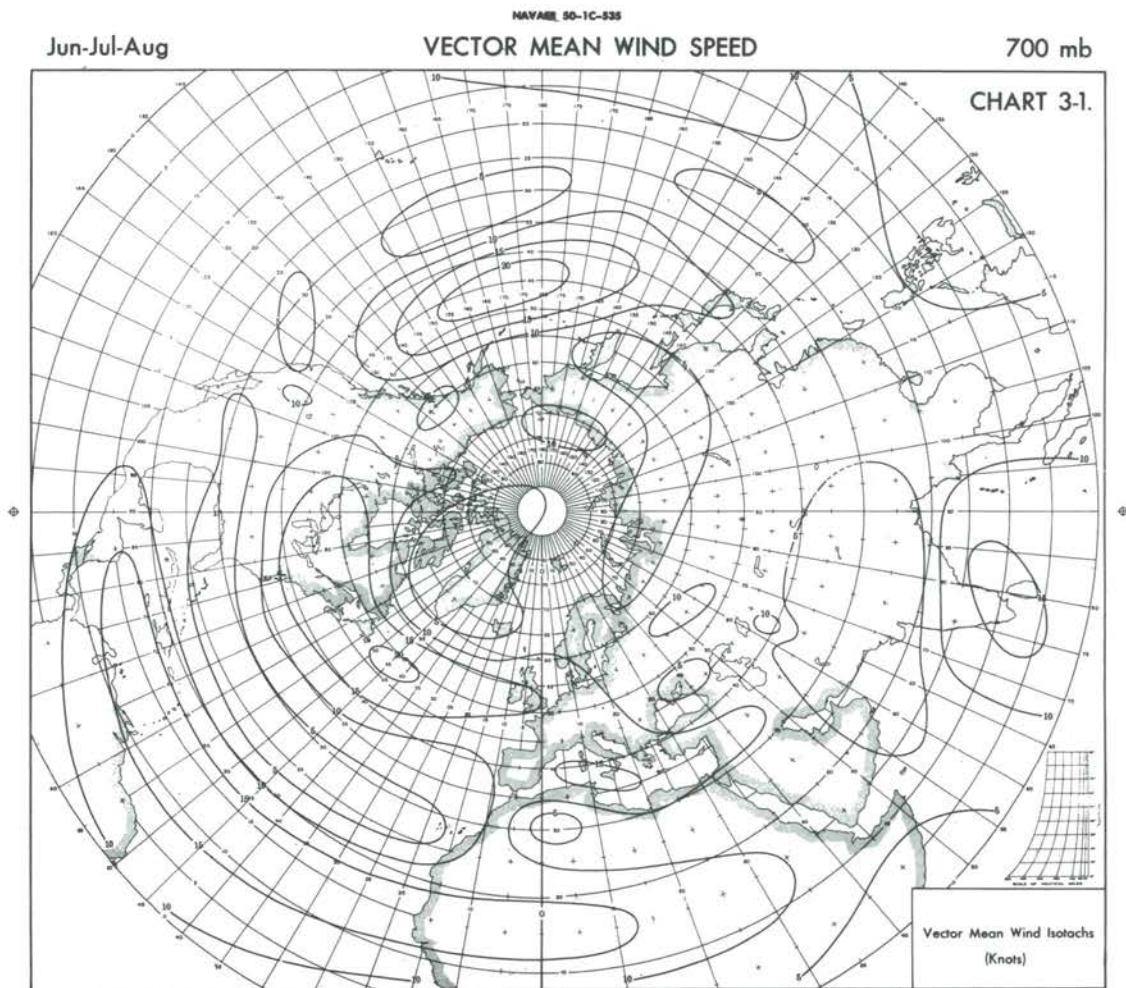


Fig. 12—cont.

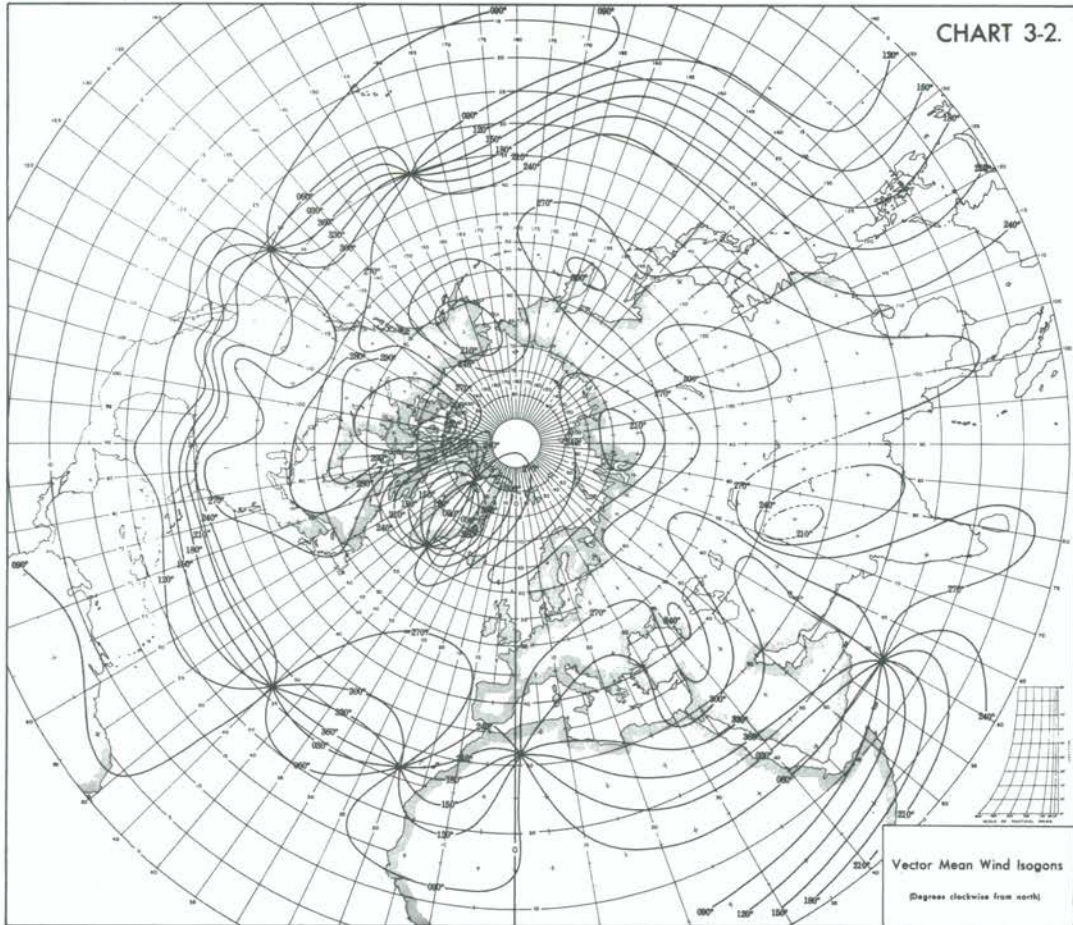


Jun-Jul-Aug

VECTOR MEAN WIND DIRECTION

700 mb

CHART 3-2.



Jun-Jul-Aug

VECTOR STANDARD DEVIATION

700 mb

CHART 3-3.

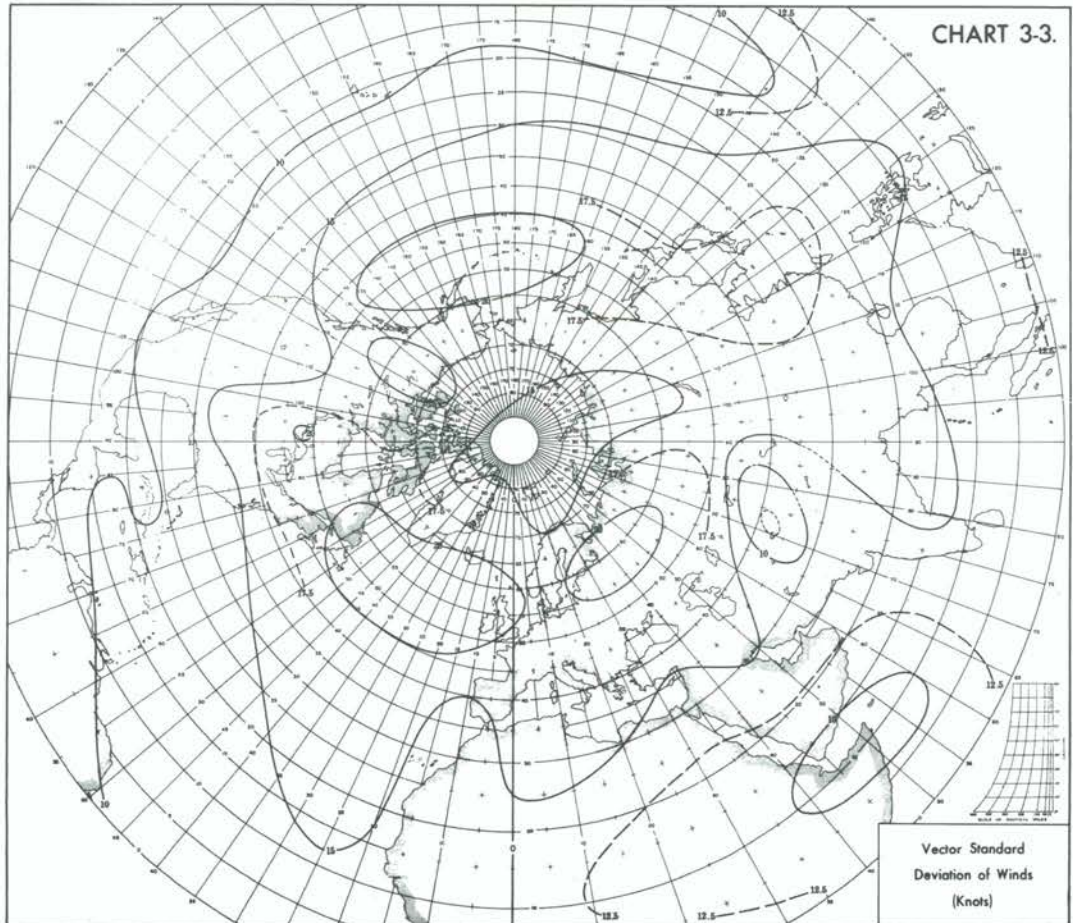
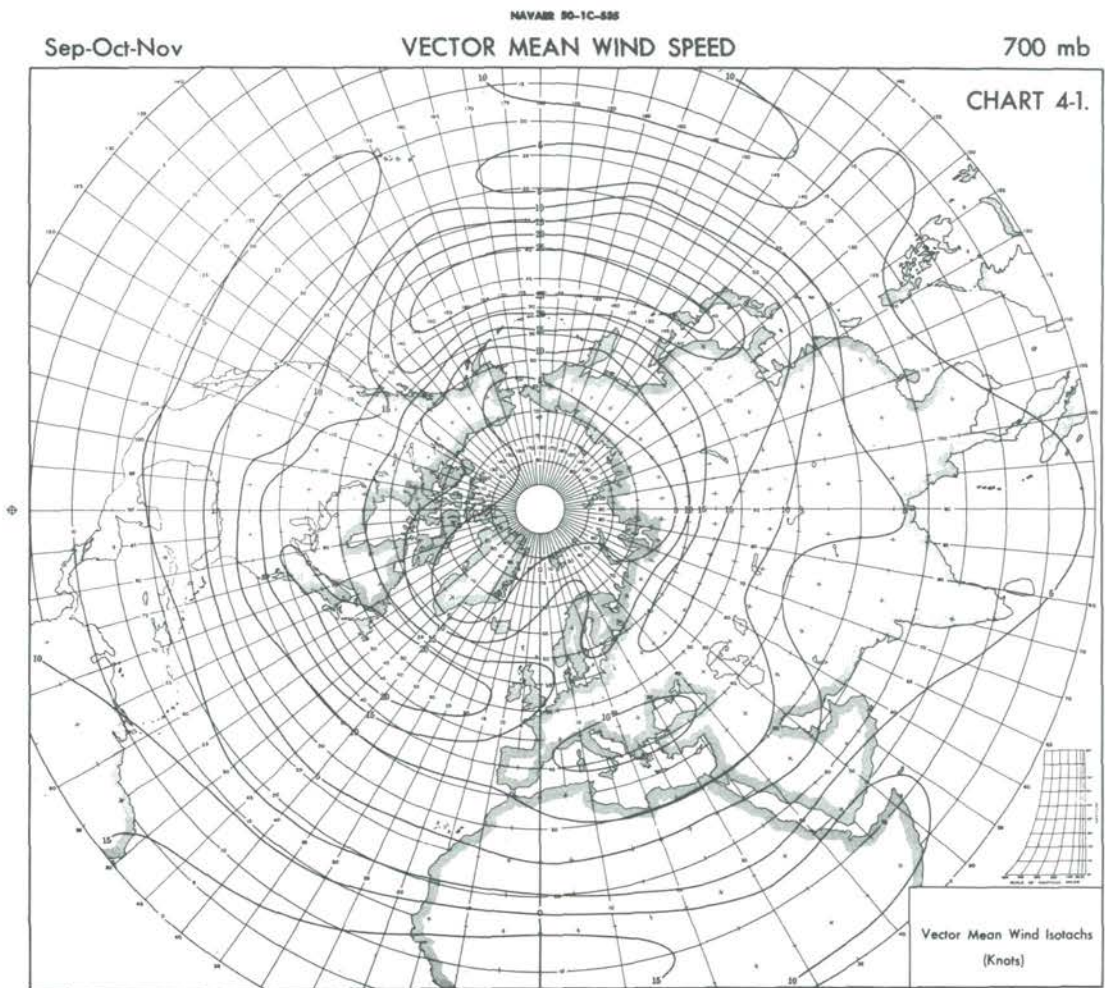


Fig. 12—cont.

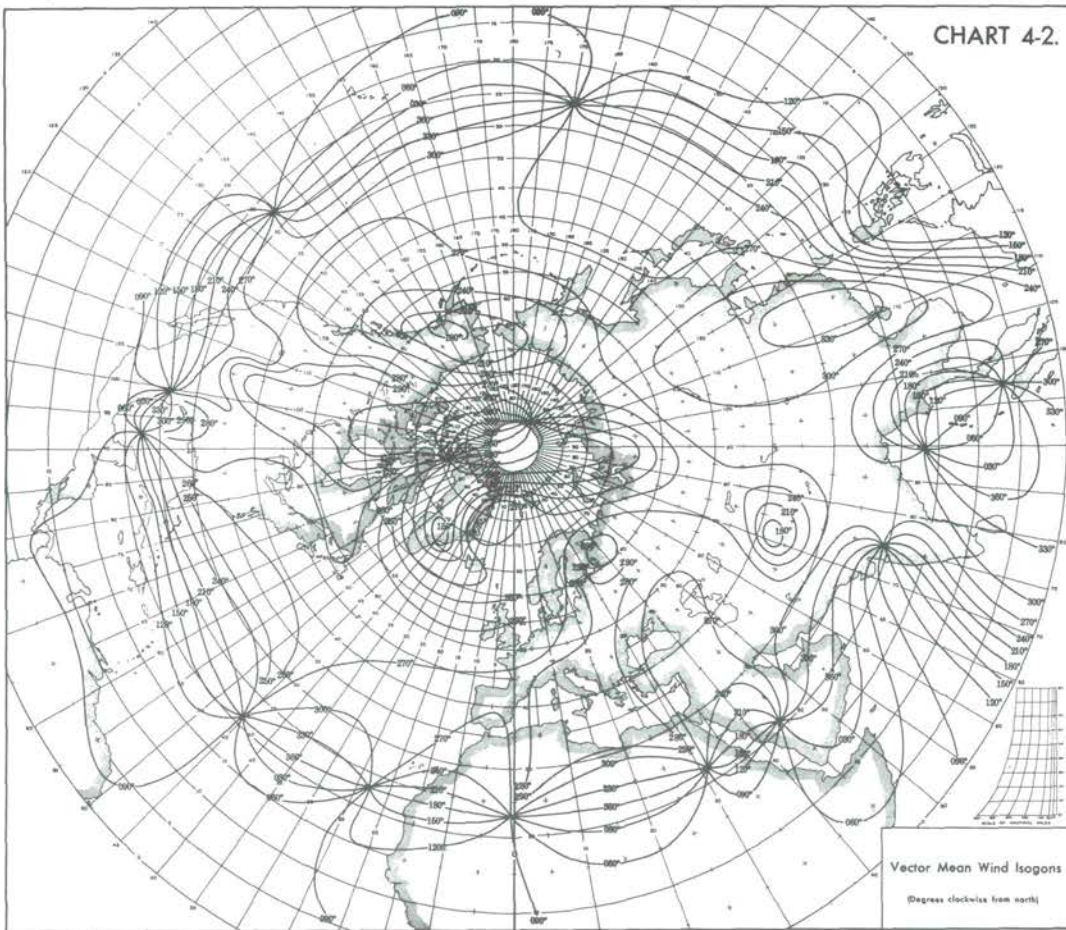


Sep-Oct-Nov

VECTOR MEAN WIND DIRECTION

700 mb

CHART 4-2.



Sep-Oct-Nov

VECTOR STANDARD DEVIATION

700 mb

CHART 4-3.

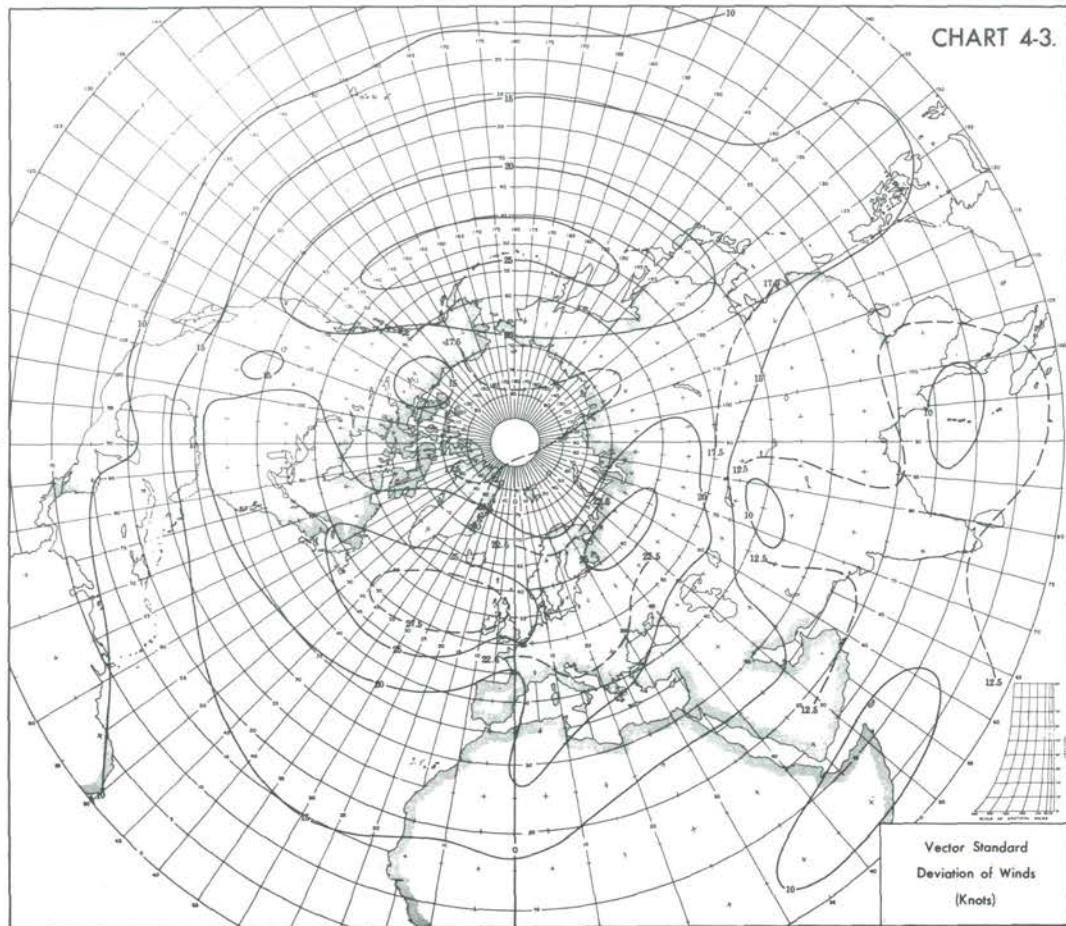


Figure 13. Integrals for climatological concentration, deposition, and (horizontal) flux. The graphs are arranged in blocks of four, each of which has a code indicating the property under investigation and the selection of numerical values for the variables. The three properties are concentration, deposition rate, and flux with codes CO, DE, and FL respectively.

The variables are deposition velocity, precipitation rate, and half-life and have the following values:—

Deposition velocity – code		Precipitation rate – code		Half-life
0 cm s ⁻¹	1	0 cm s ⁻¹	1	Infinite
1 x 10 ⁻¹ cm s ⁻¹	2	2.17 x 10 ⁻⁵ cm s ⁻¹	2	3.6 x 10 ⁵ s
3 x 10 ⁻¹ cm s ⁻¹	3	2.42 x 10 ⁻⁶ cm s ⁻¹	3	3.6 x 10 ⁴ s
1 cm s ⁻¹	4	7.25 x 10 ⁻⁶ cm s ⁻¹	4	3.6 x 10 ³ s

The properties are calculated for each value of the deposition velocity with each value of the precipitation rate for all four half-lives. The code arrangement is as follows: property, deposition velocity, precipitation rate. For example: CO-1-3 indicates the graphs for concentration with deposition velocity 0 cm s⁻¹ and precipitation rate 2.42 x 10⁻⁶ cm s⁻¹; FL-4-2 is for flux with deposition velocity 1 cm s⁻¹ and precipitation rate 2.17 x 10⁻⁵ cm s⁻¹, and so on.

The legend in the upper left section of each graph gives the values of the variables for that graph.

The abscissa (horizontal scale) is $1/t_m (= \frac{\bar{V} \cos \Delta \theta}{1.5S})$ in s⁻¹. Since $\cos \Delta \theta$ may vary between +1 and -1 (equivalent to the point of interest lying in directions generally along or opposite to the mean wind), $1/t_m$ can be negative as well as positive. All values along the abscissa are to be multiplied by 10 raised to the power of the number following the letter E on the right side of the abscissa (e.g. E-5 means 10⁻⁵).

The ordinate (vertical axis) provides the value of the integral, which is the desired quantity. The units are: for concentration, (cm s)⁻¹, for deposition rate, s⁻², and for flux, cm s⁻². Values indicating the ordinate scale appear on opposite sides of the line solely for printing convenience.

The curved lines are $t_\sigma (= \frac{1.5S}{\sigma})$ in s. Letters on right side near the top of lines represent the values of t_σ as given below:

$$A = 5 \times 10^3 \text{ s}; \quad B = 7.5 \times 10^3 \text{ s}; \quad C = 1 \times 10^4 \text{ s}; \quad D = 2 \times 10^4 \text{ s}; \\ E = 5 \times 10^4 \text{ s}; \quad F = 7.5 \times 10^4 \text{ s}; \quad G = 1 \times 10^5 \text{ s}; \quad H = 2 \times 10^5 \text{ s}.$$

The number to the right of the letter denotes the power of 10 by which the ordinate value should be multiplied (e.g. F 3 means that the ordinate should be multiplied by 10³ or 1000).

CO-1-1

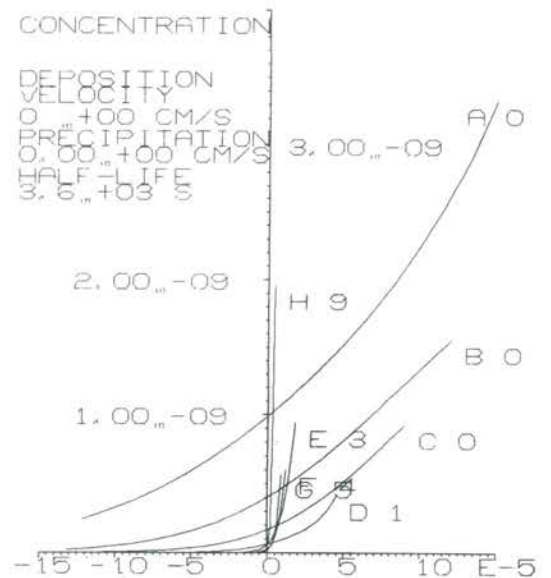
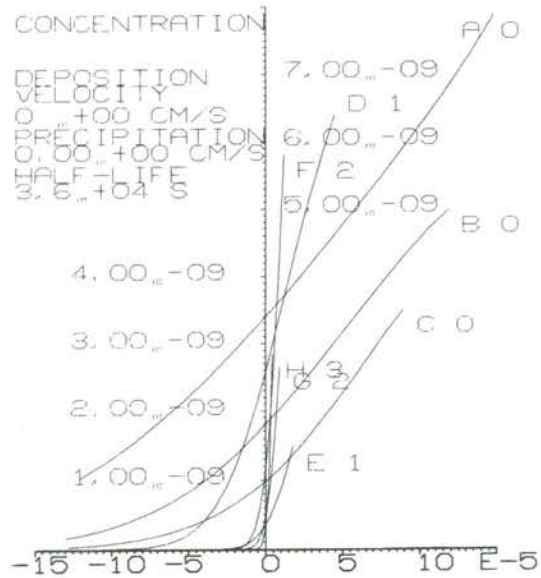
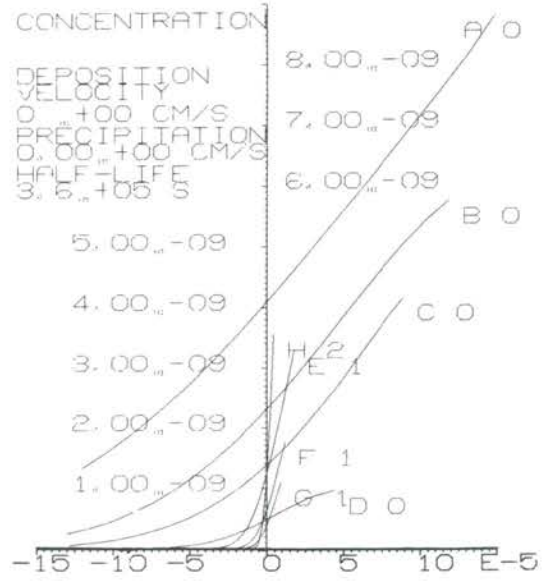
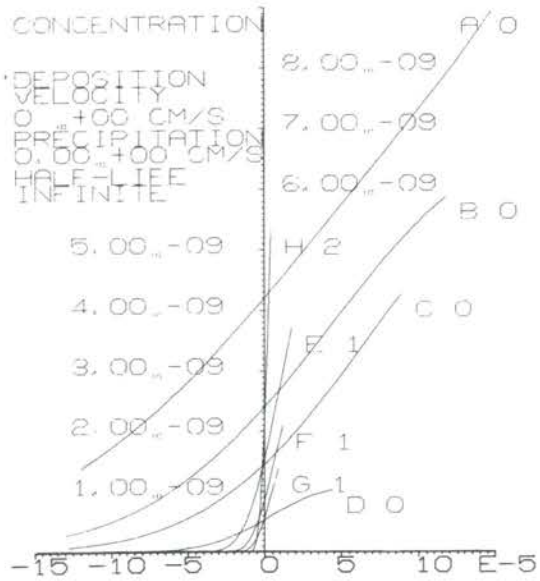


Fig. 13—cont.

CO-2-1

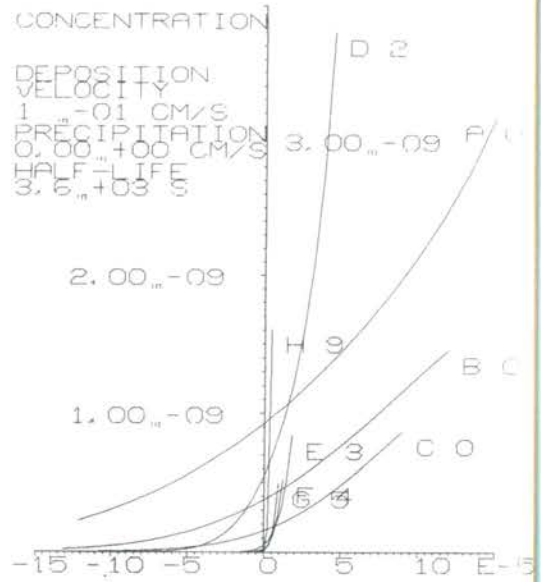
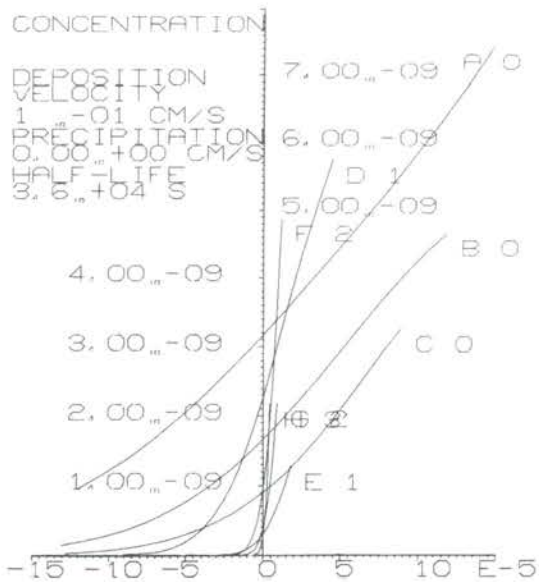
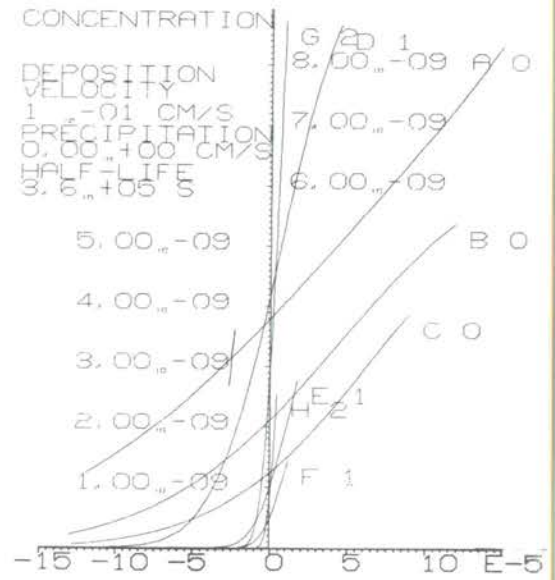
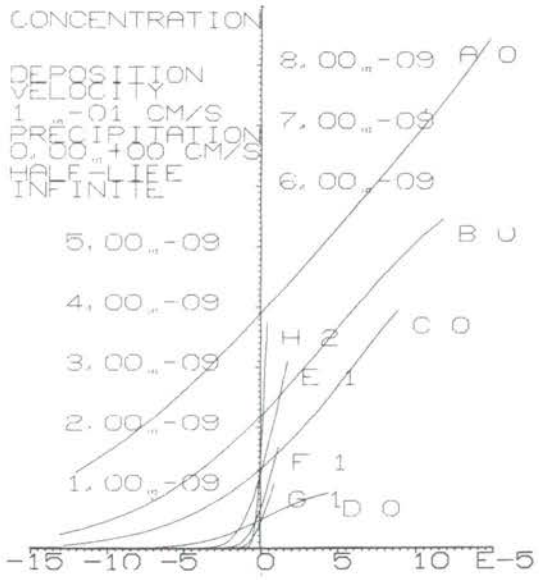


Fig. 13—cont.

CO-3-1

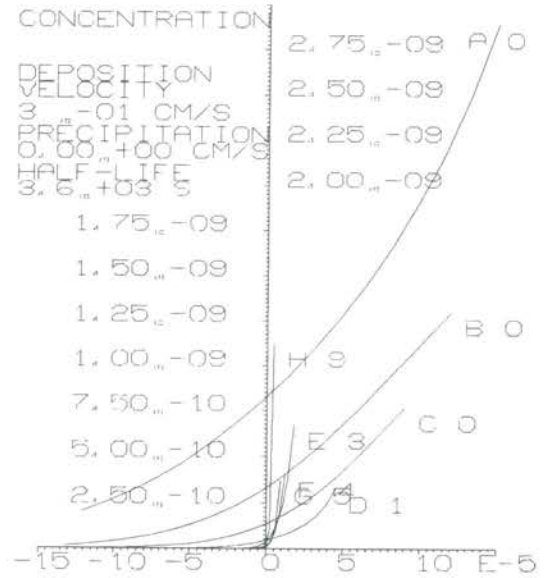
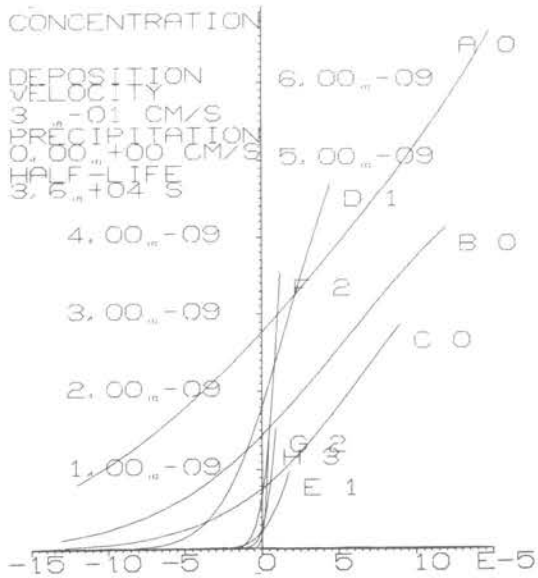
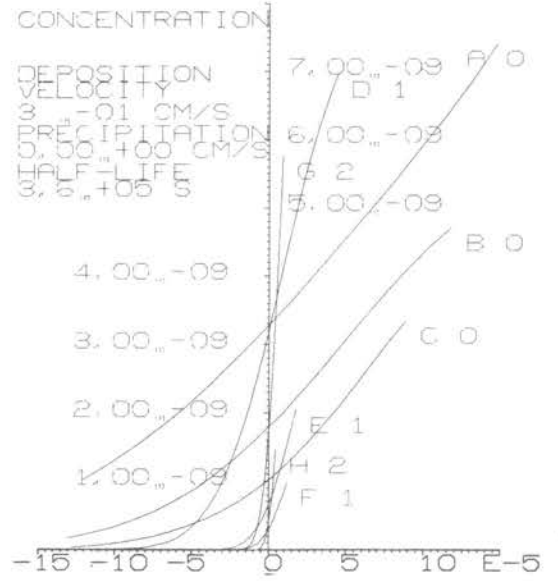
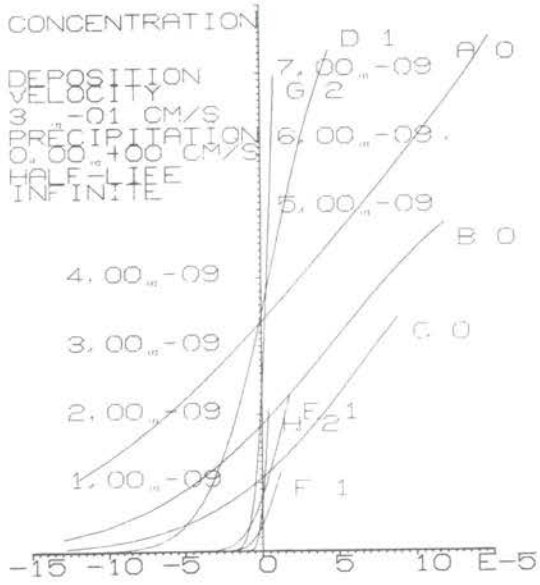


Fig. 13—cont.

CO-4-1

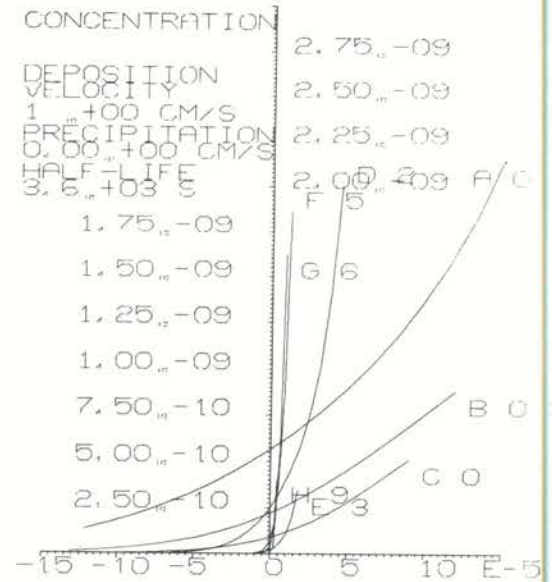
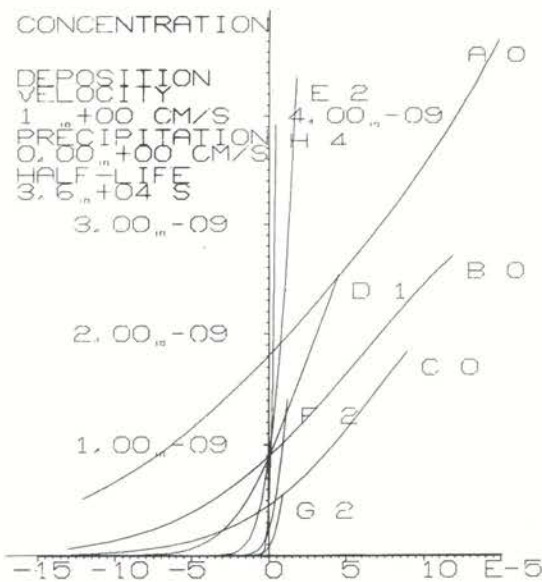
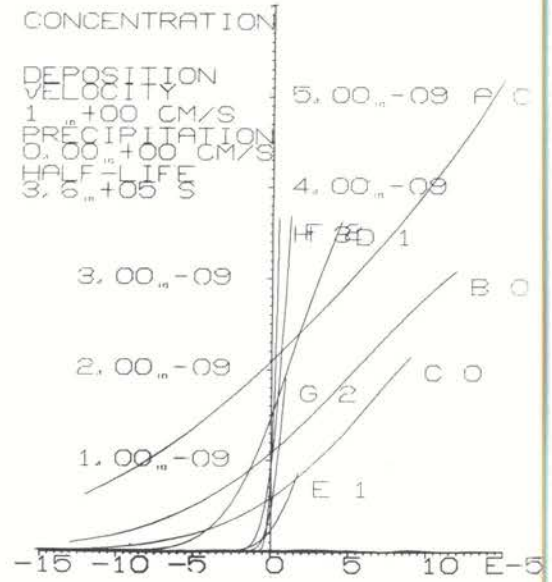
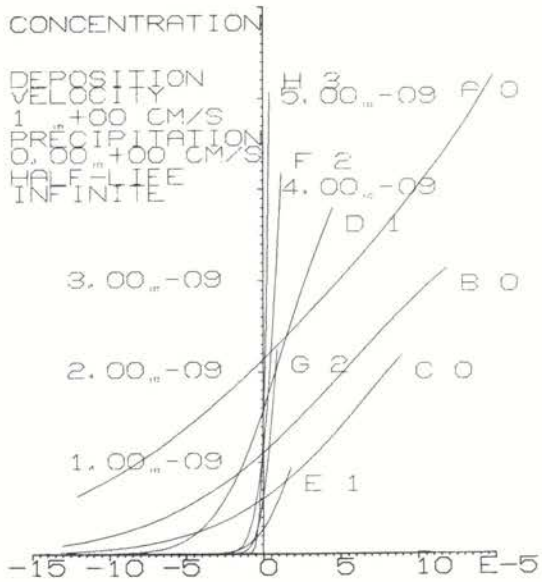


Fig. 13—cont.

CO-1-2

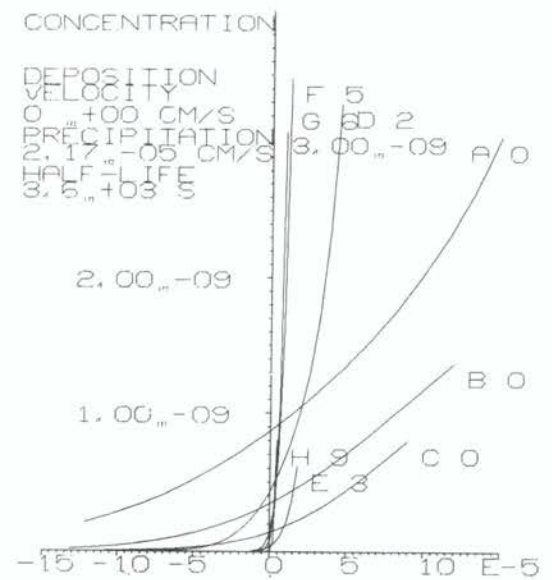
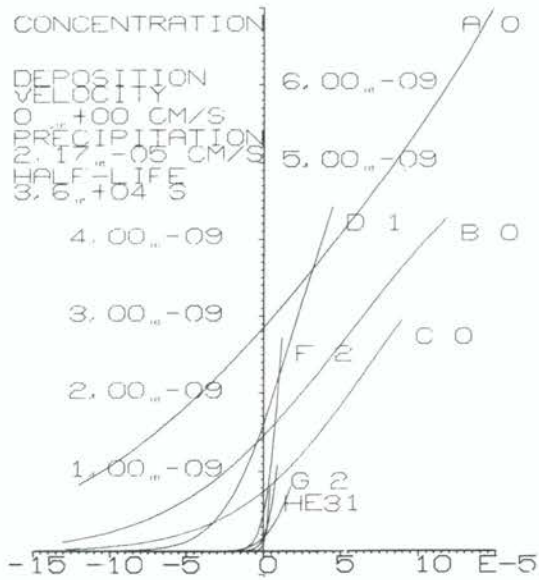
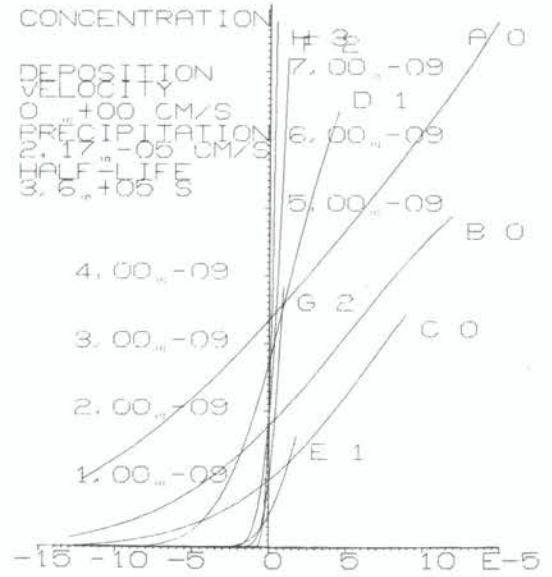
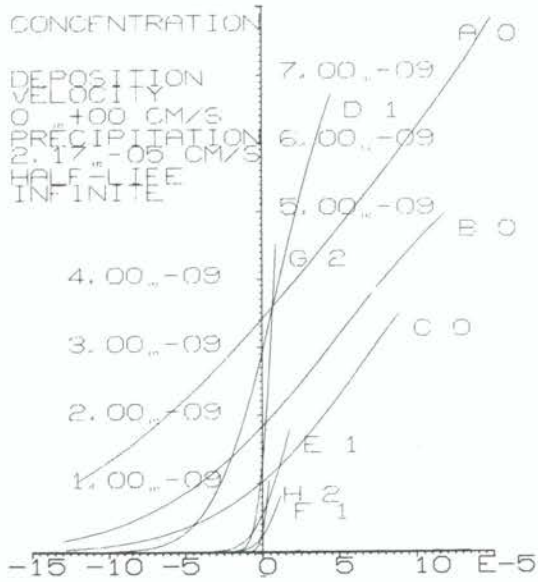


Fig. 13—cont.

CO-2-2

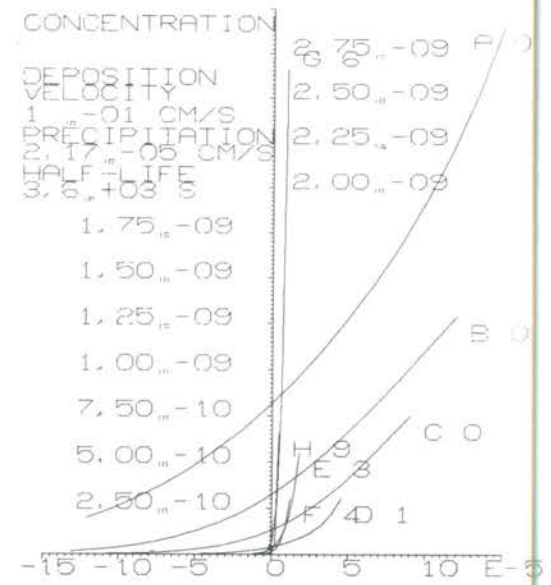
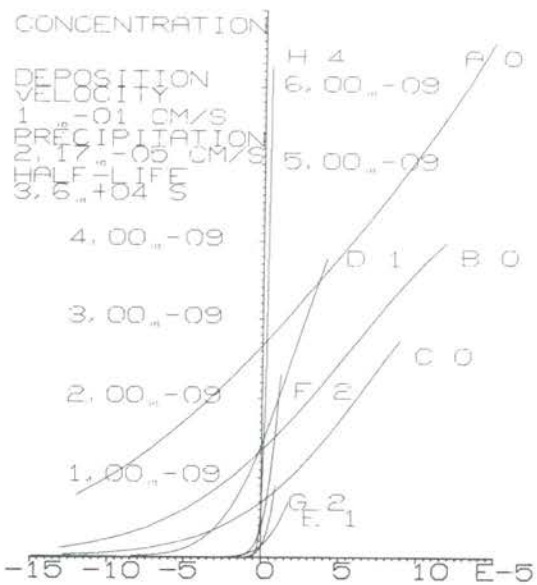
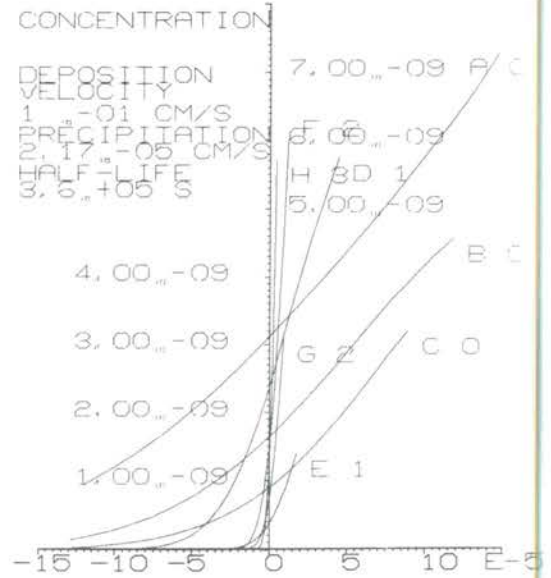
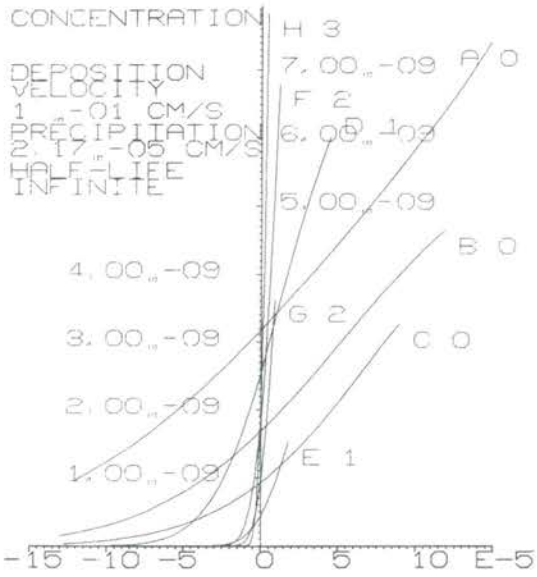


Fig. 13—cont.

CO-3-2

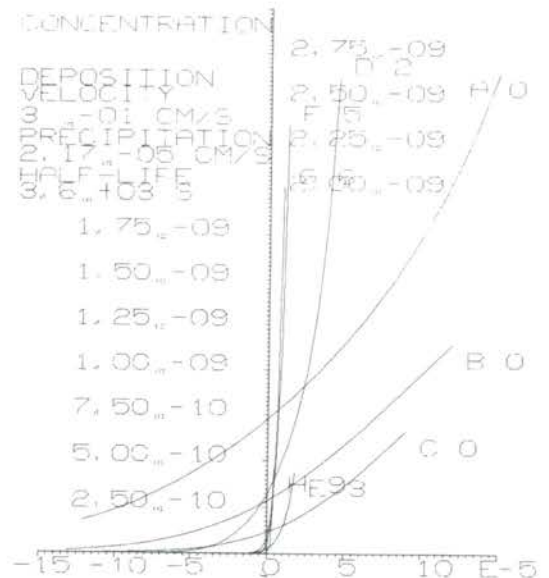
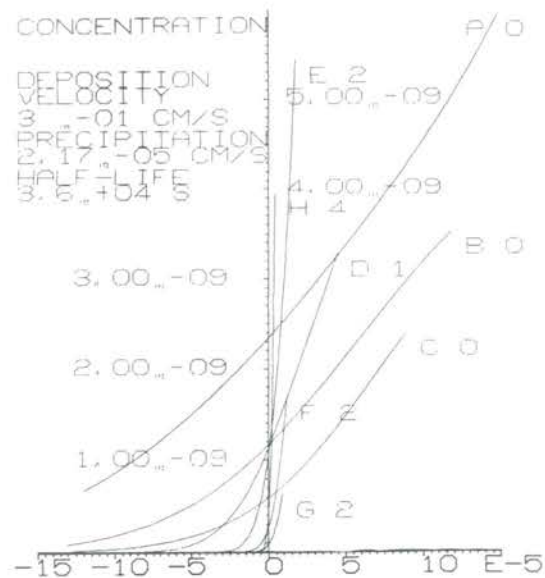
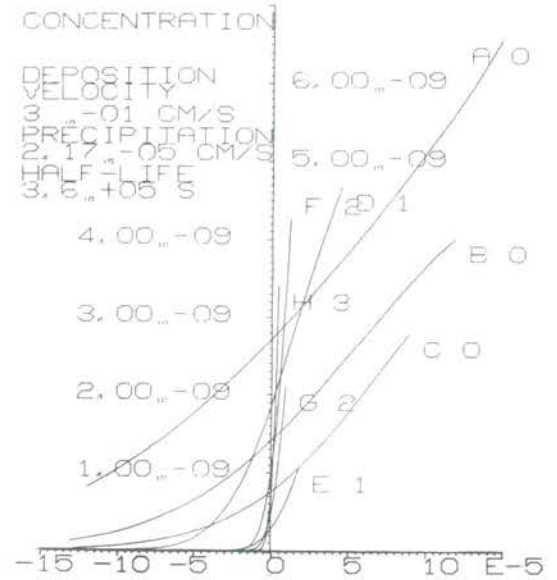
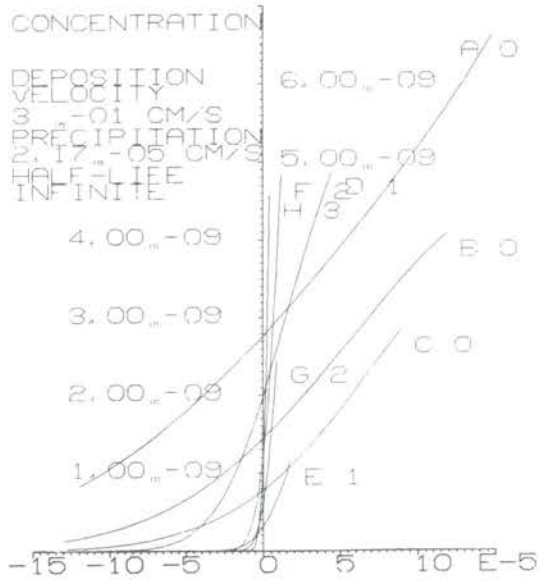


Fig. 13—cont.

CO-4-2

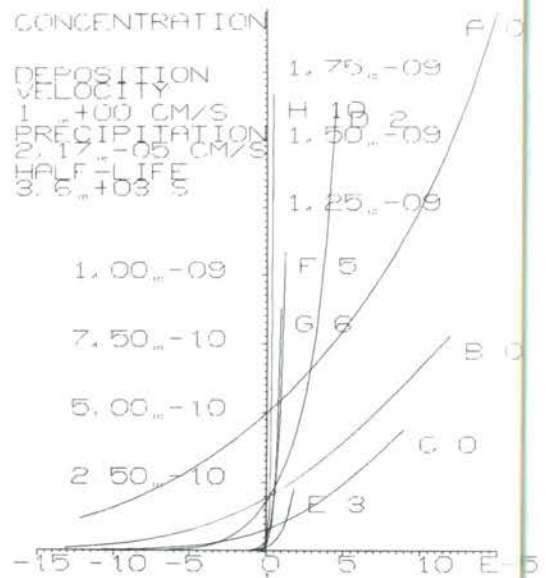
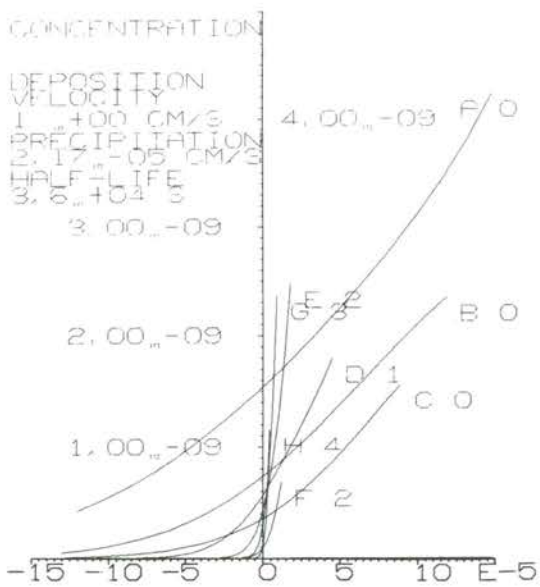
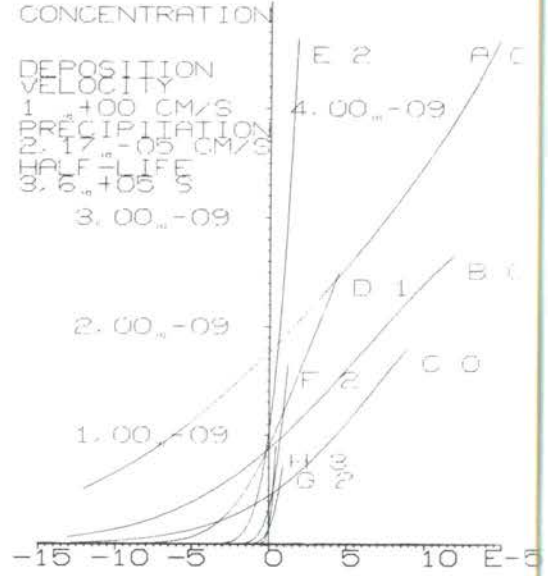
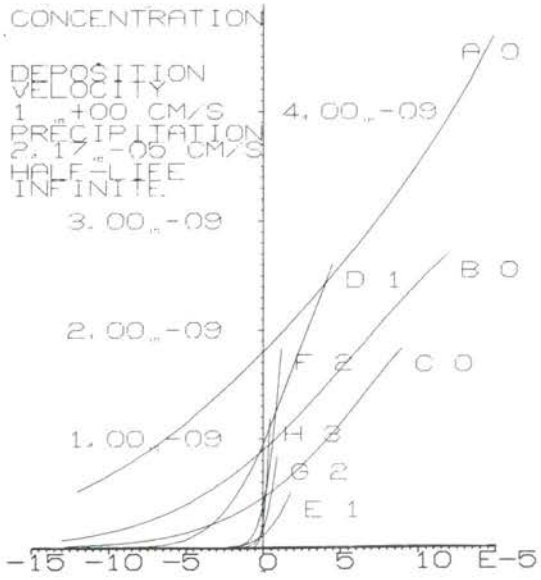


Fig. 13—cont.

CO-1-3

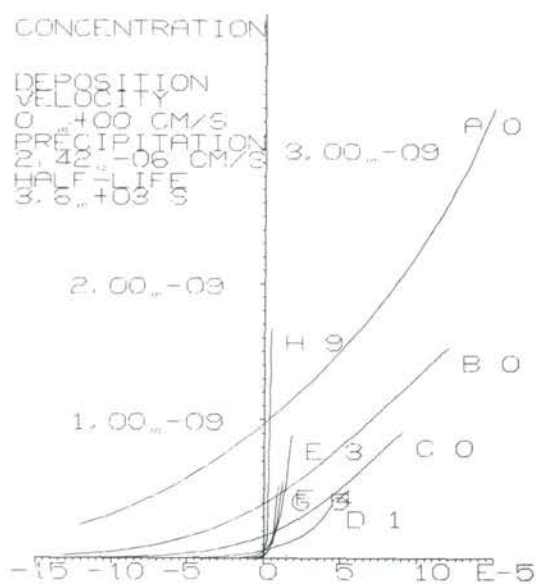
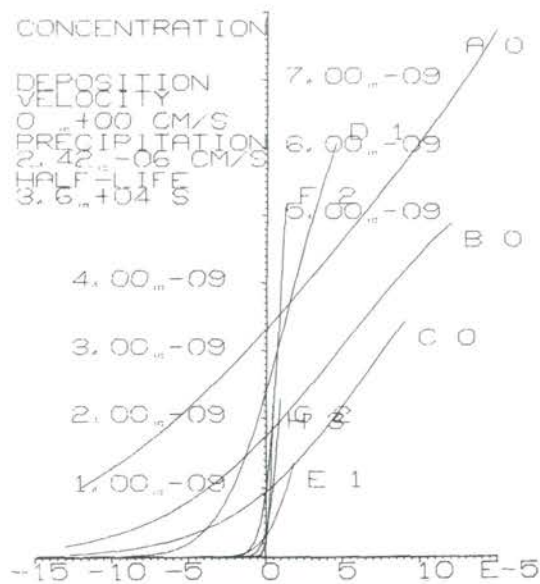
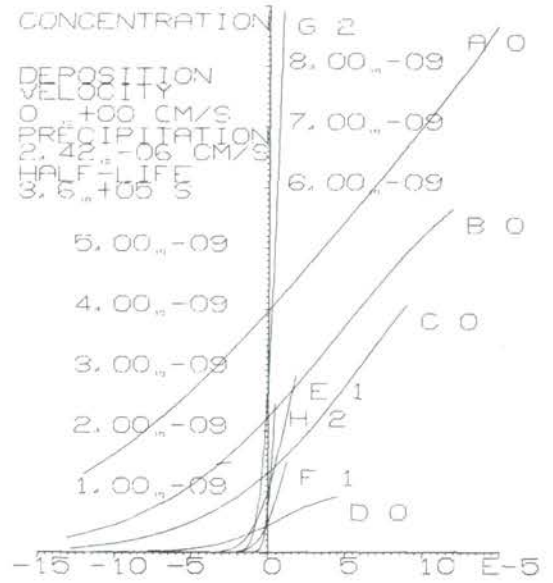
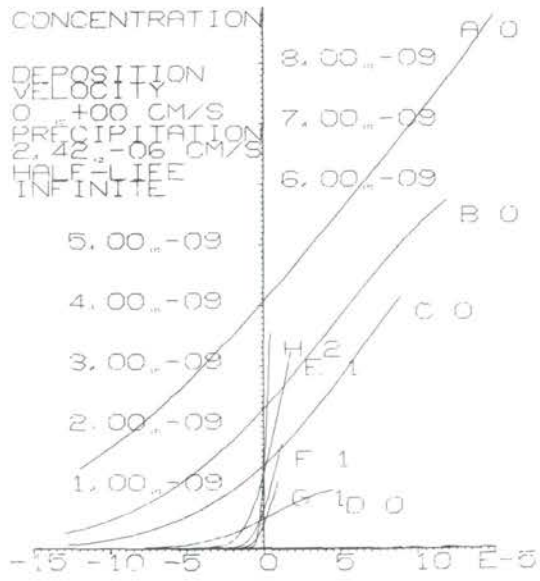


Fig. 13—cont.

CO-2-3

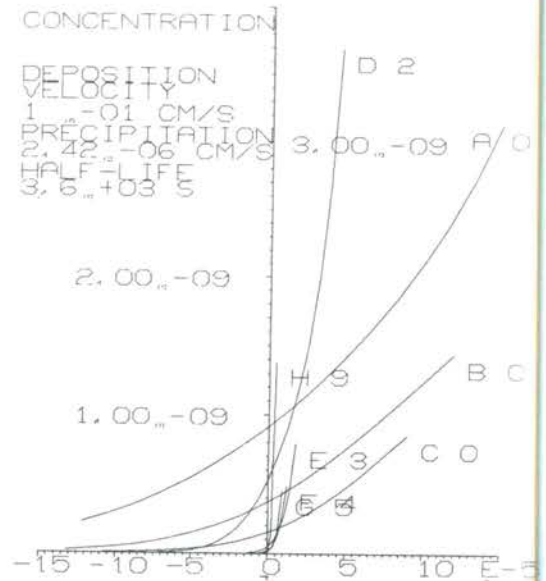
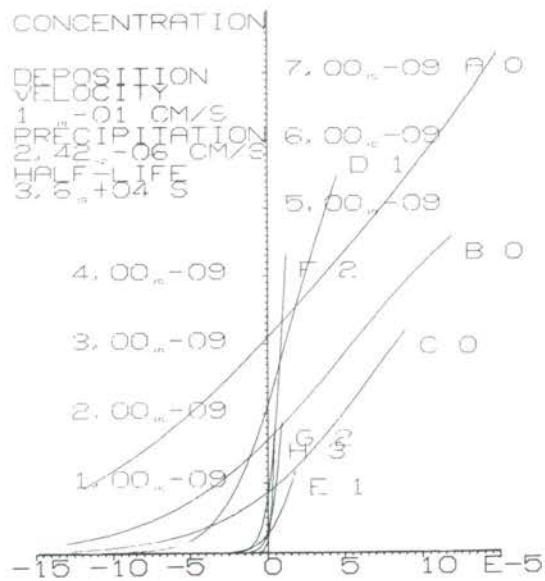
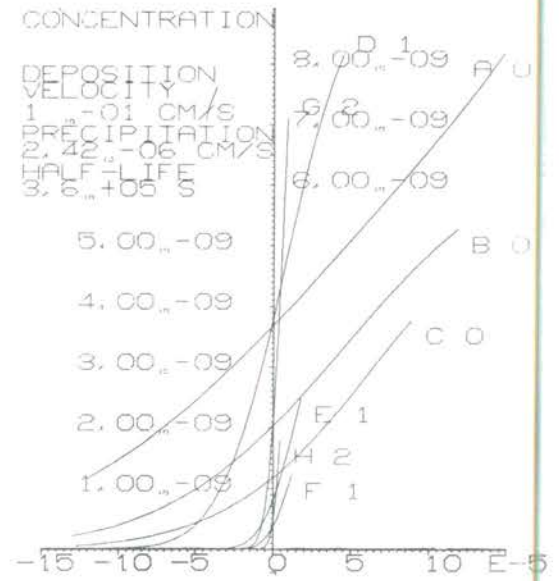
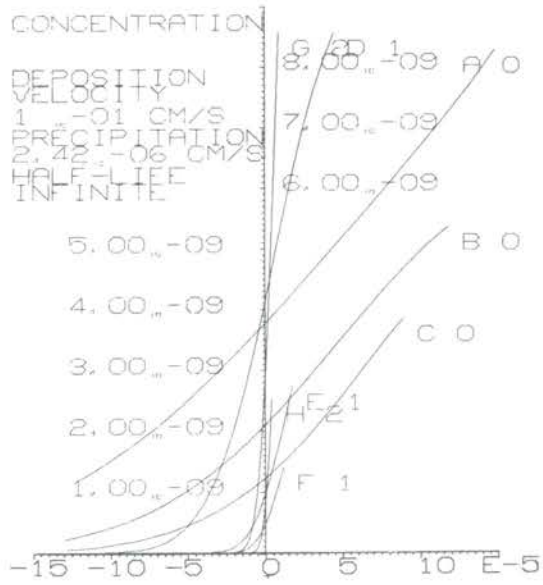


Fig. 13—cont.

CO-3-3

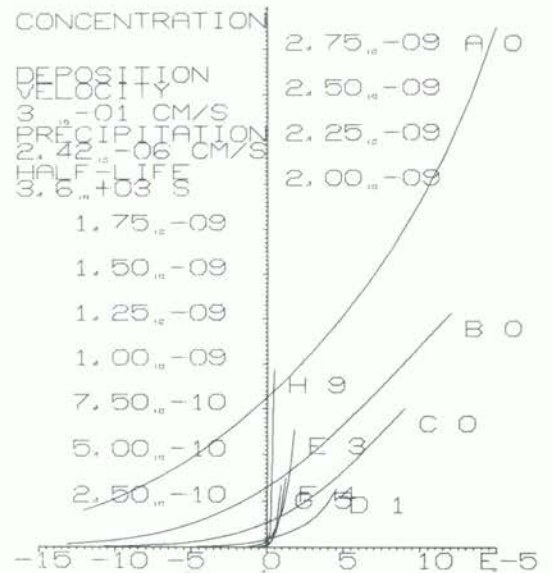
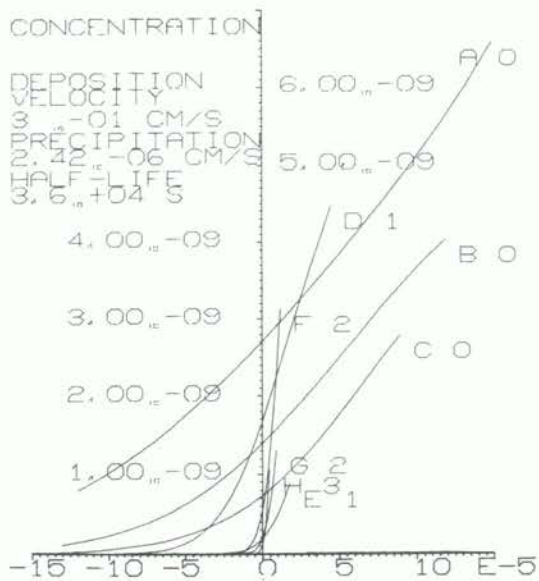
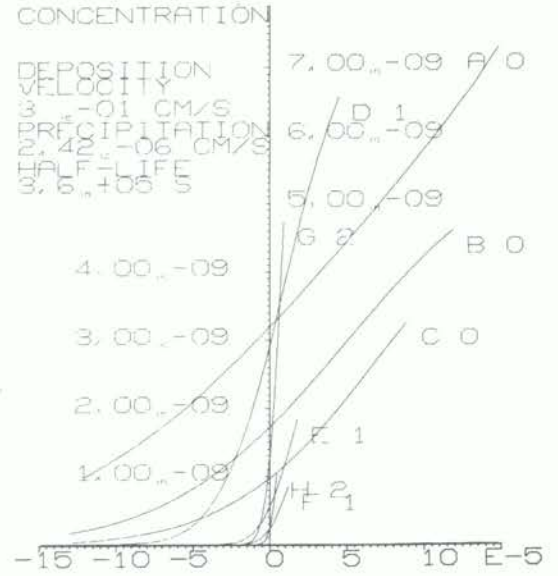
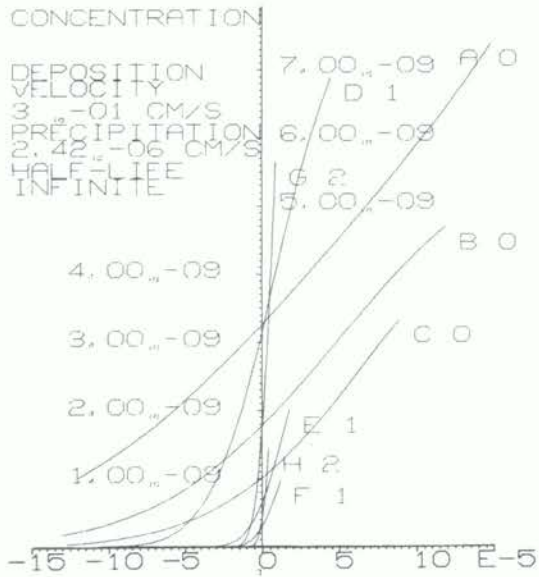


Fig. 13—cont.

CO-4-3

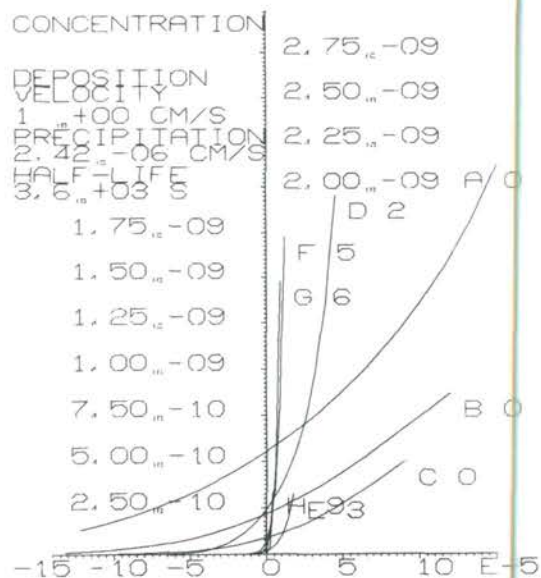
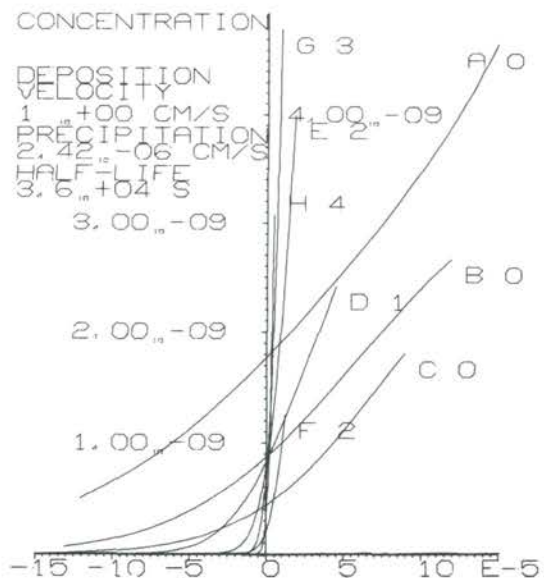
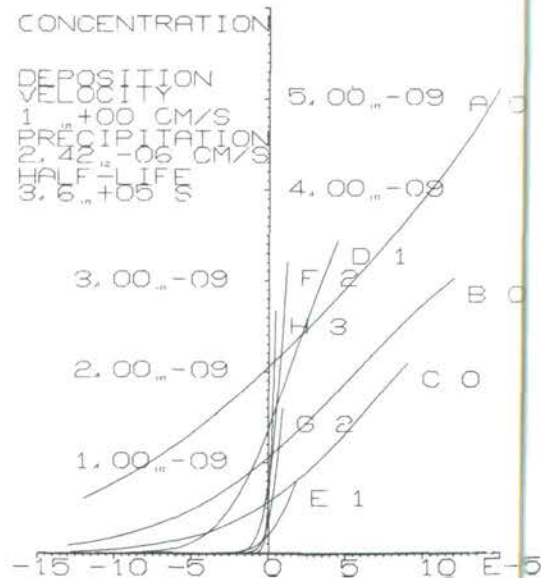
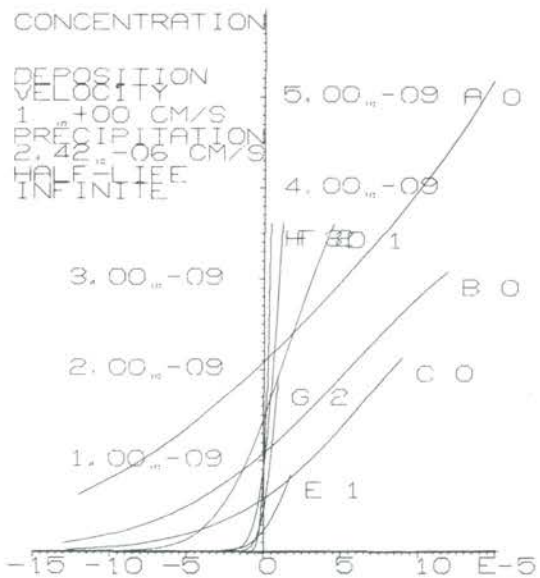


Fig. 13—cont.

CO-1-4

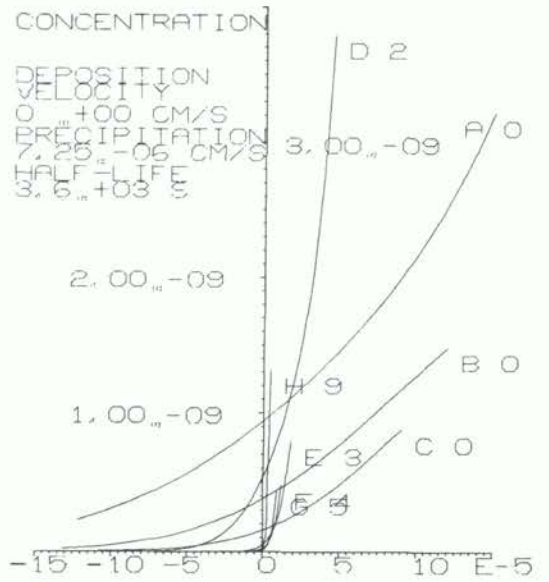
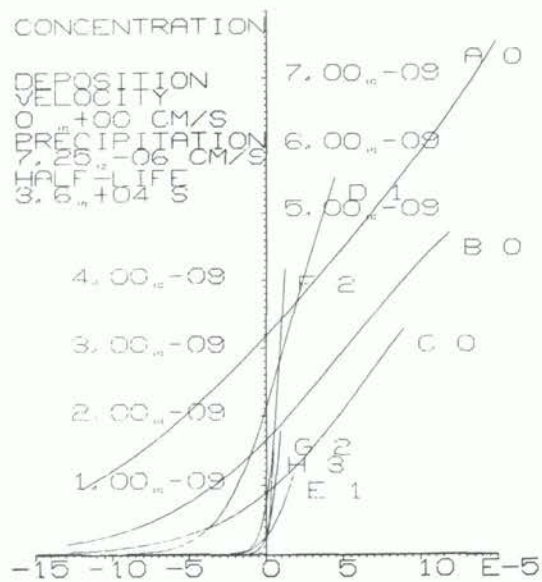
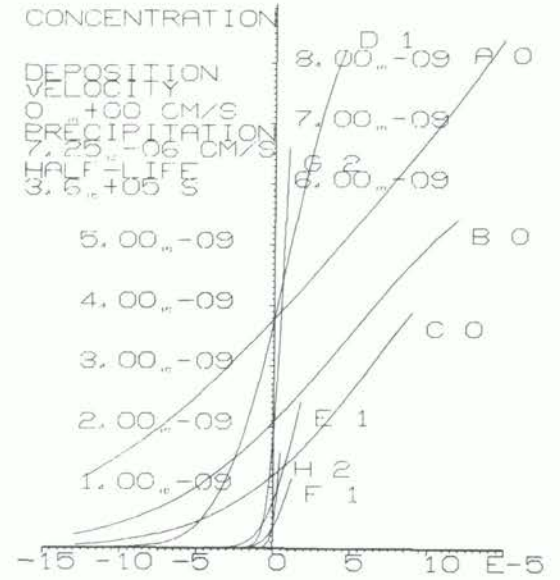
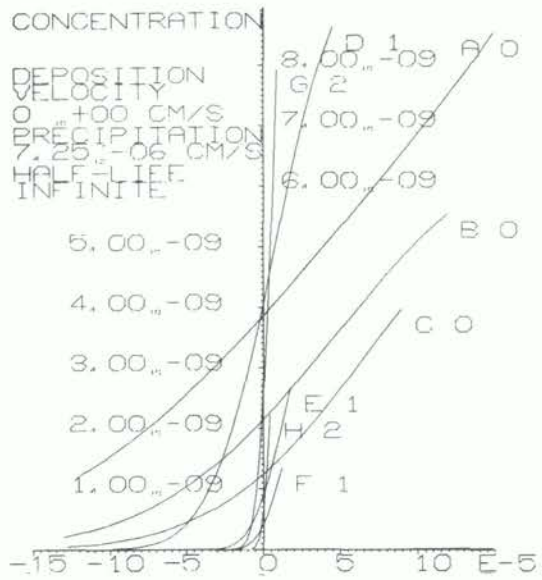


Fig. 13—cont.

CO-2-4

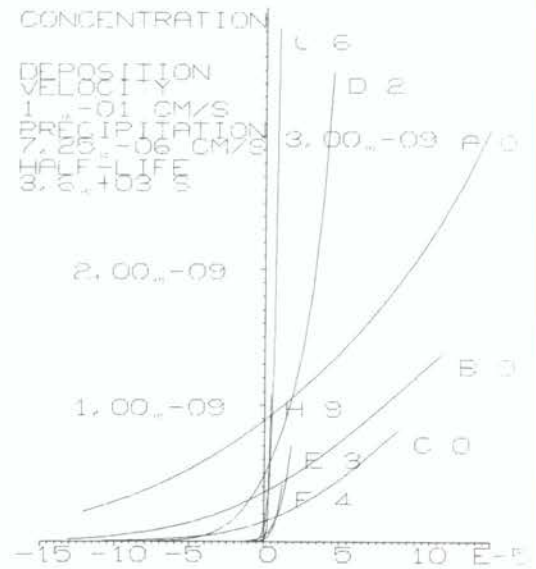
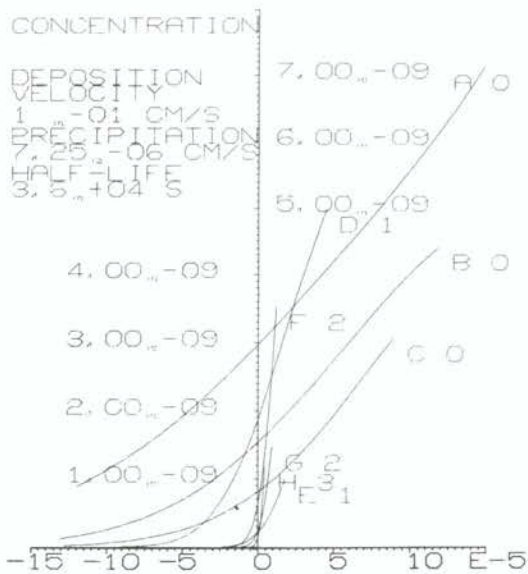
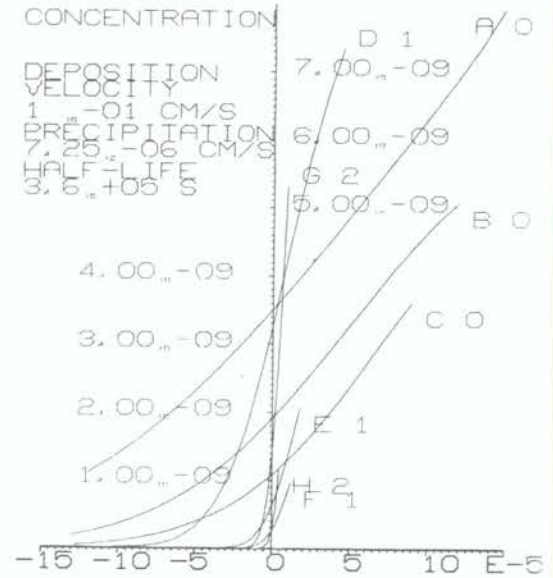
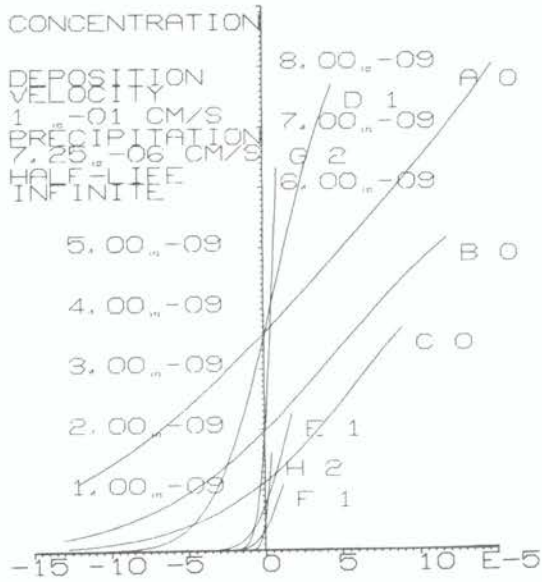


Fig. 13—cont.

CO-3-4

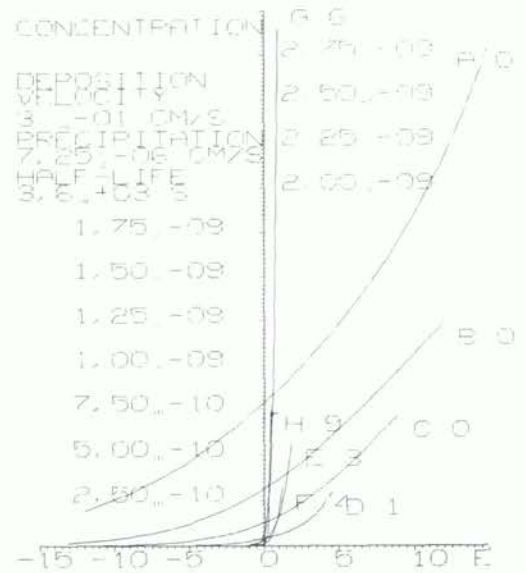
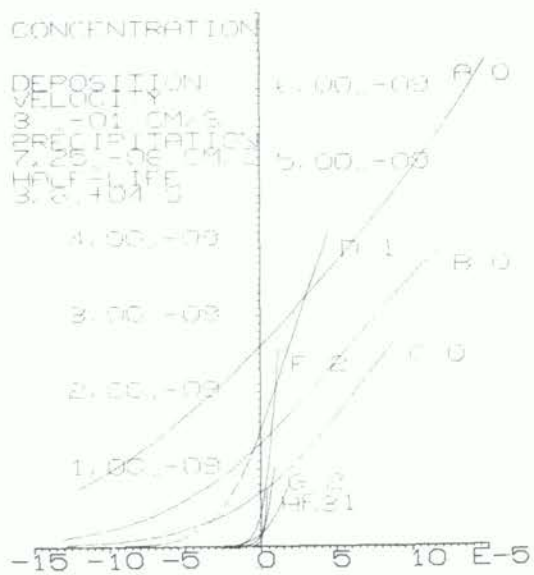
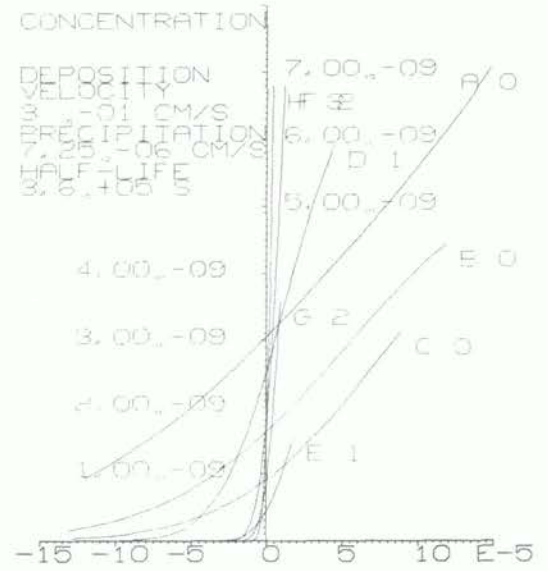
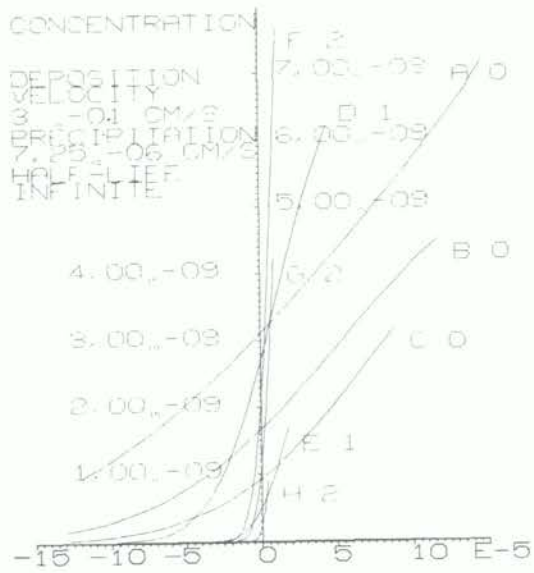


Fig. 13—cont.

CO-4-4

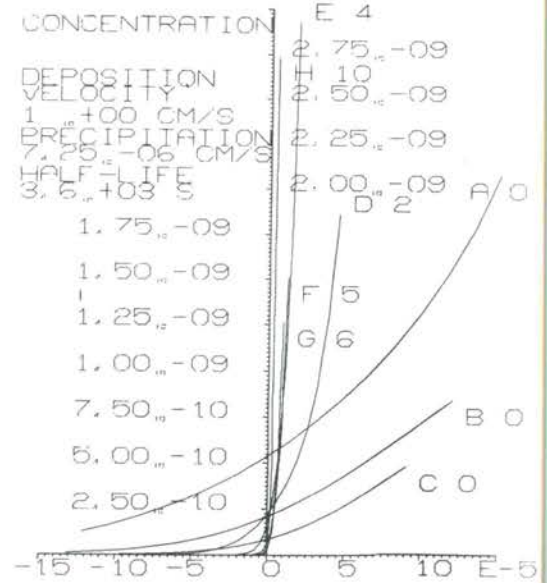
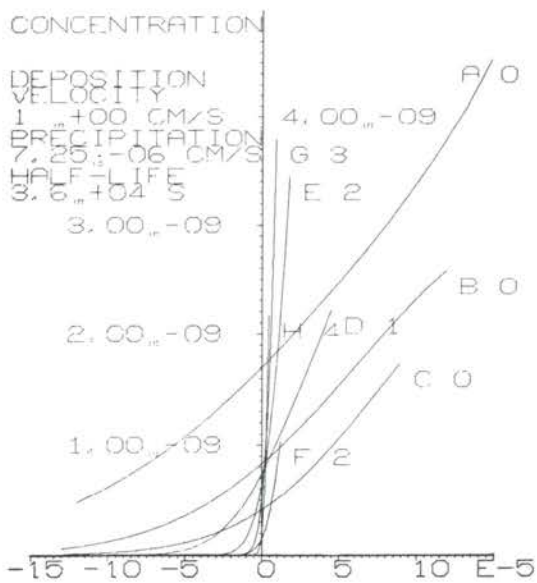
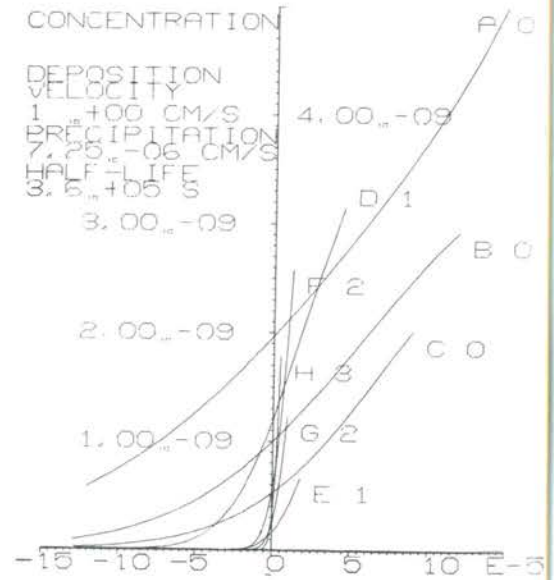
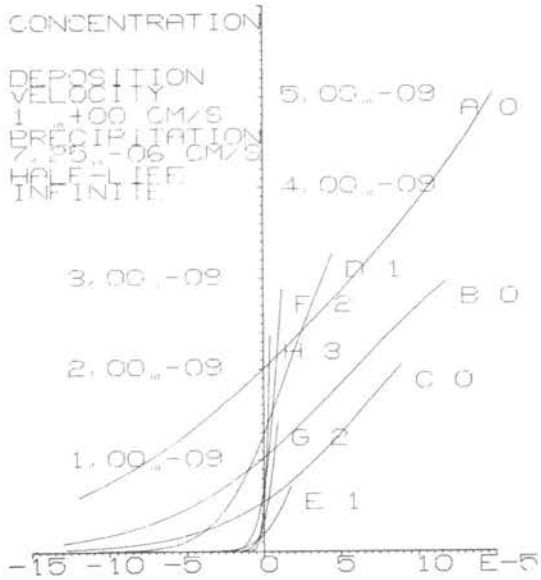


Fig. 13—cont.

DE-2-1

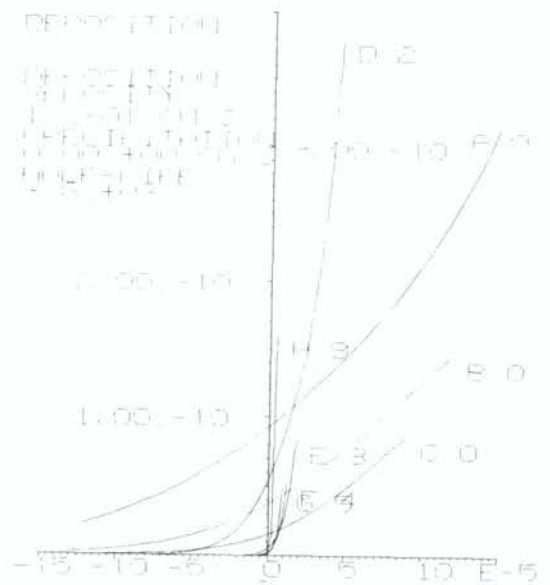
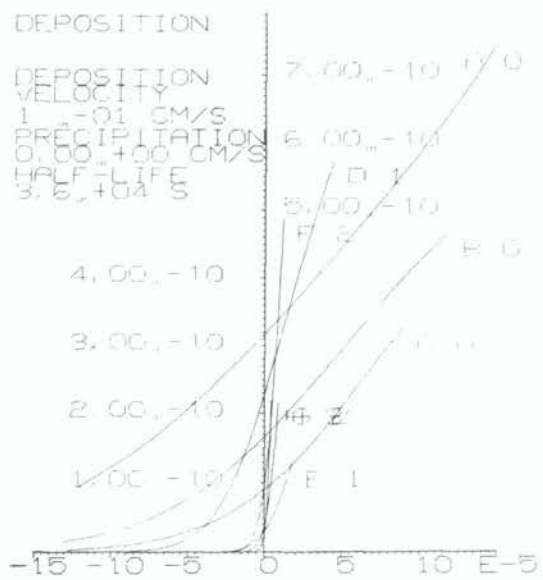
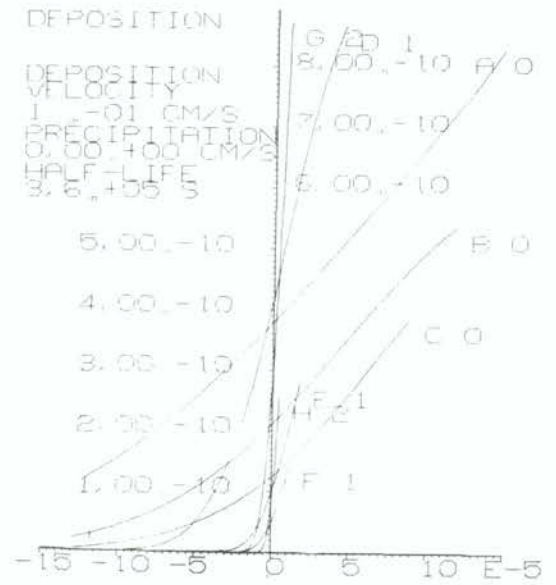
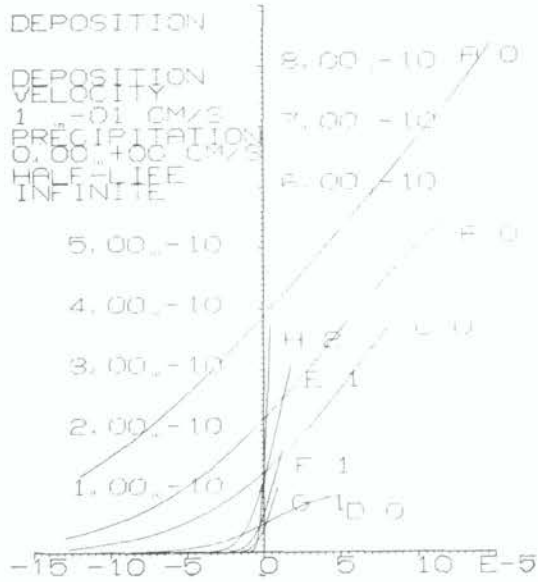


Fig. 13—cont.

DE-3-1

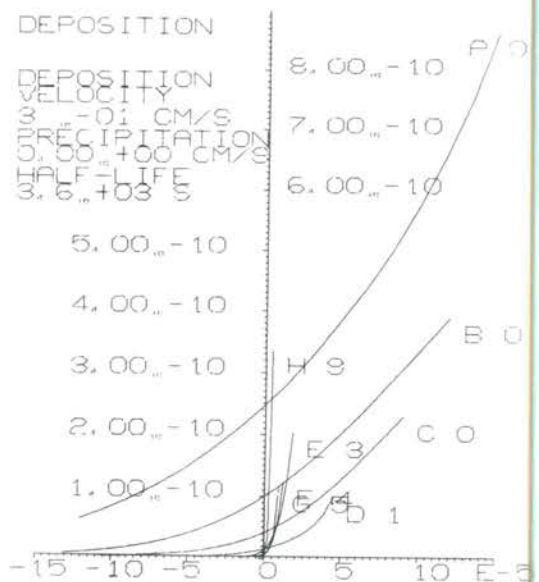
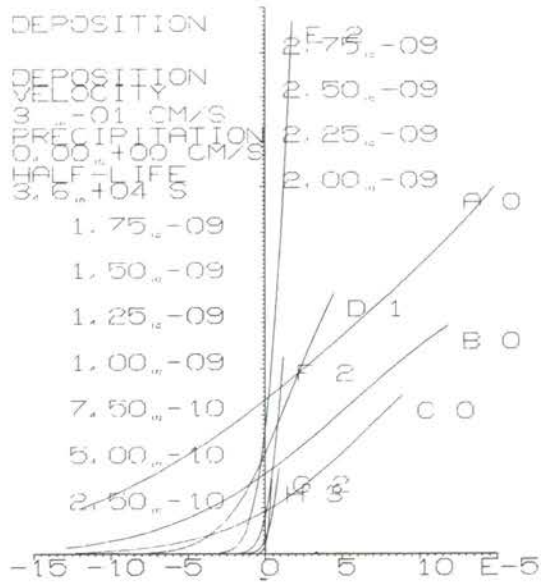
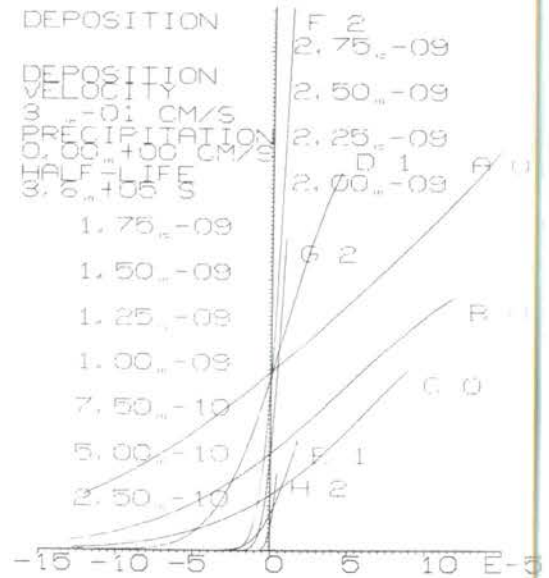
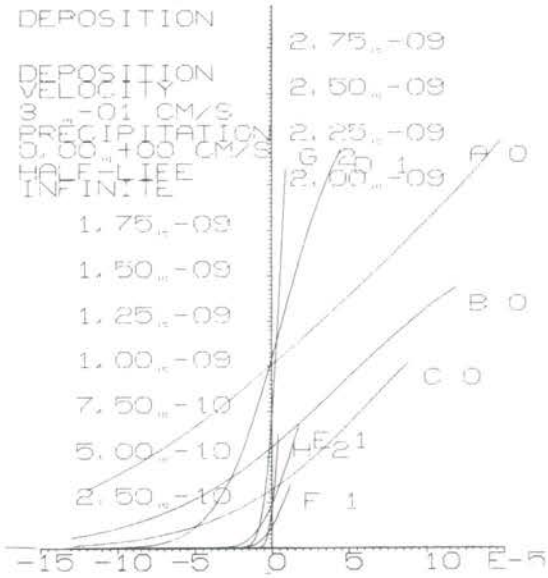


Fig. 13—cont.

DE-4-1

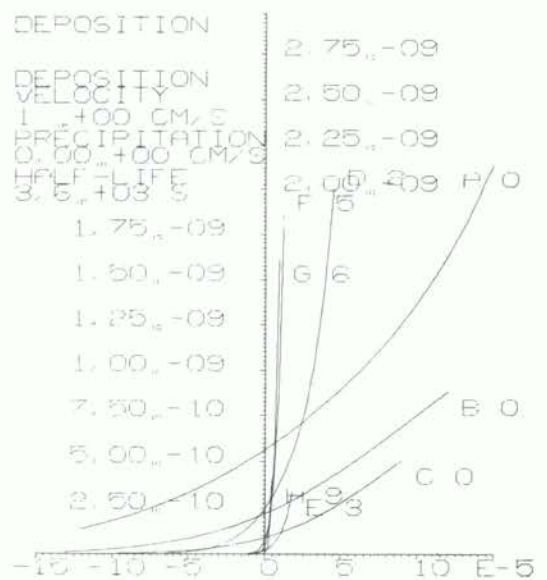
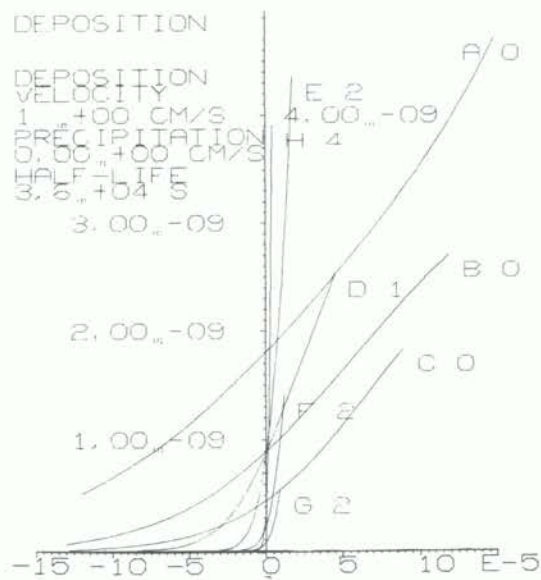
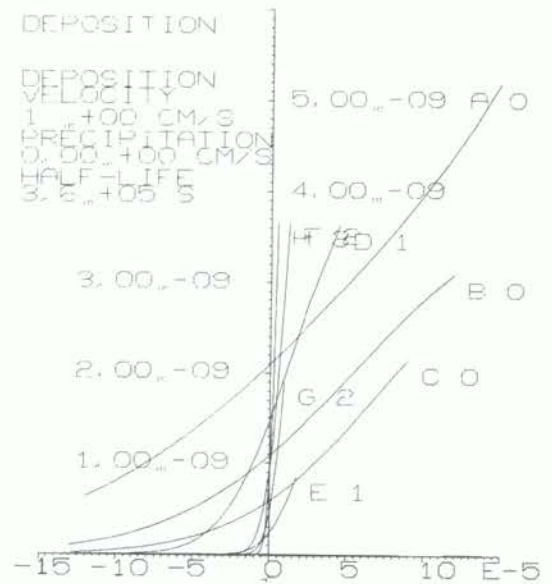
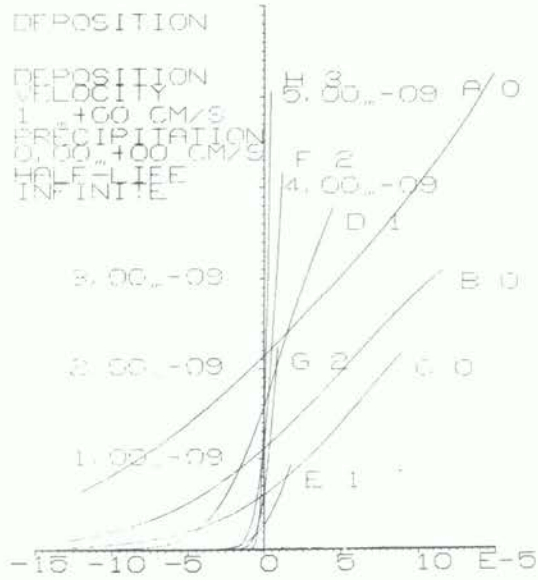


Fig. 13—cont.

DE-1-2

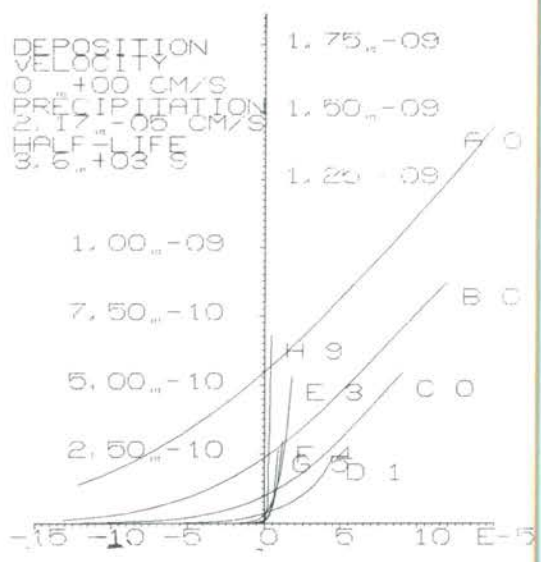
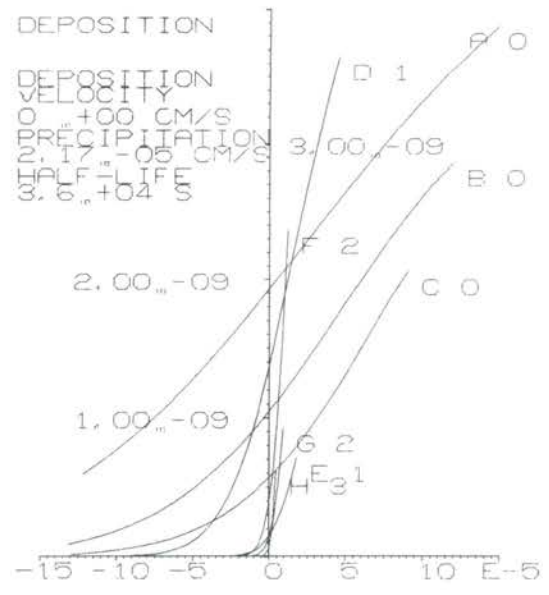
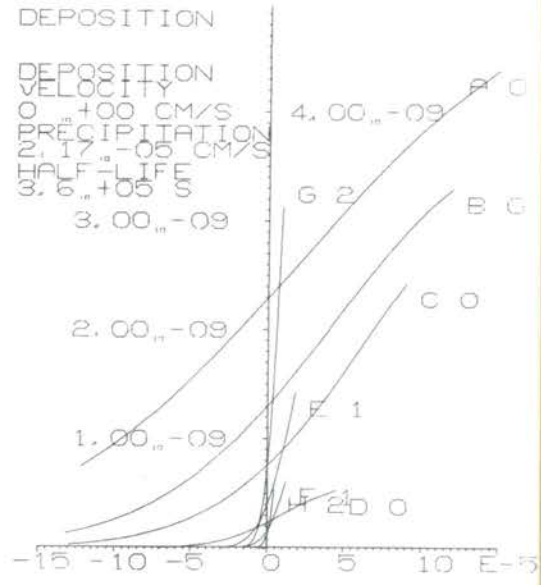
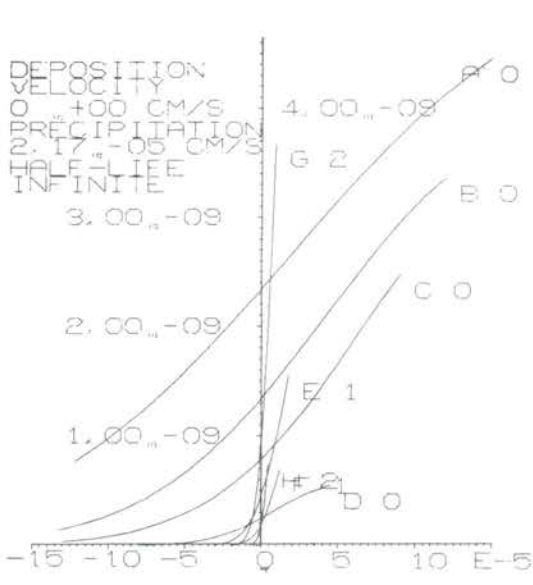


Fig. 13—cont.

DE-2-2

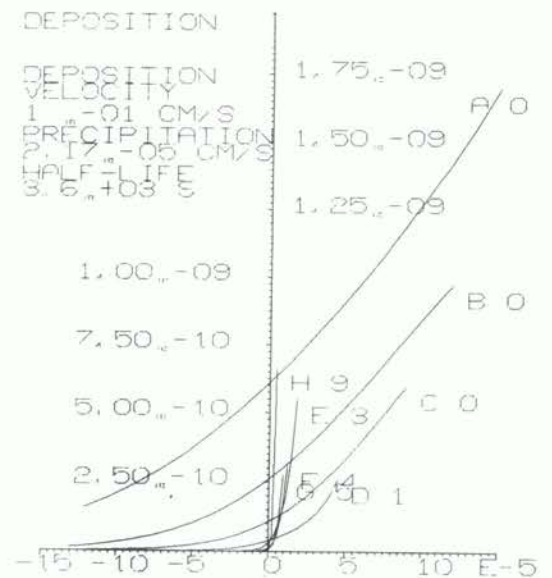
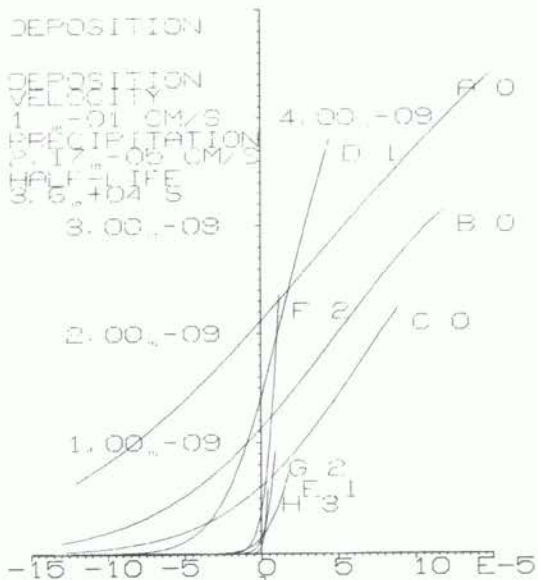
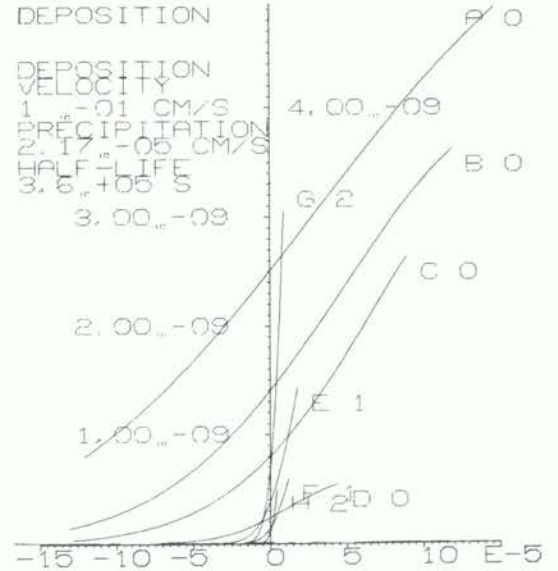
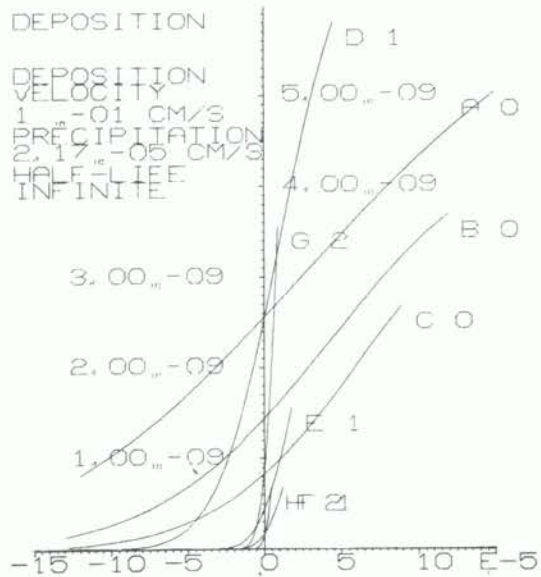


Fig. 13—cont.

DE-3-2

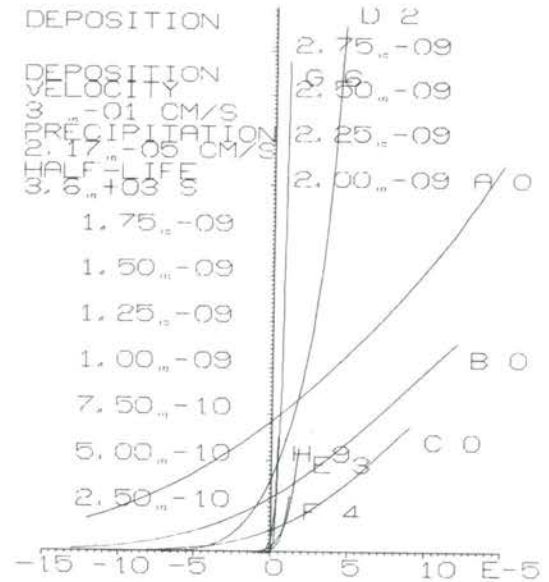
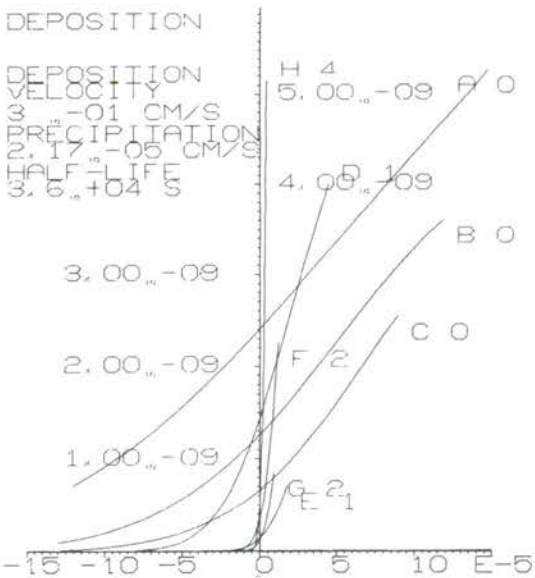
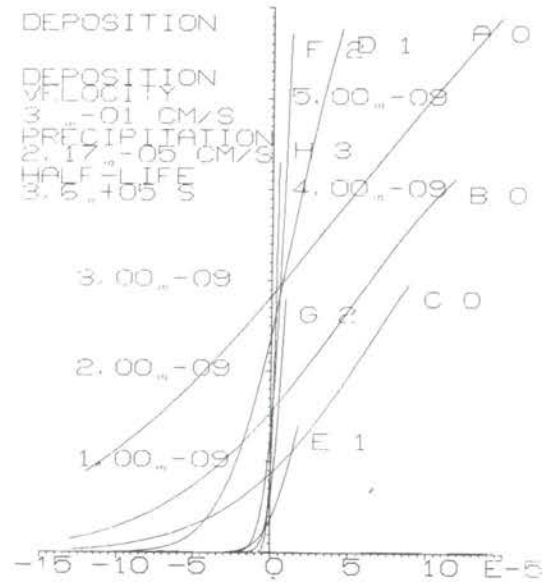
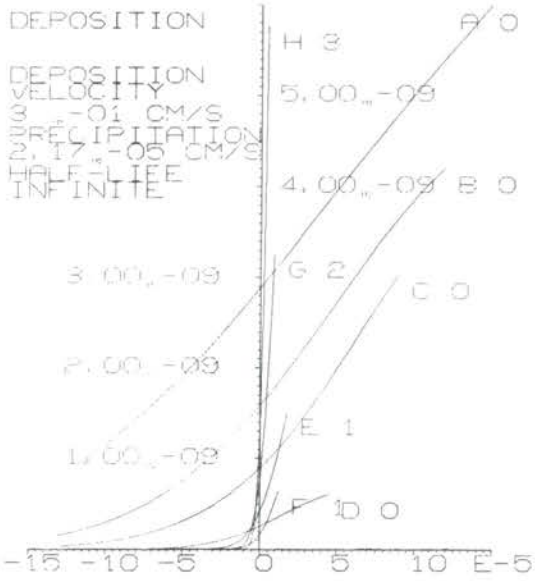


Fig. 13—cont.

DE-4-2

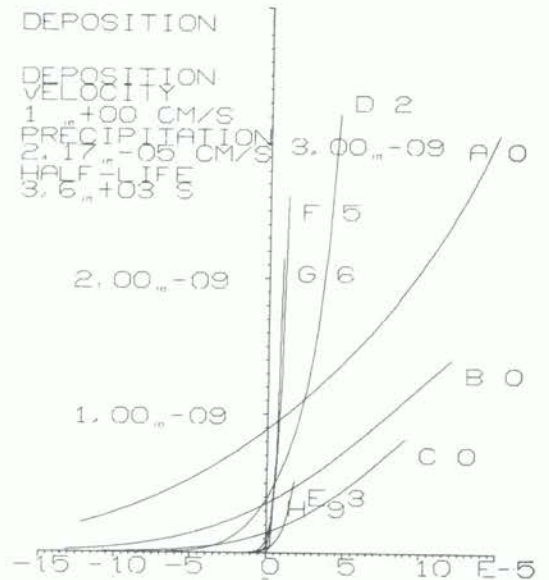
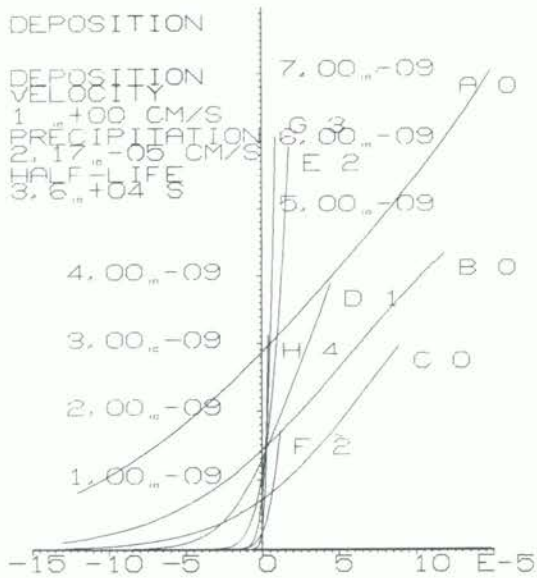
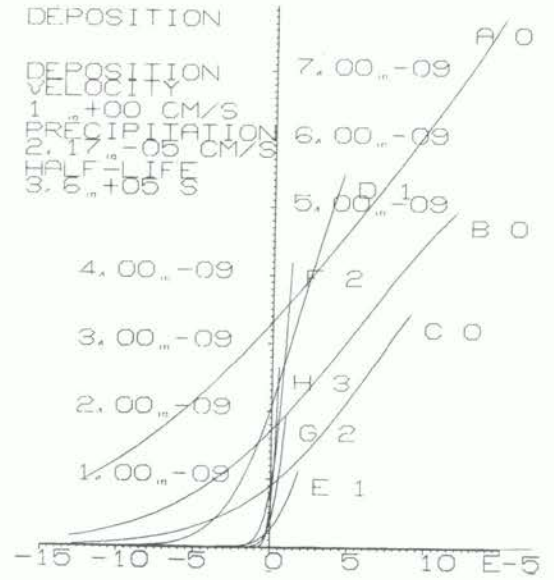
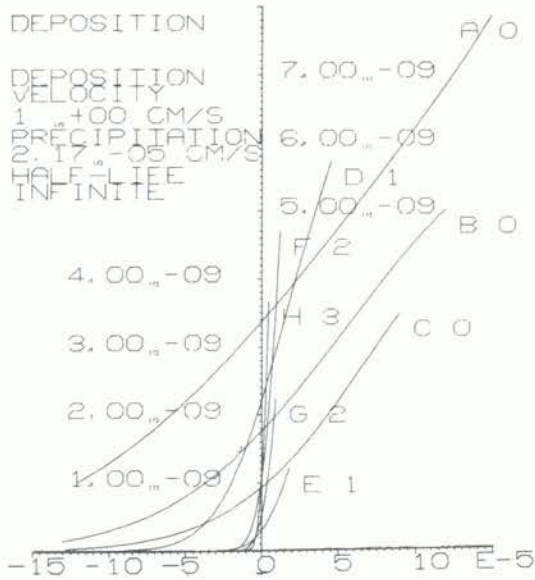


Fig. 13—cont.

DE-1-3

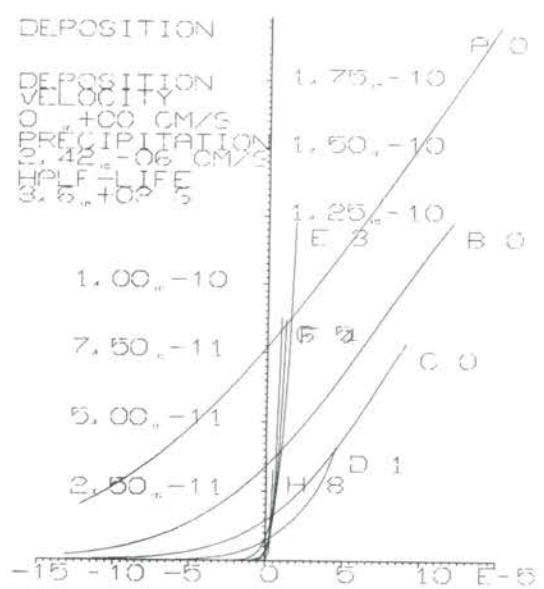
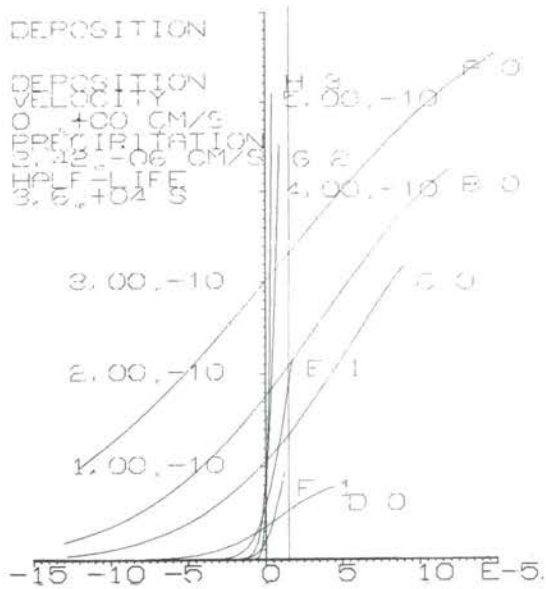
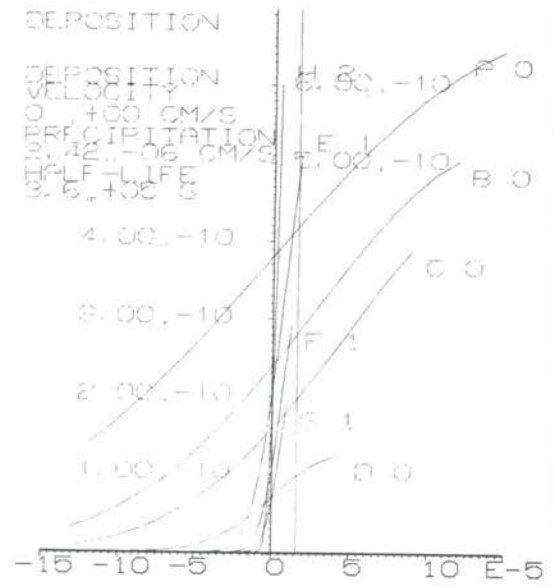
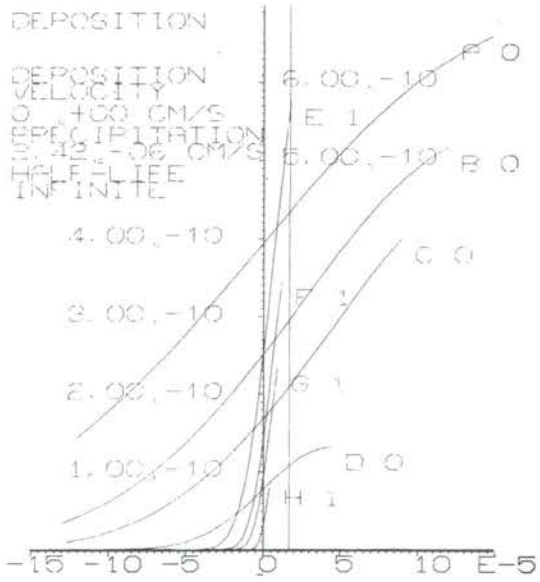


Fig. 13—cont.

DE-2-3

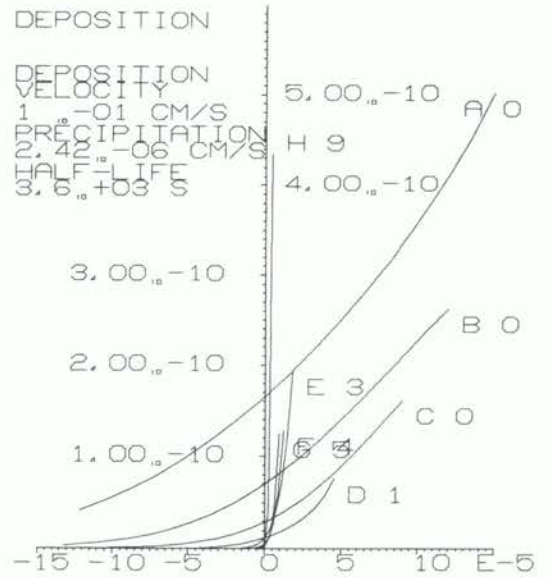
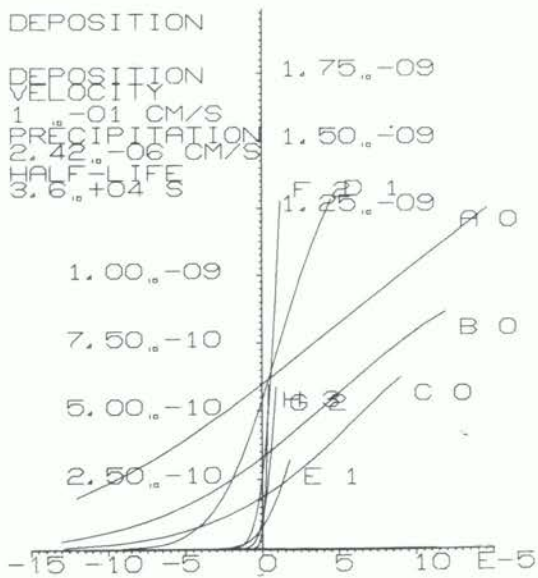
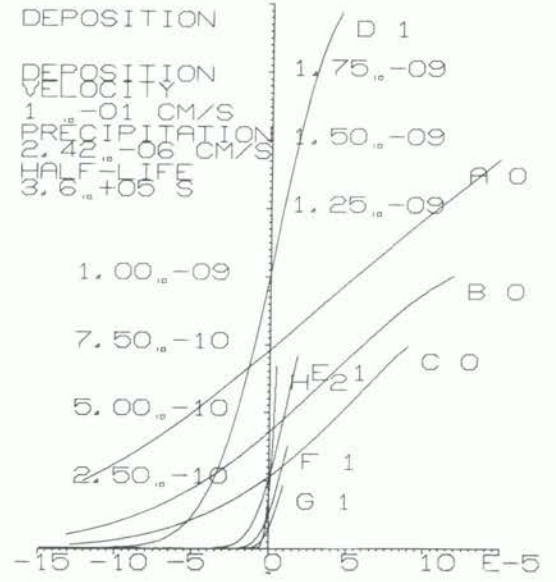
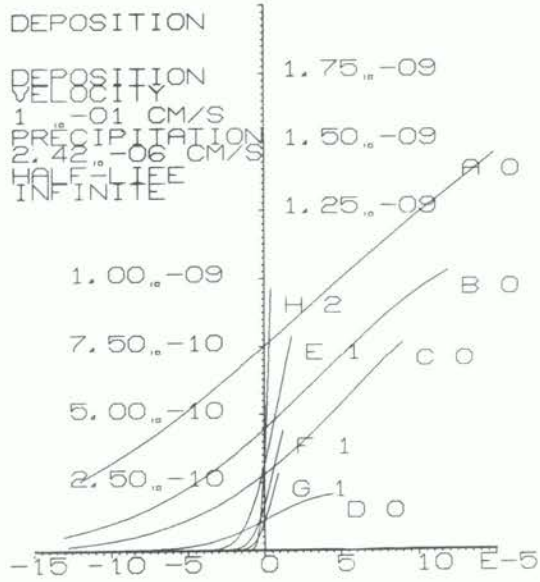


Fig. 13—cont.

DE-3-3

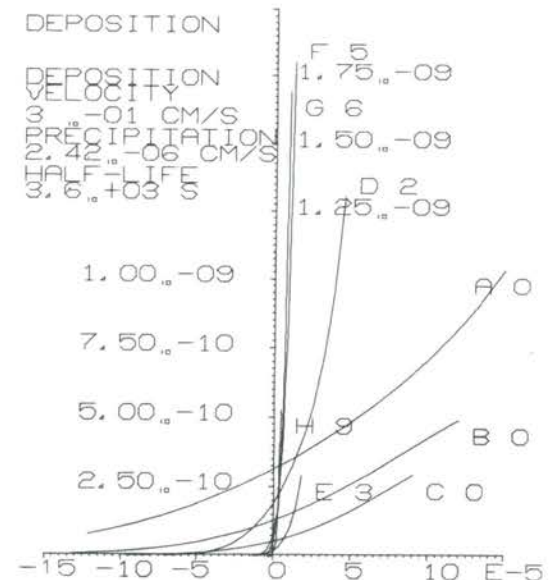
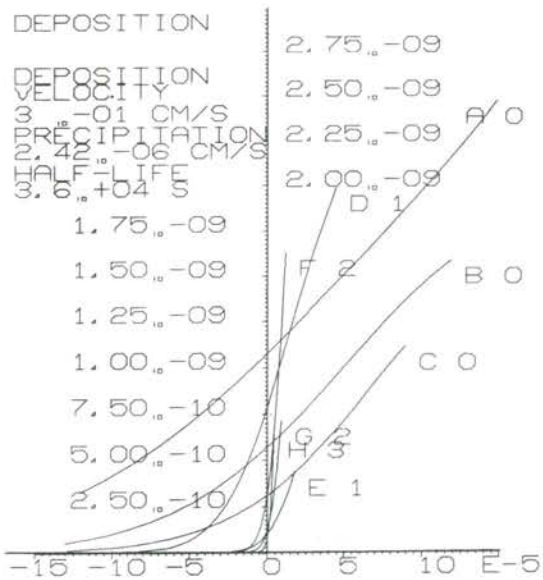
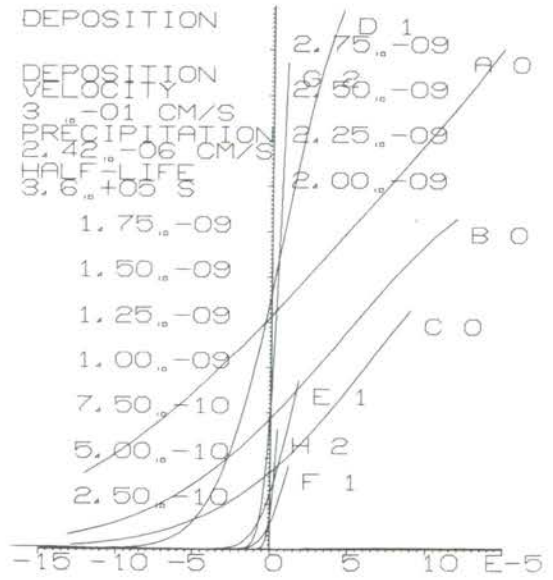
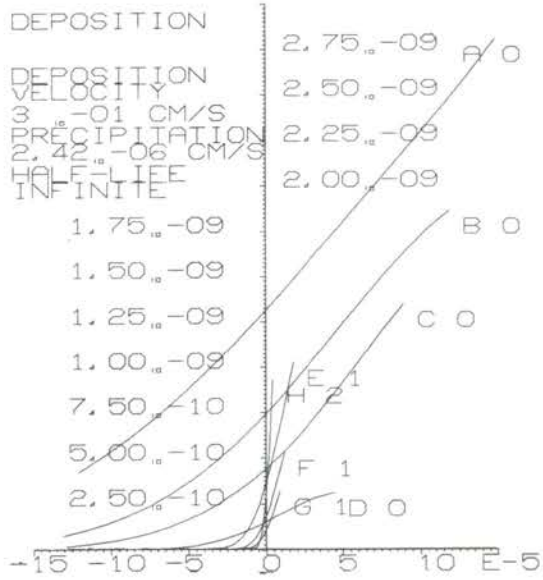


Fig. 13—cont.

DE-4-3

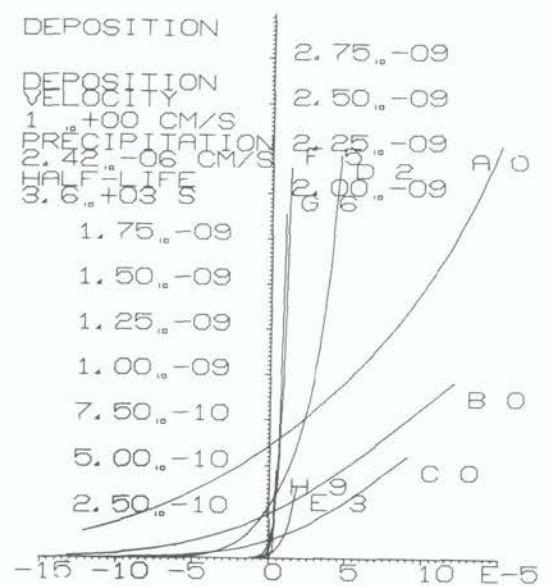
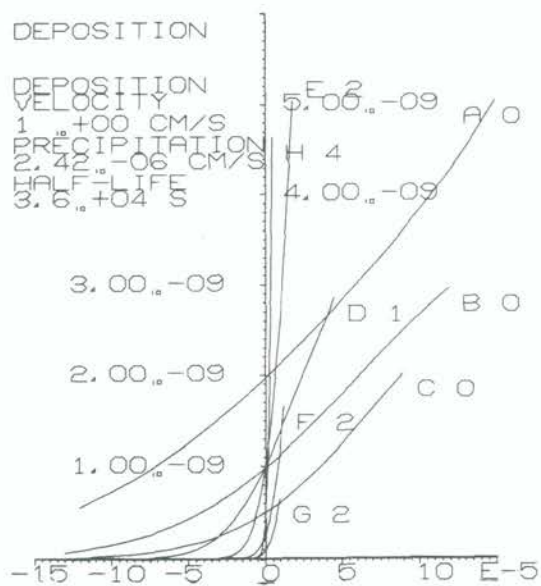
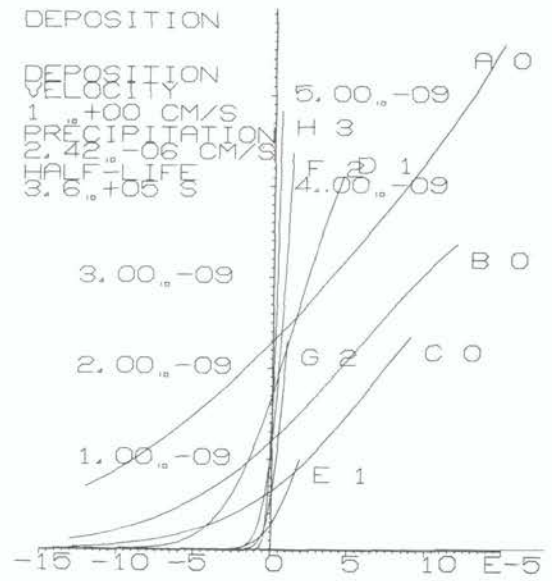
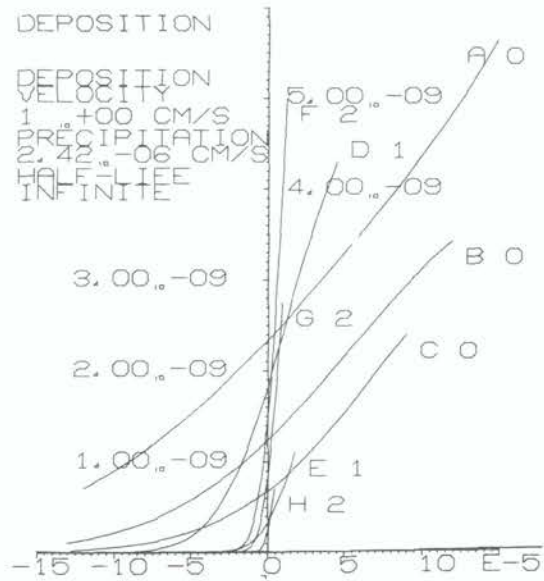


Fig. 13—cont.

DE-1-4

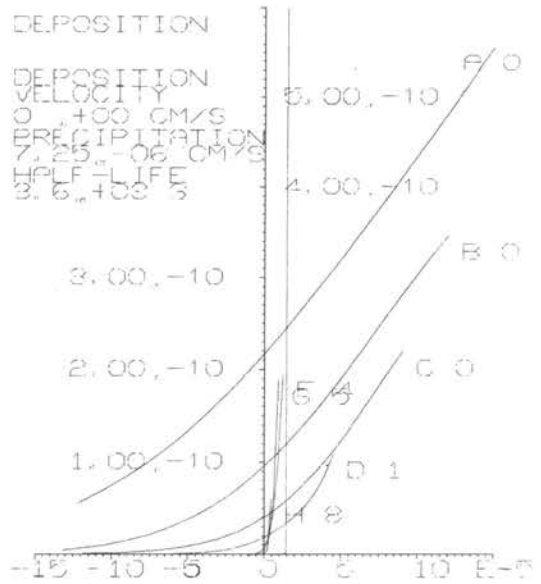
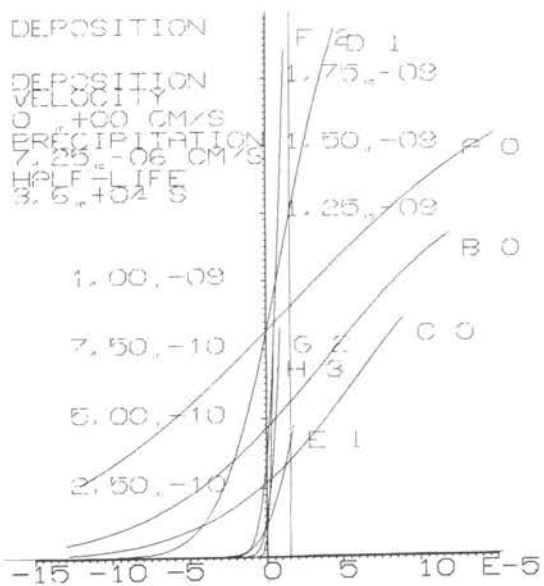
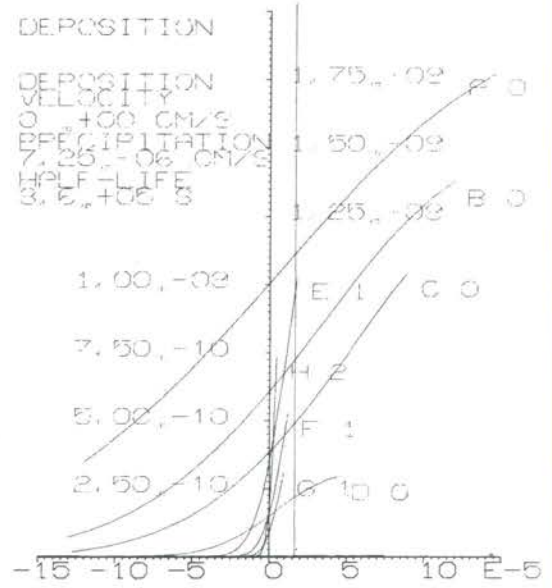
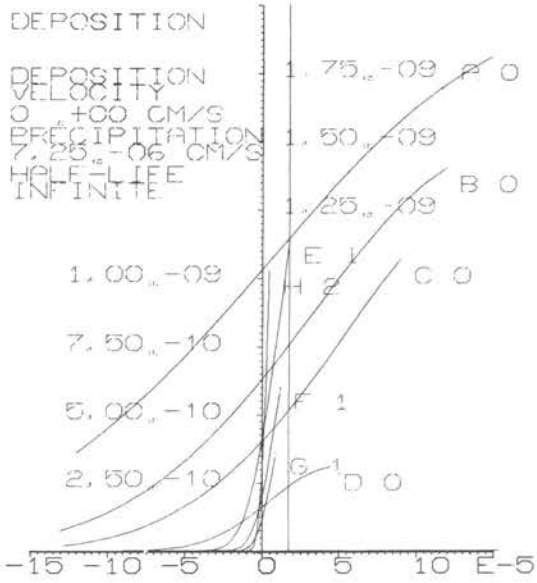


Fig. 13—cont.

DE-2-4

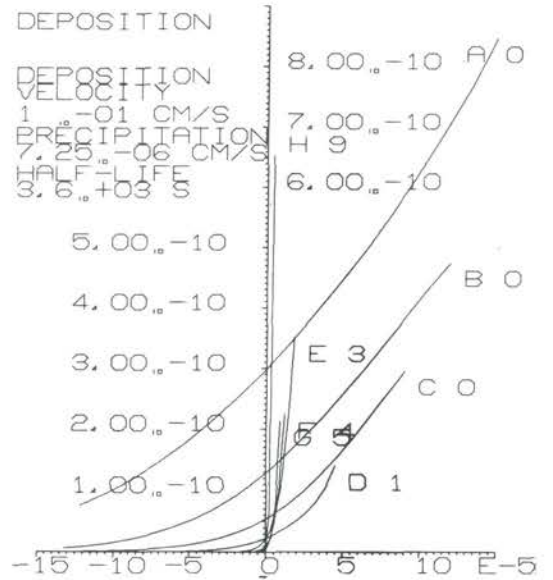
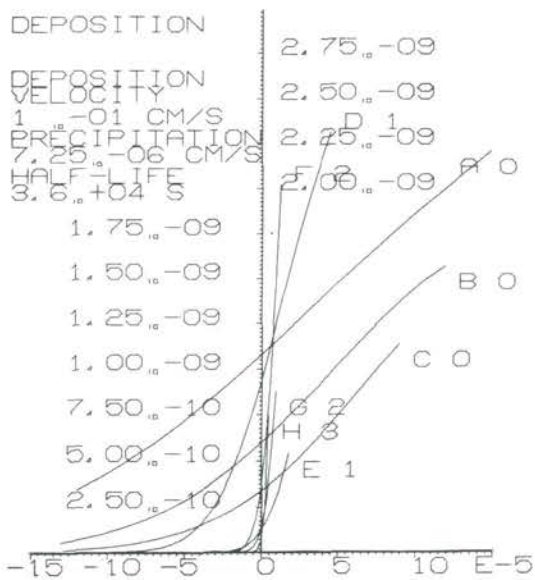
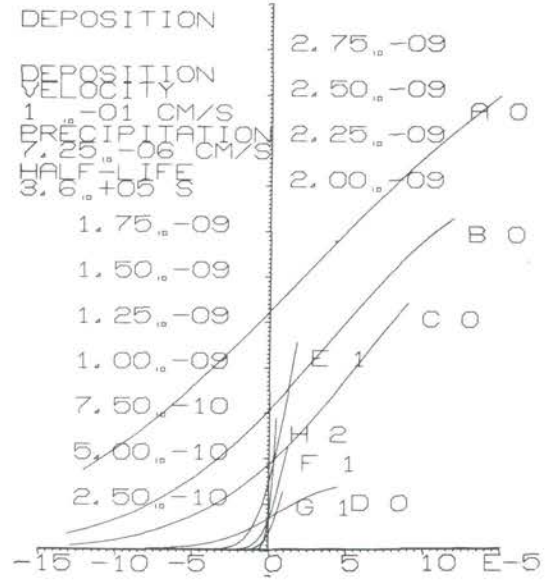
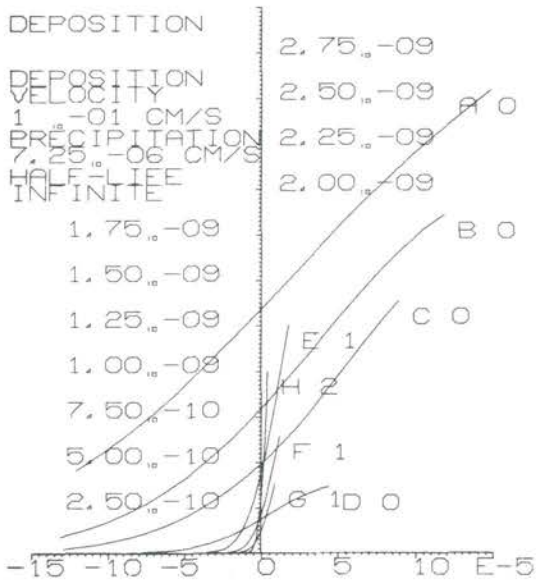


Fig. 13—cont.

DE-3-4

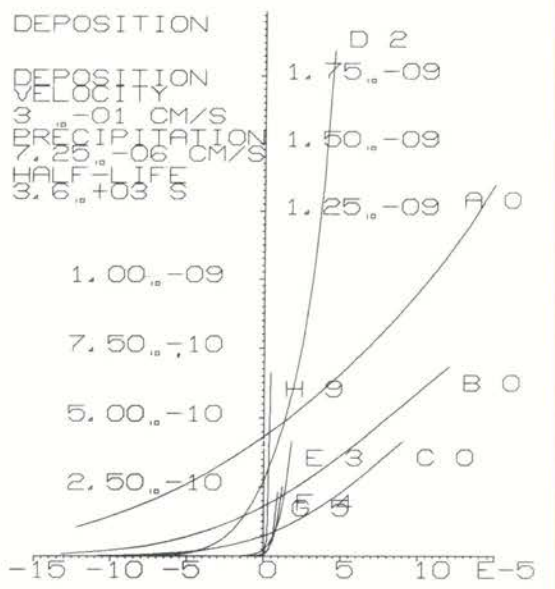
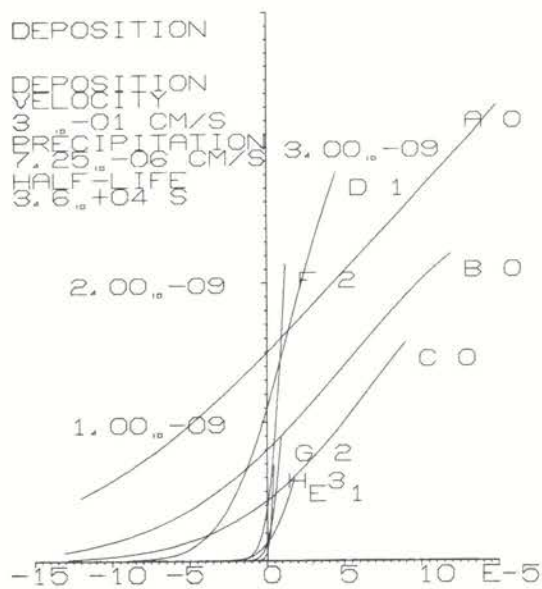
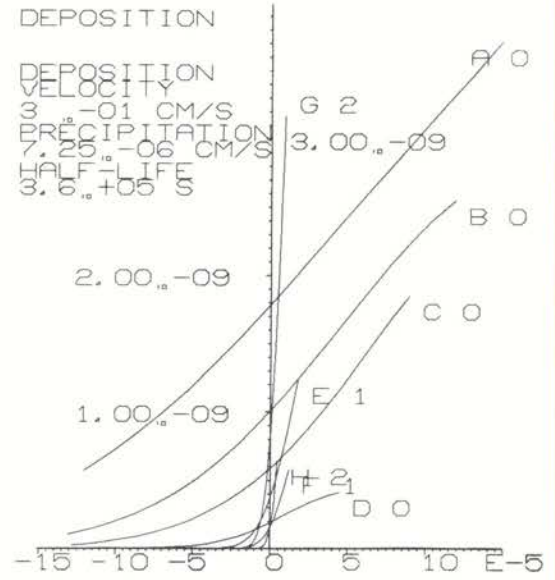
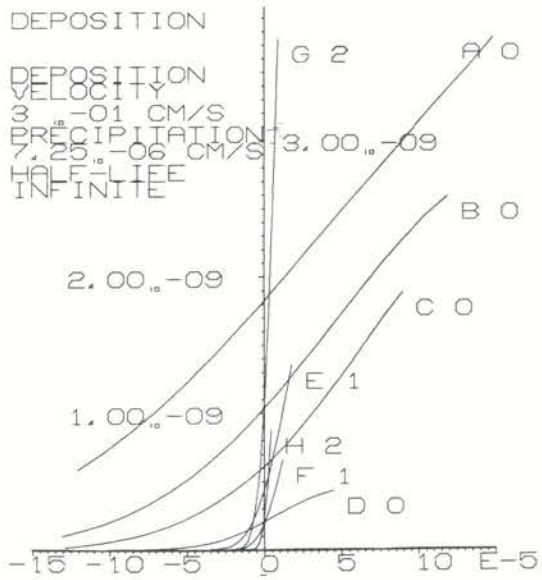


Fig. 13—cont.

DE-4-4

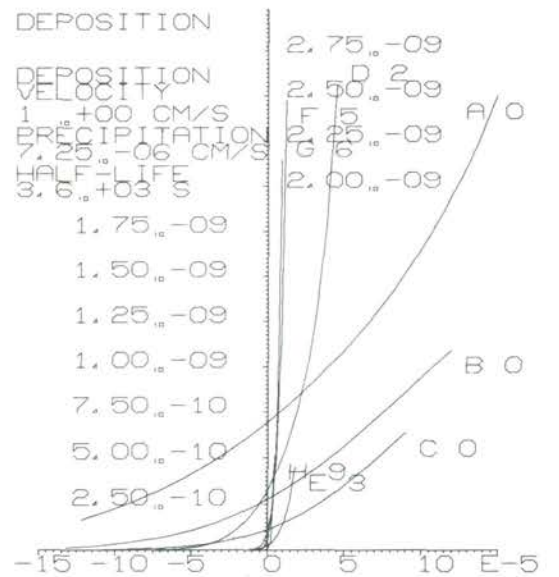
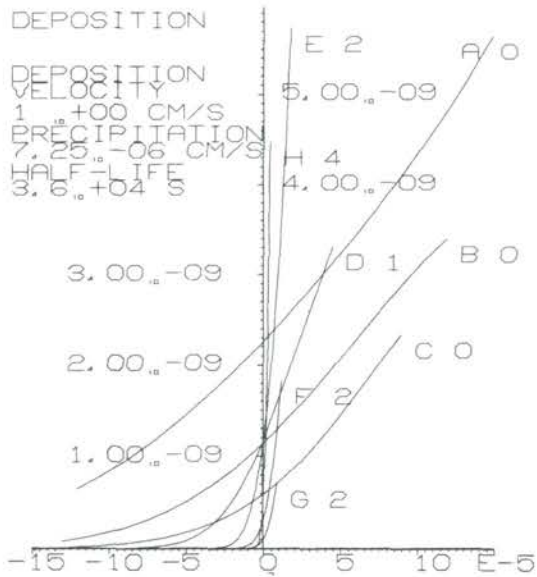
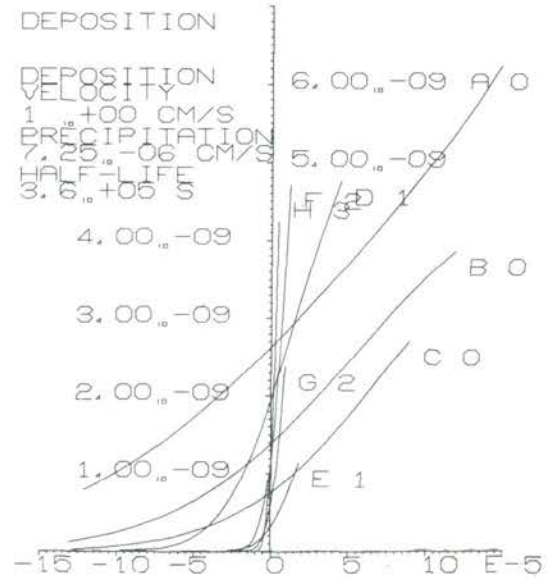
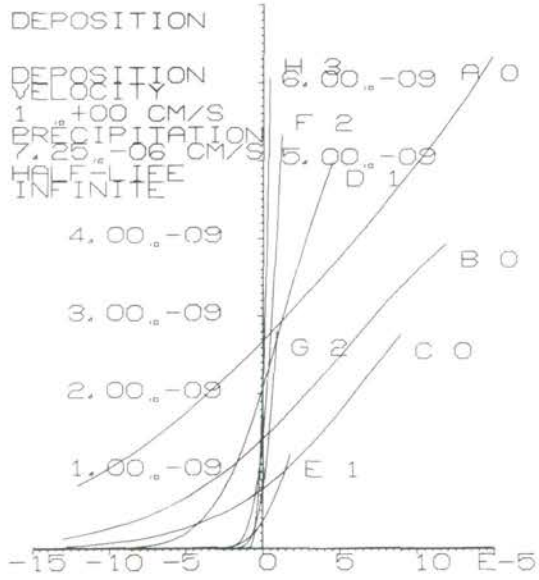


Fig. 13—cont.

FL-1-1

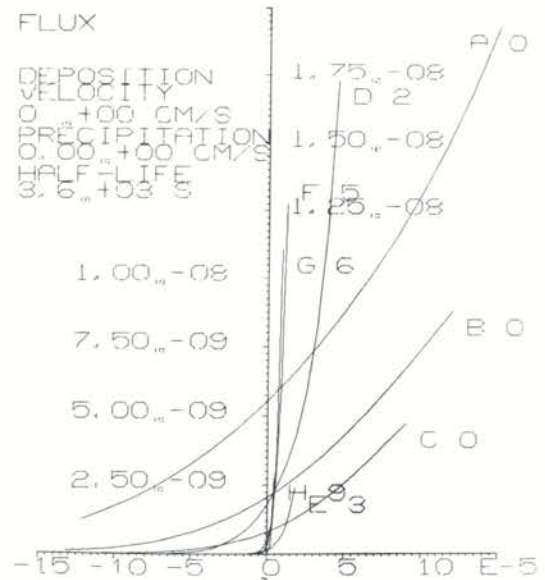
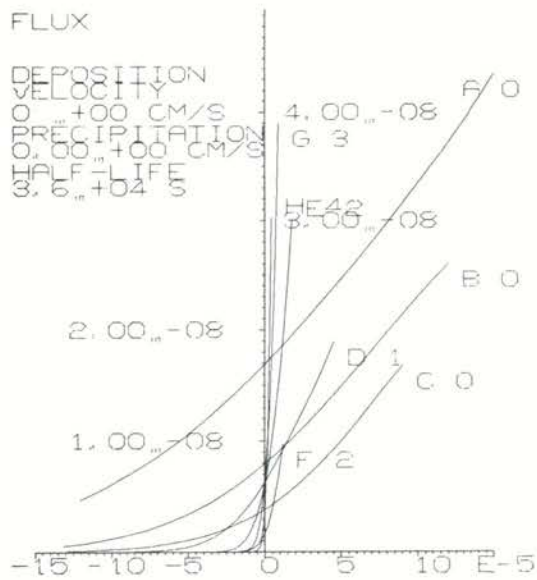
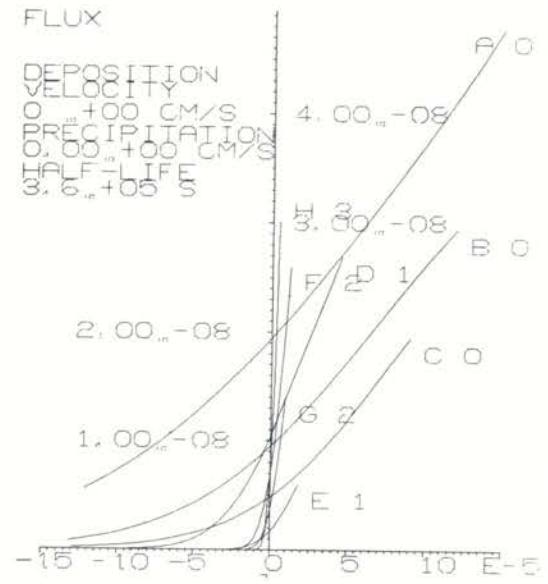
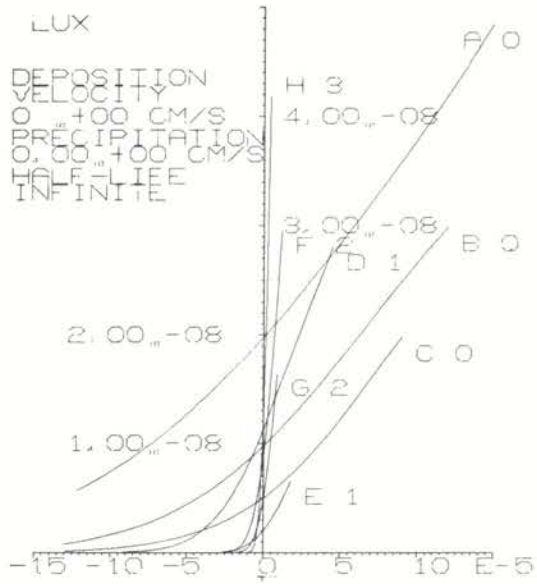


Fig. 13—cont.

FL-2-1

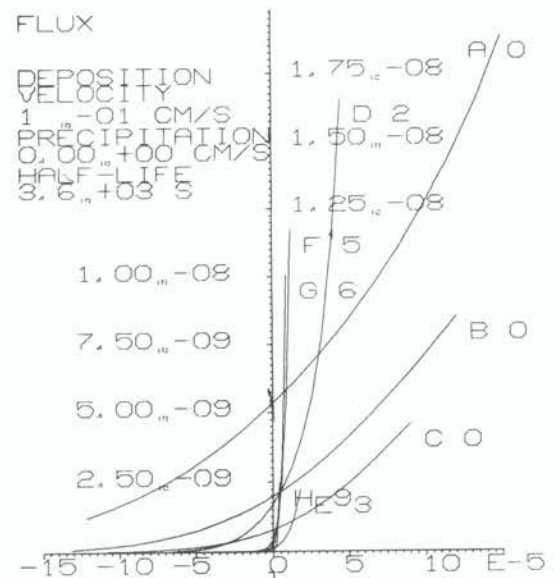
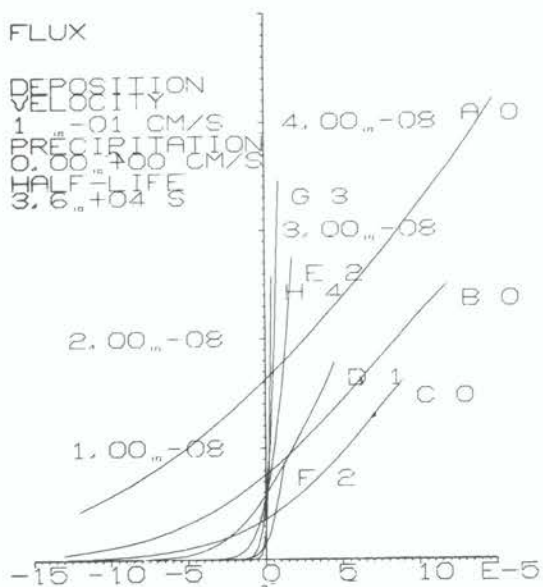
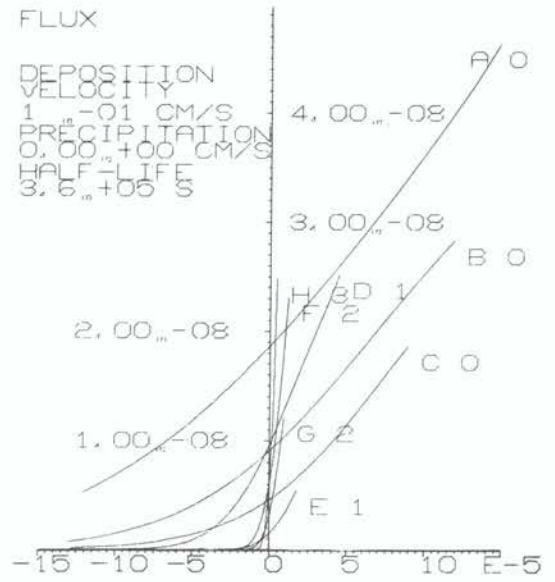
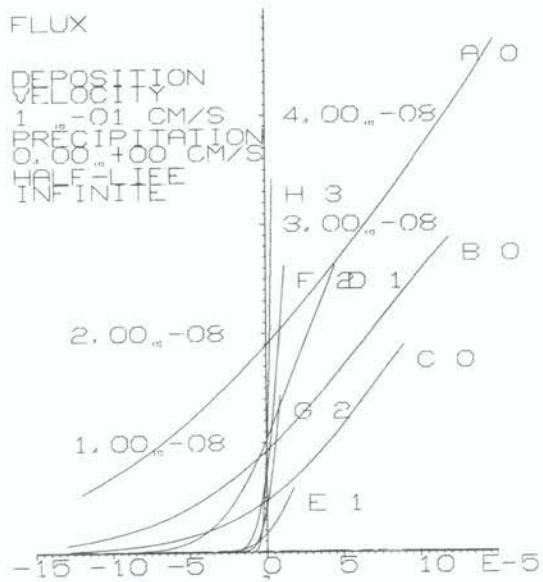


Fig. 13—cont.

FL-3-1

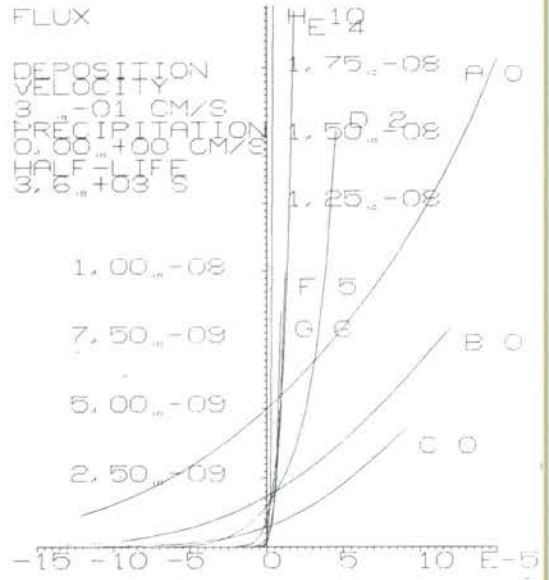
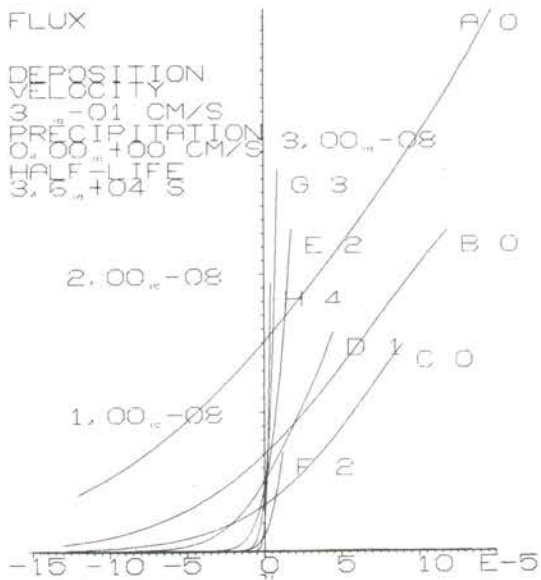
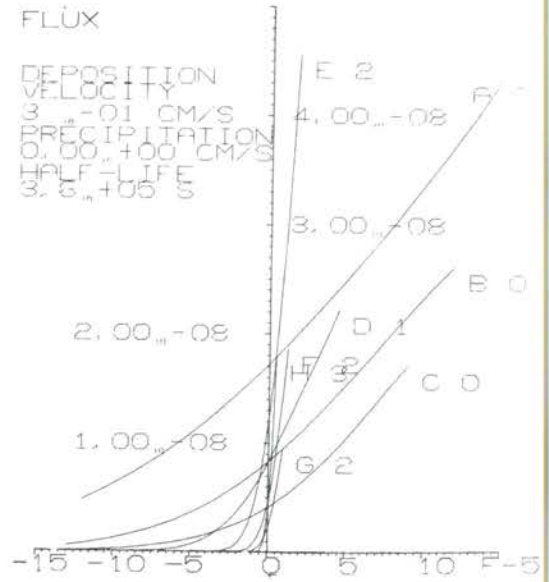
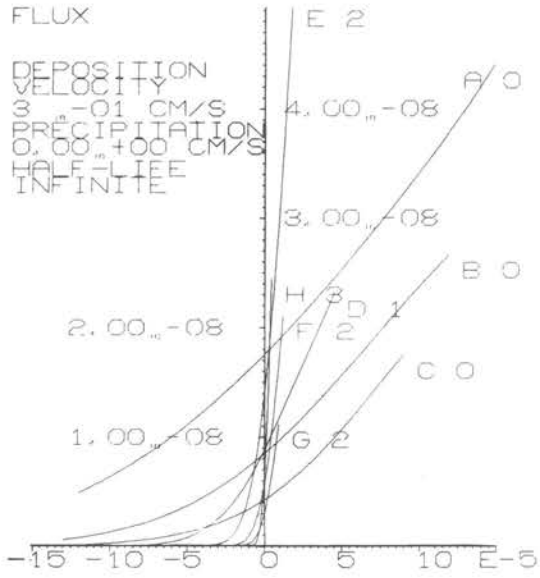


Fig. 13—cont.

FL-4-1

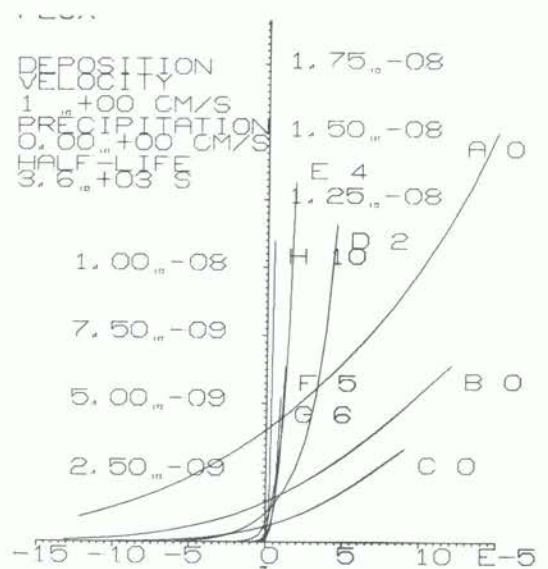
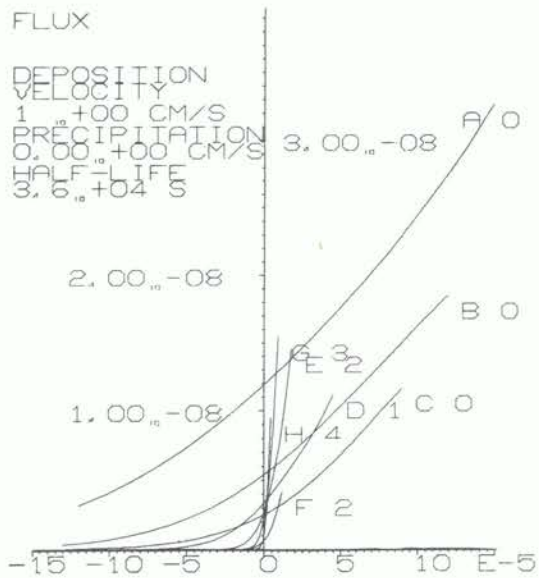
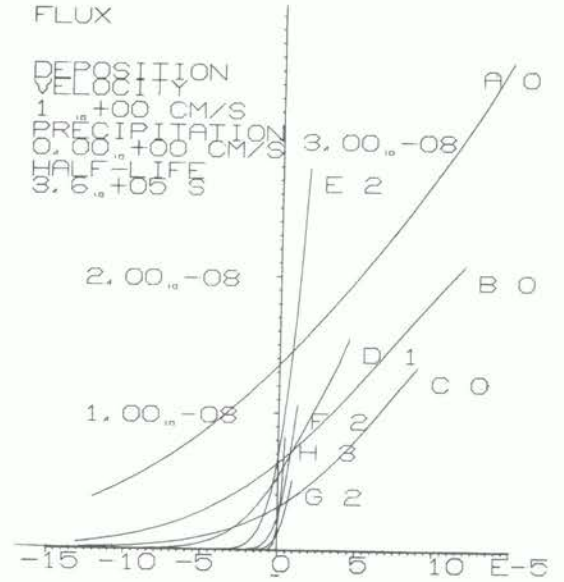
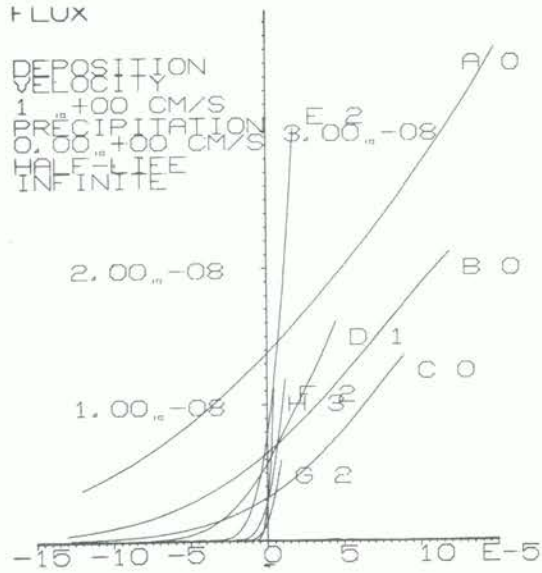


Fig. 13—cont.

FL-1-2

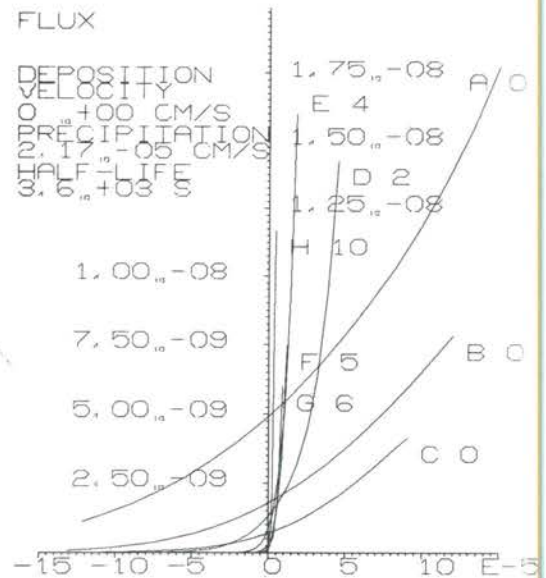
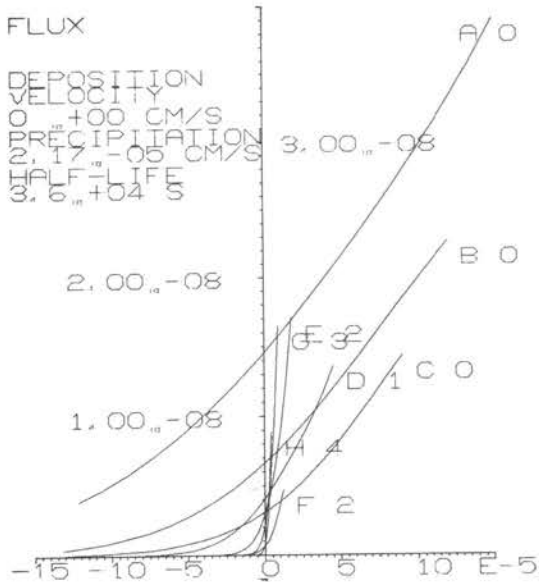
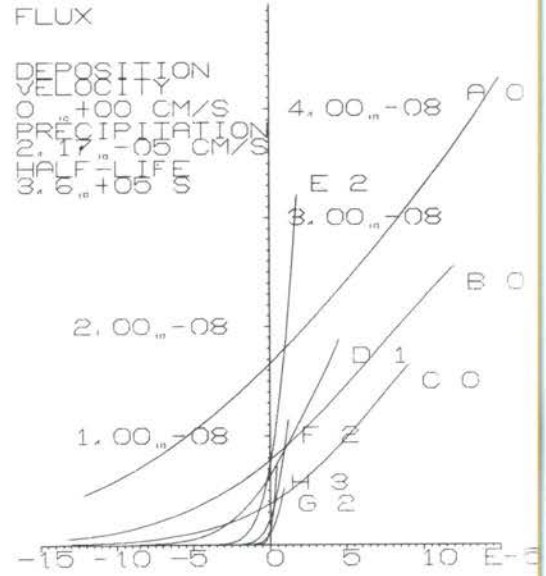
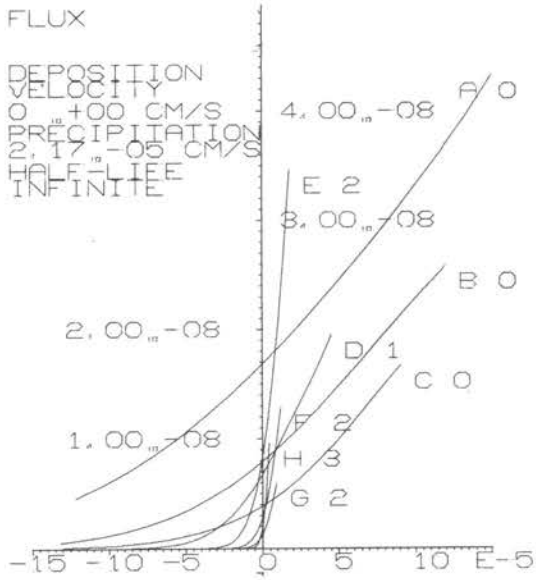


Fig. 13—cont.

FL-2-2

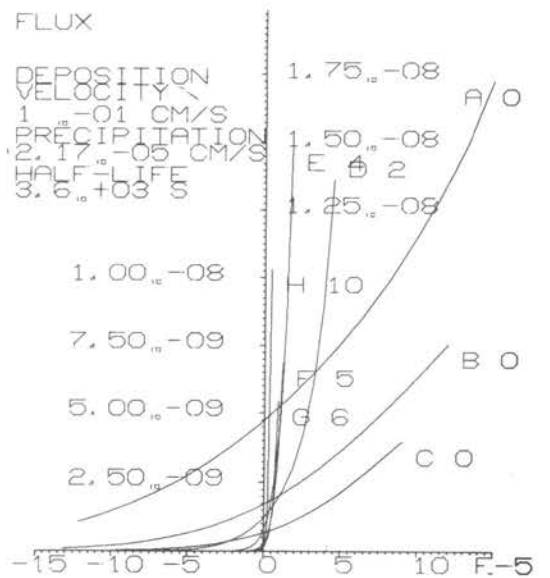
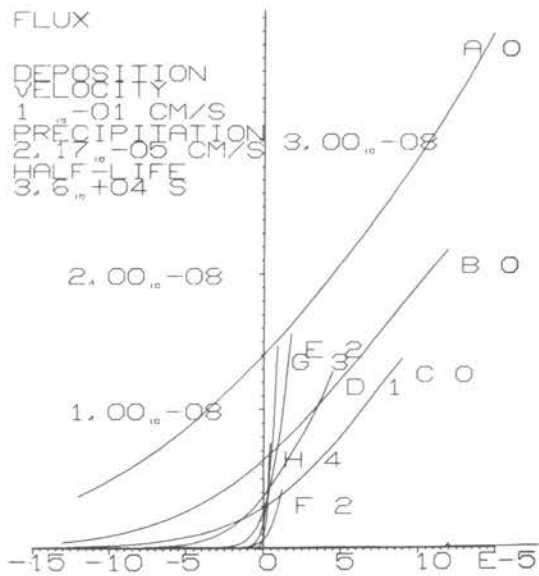
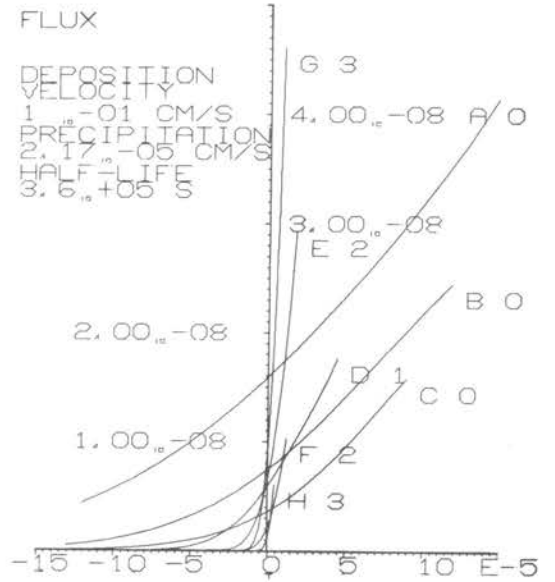
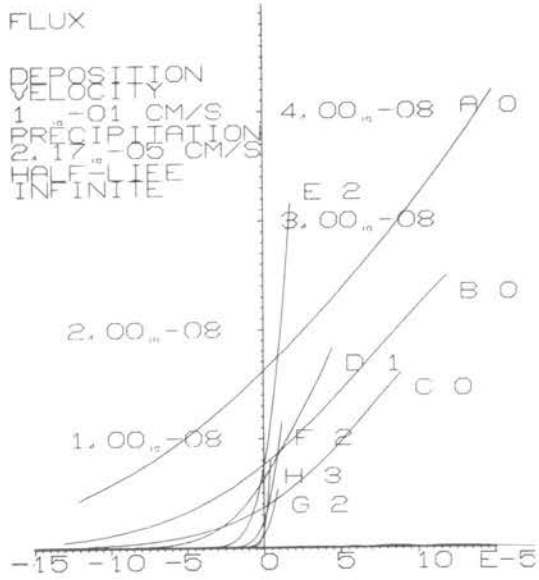


Fig. 13—cont.

FL-3-2

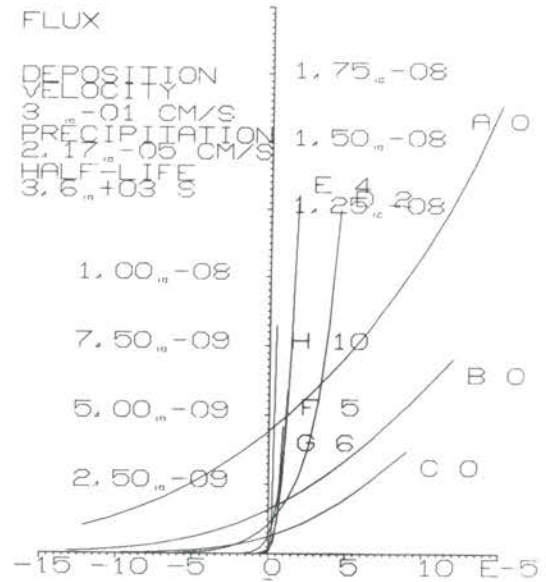
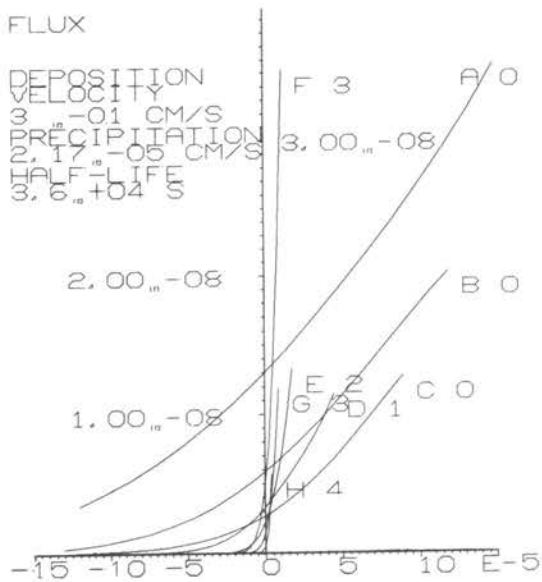
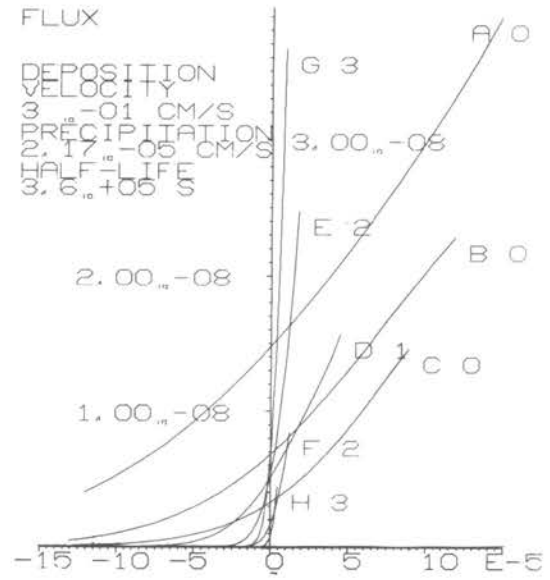
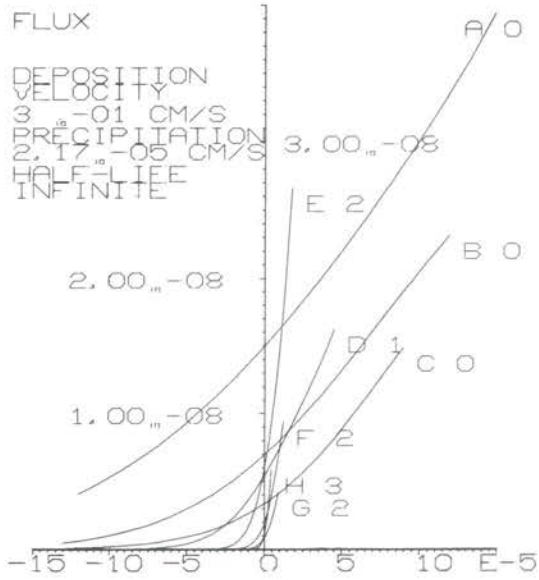


Fig. 13—cont.

FL-4-2

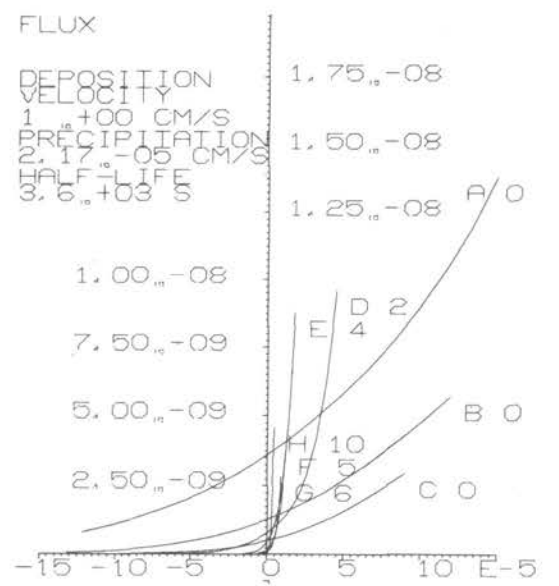
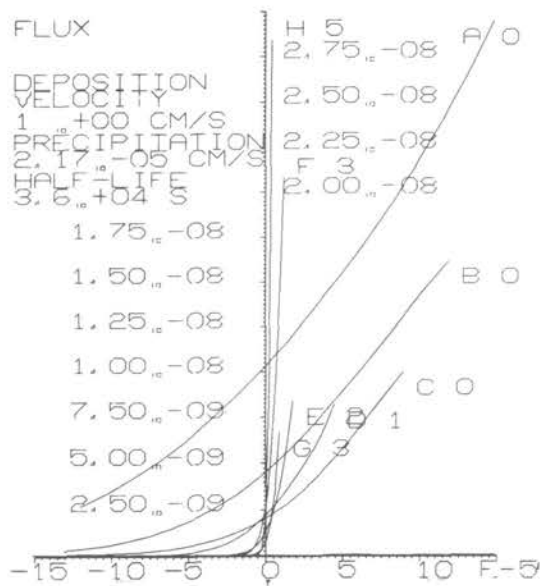
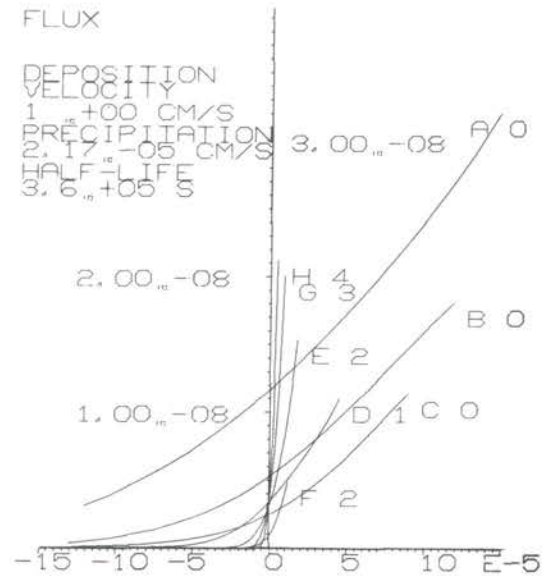
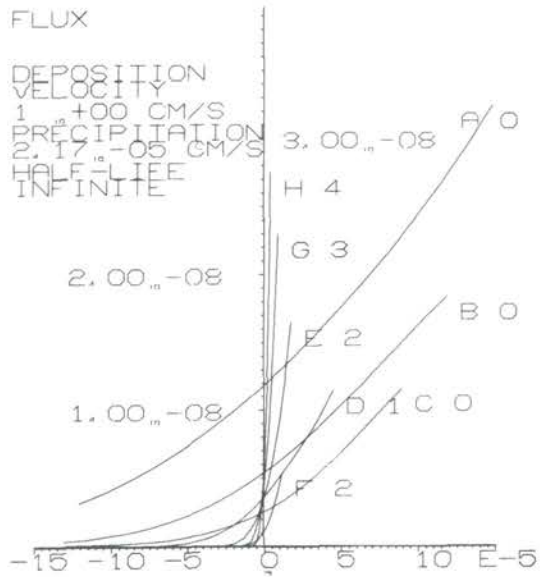


Fig. 13—cont.

FL-1-3

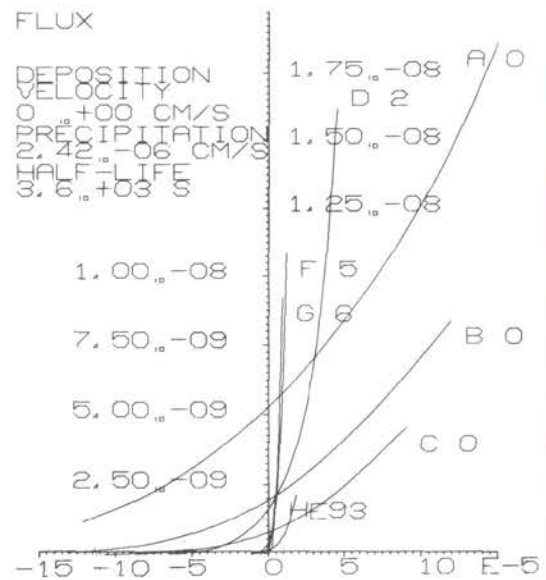
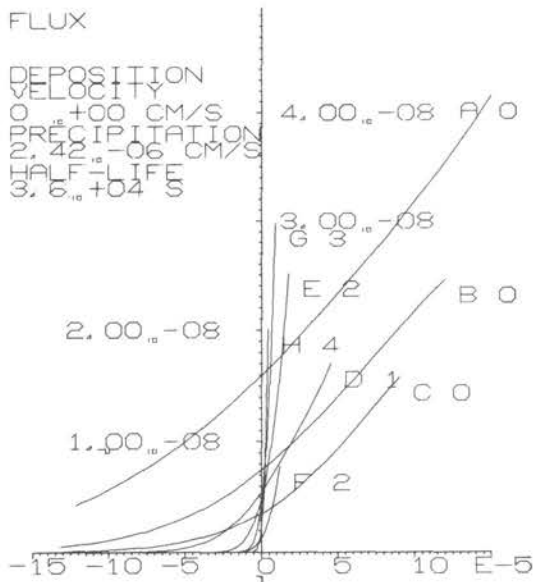
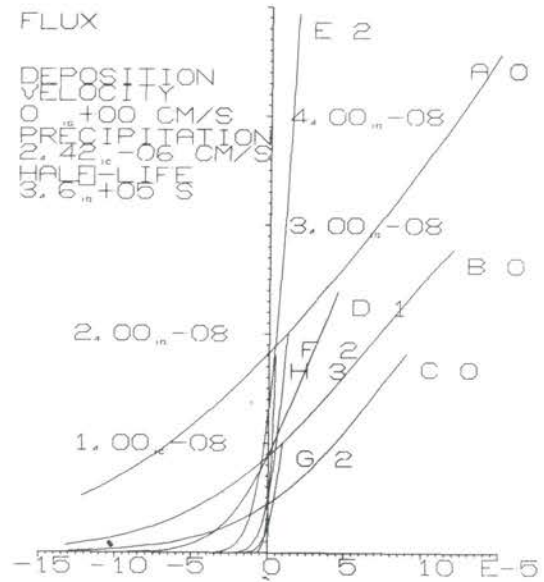
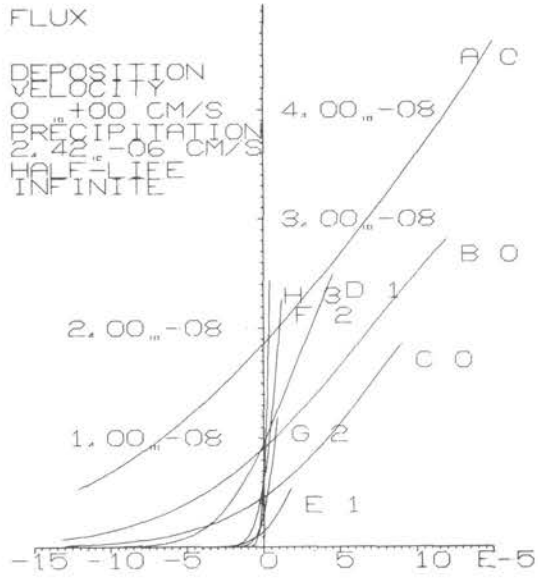


Fig. 13—cont.

FL-2-3

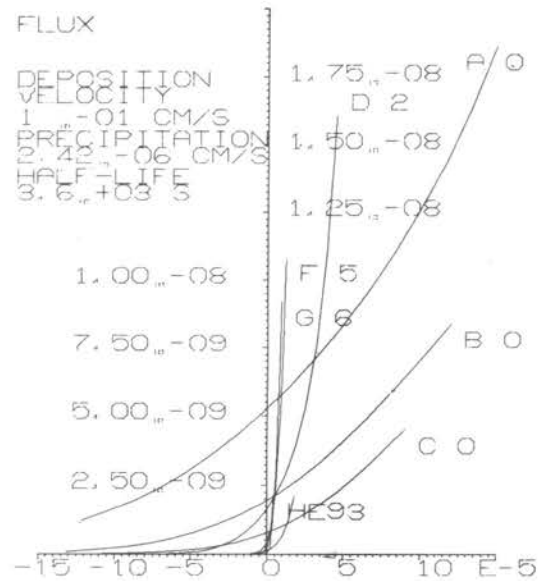
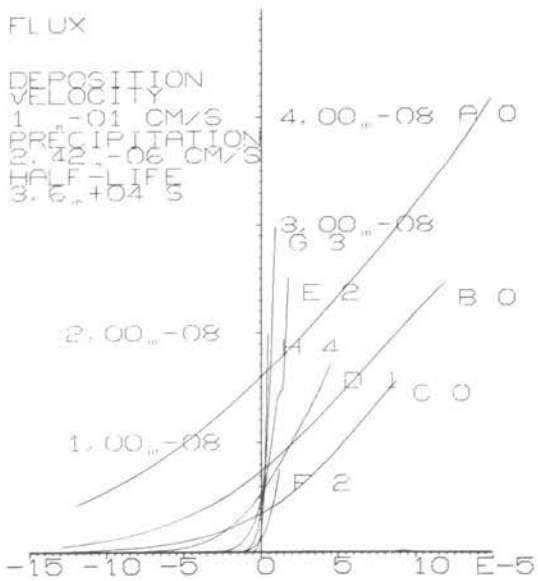
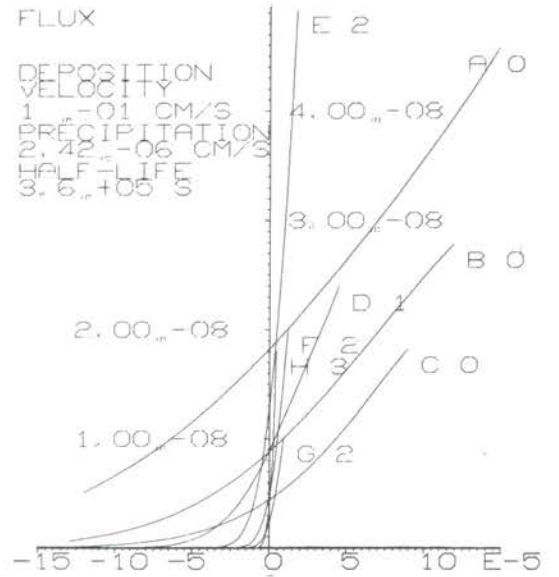
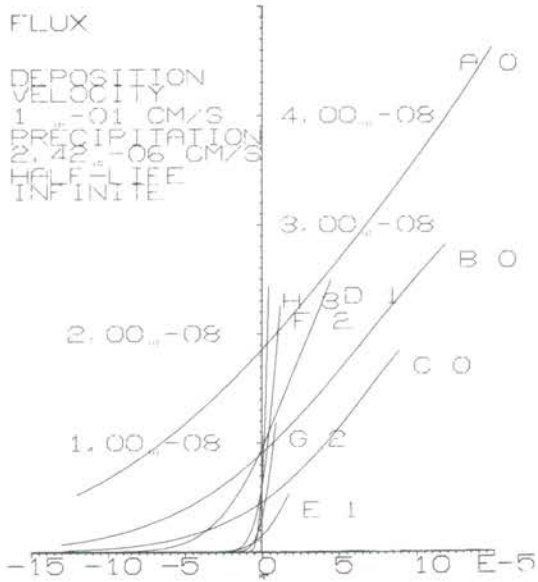


Fig. 13—cont.

FL-3-3

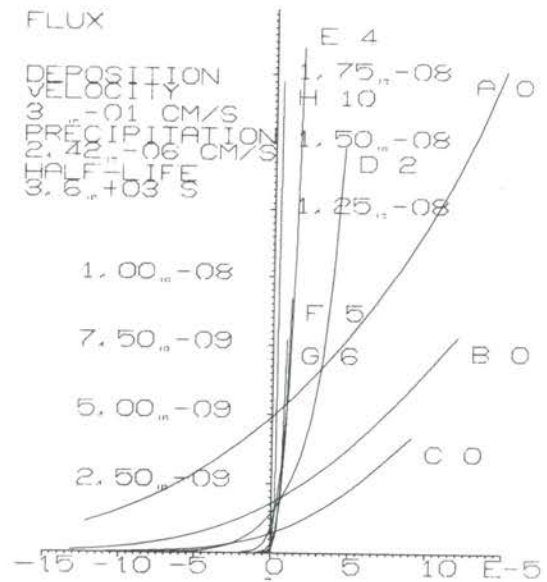
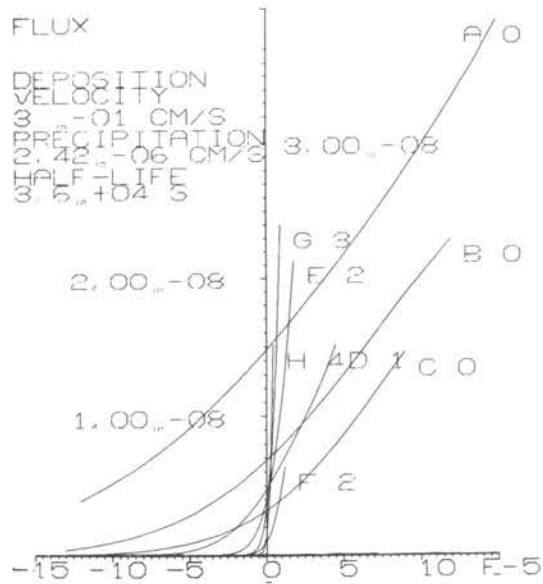
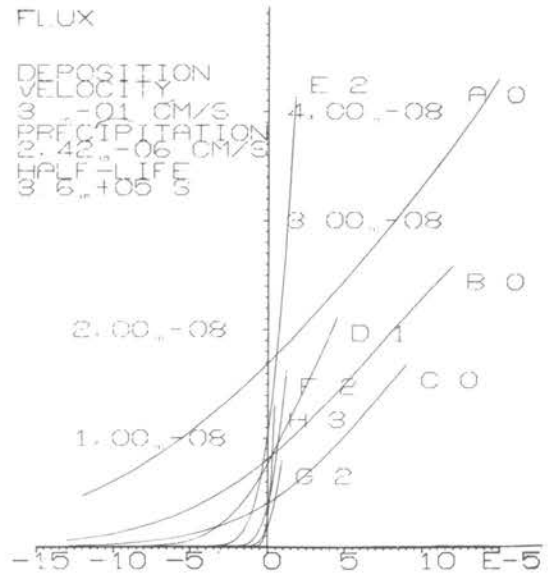
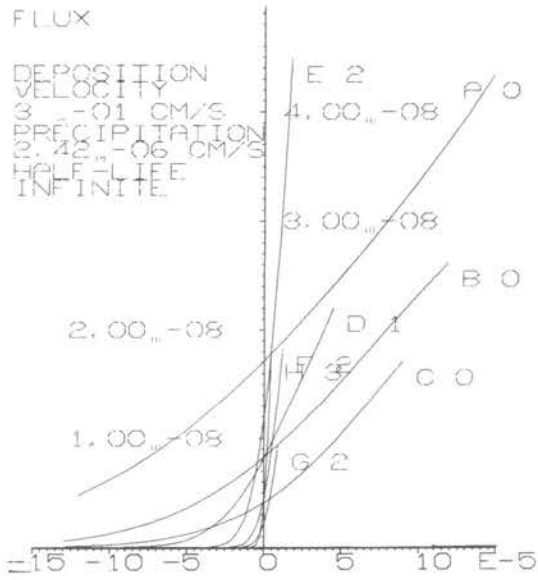


Fig. 13—cont.

FL-4-3

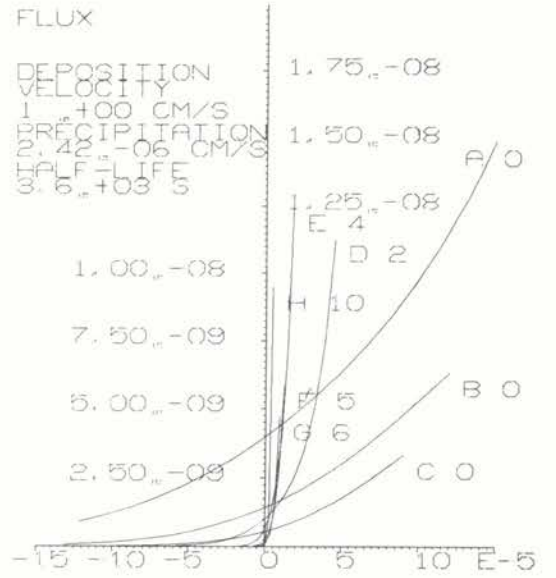
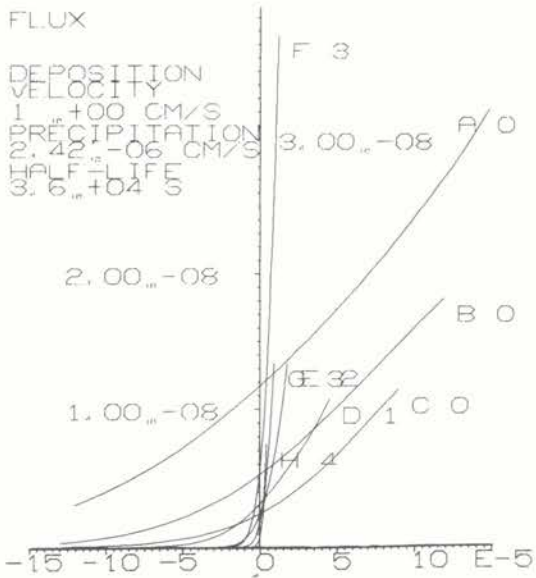
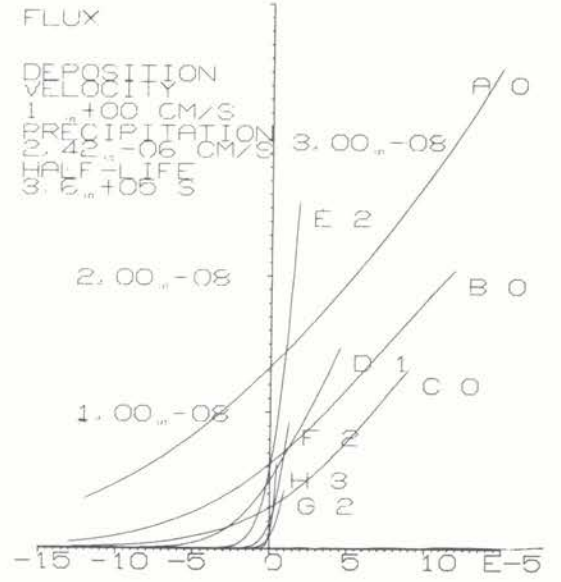
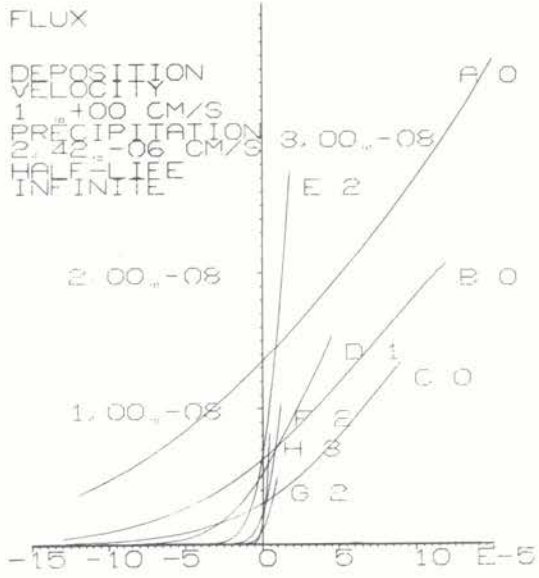


Fig. 13—cont.

FL-1-4

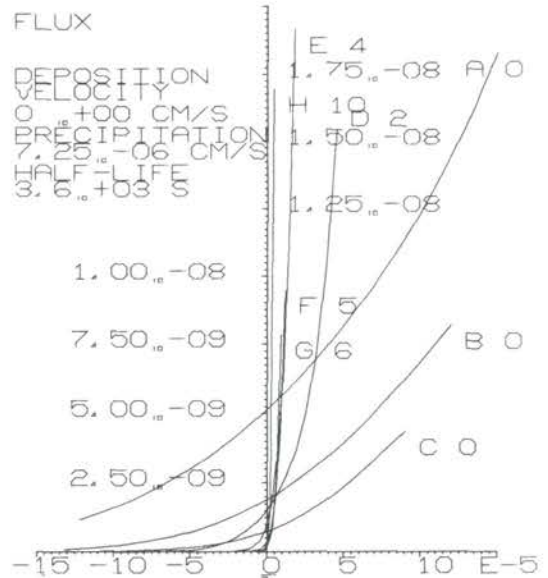
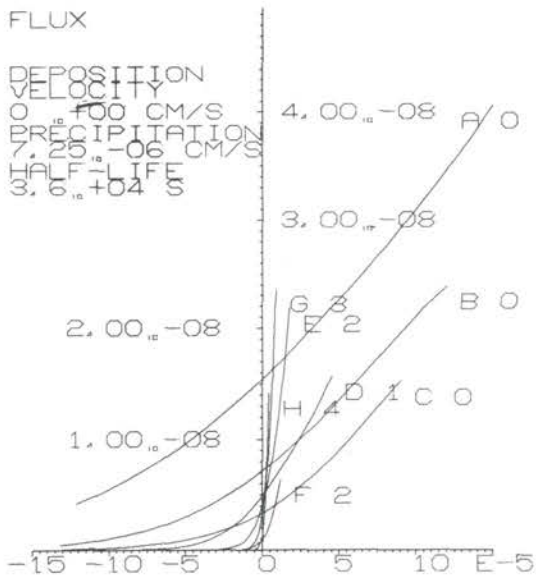
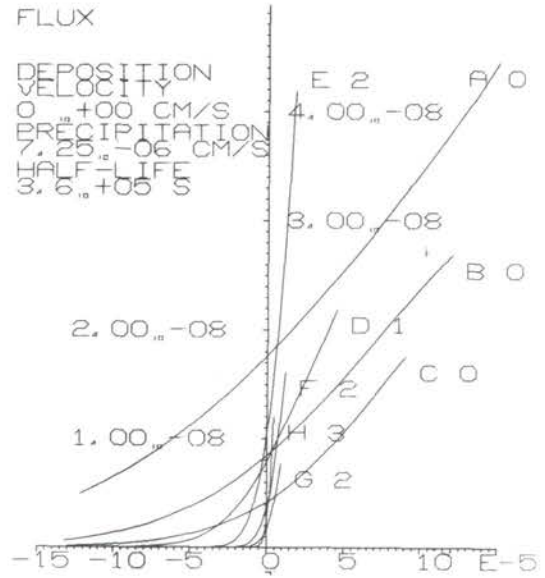
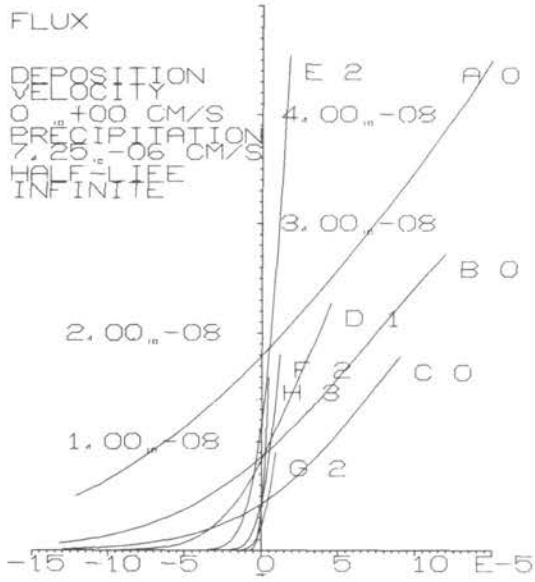


Fig. 13—cont.

FL-2-4

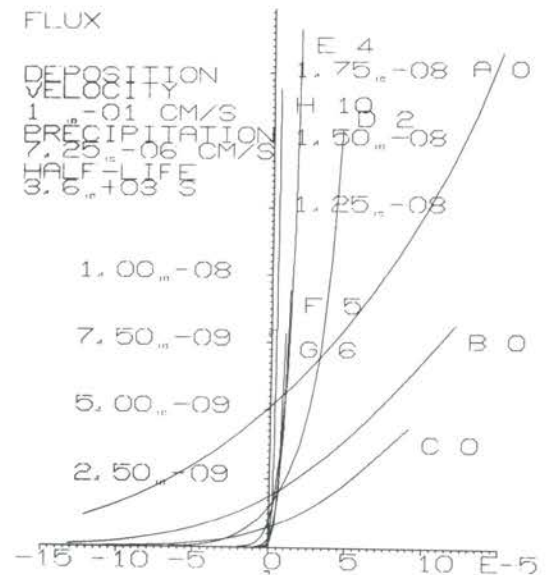
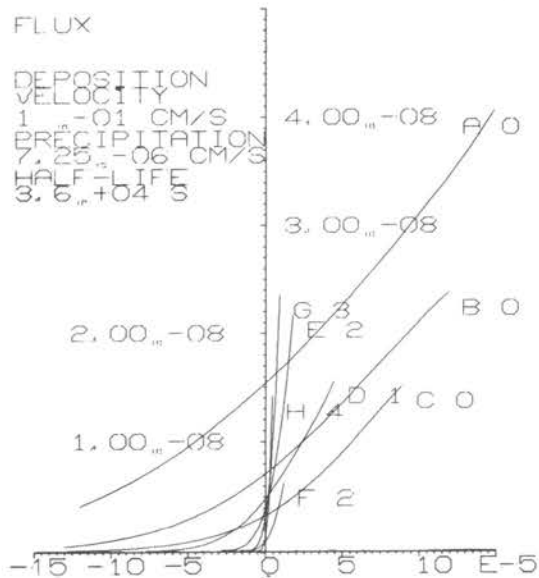
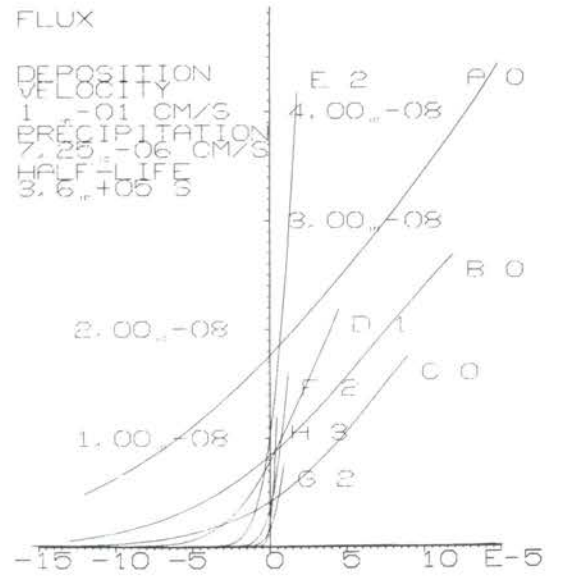
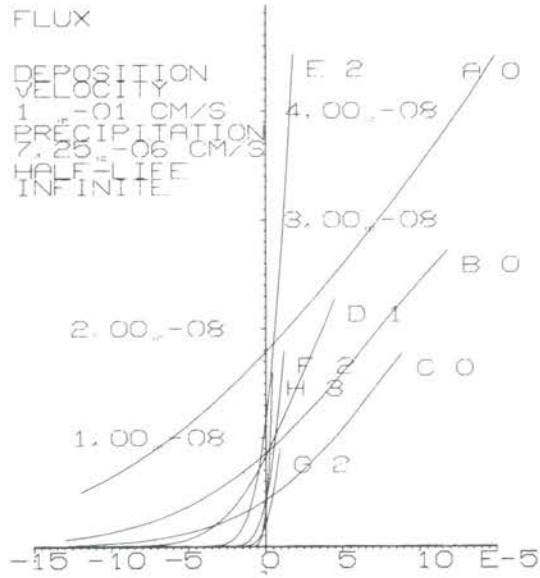


Fig. 13—cont.

FL-3-4

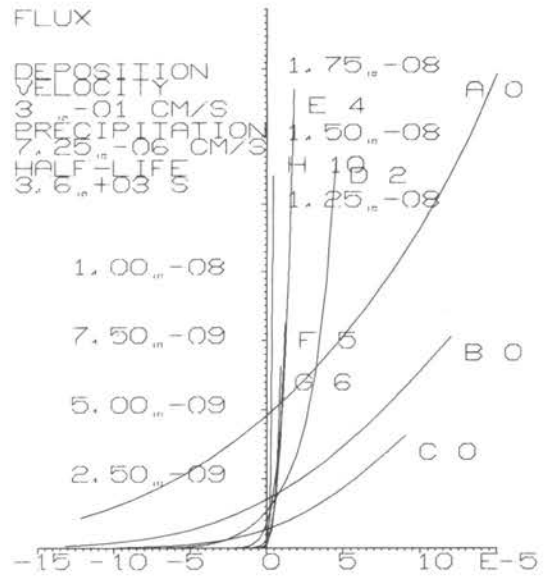
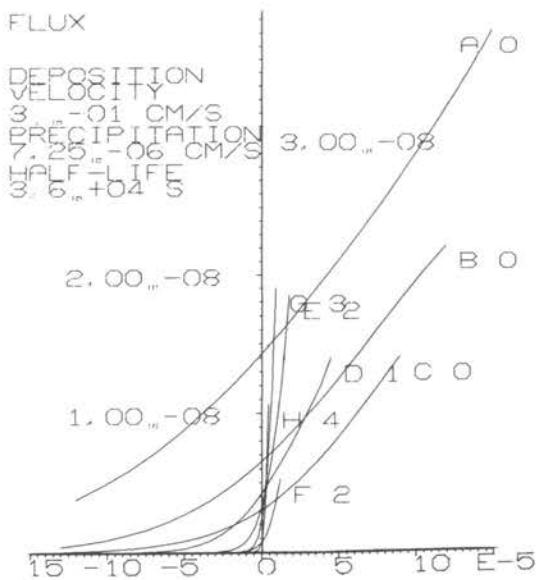
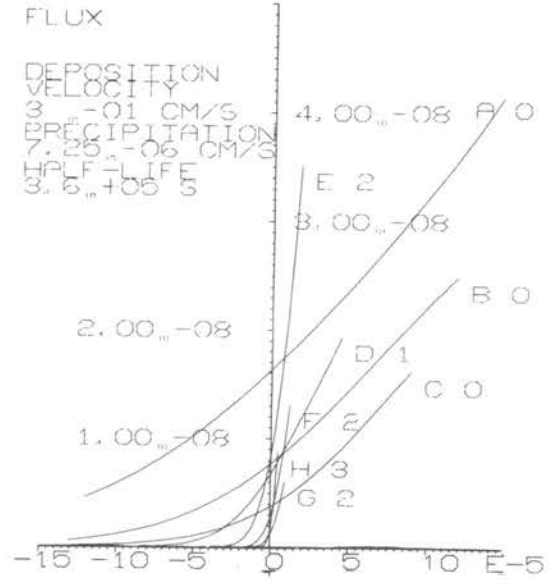
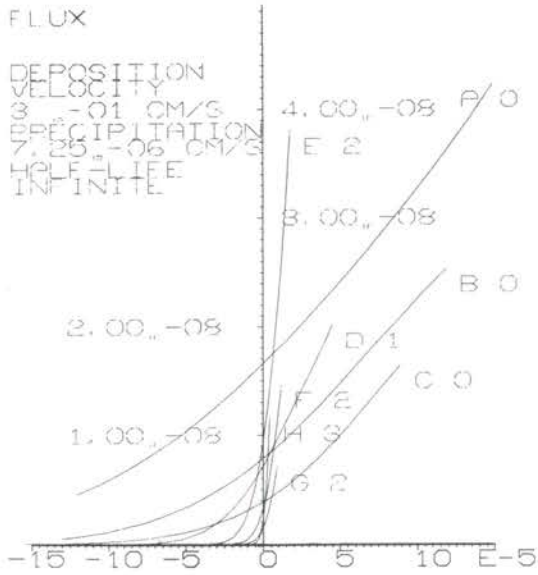
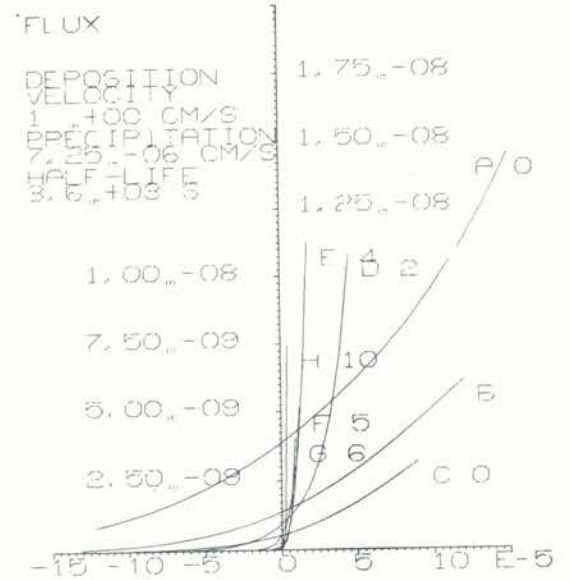
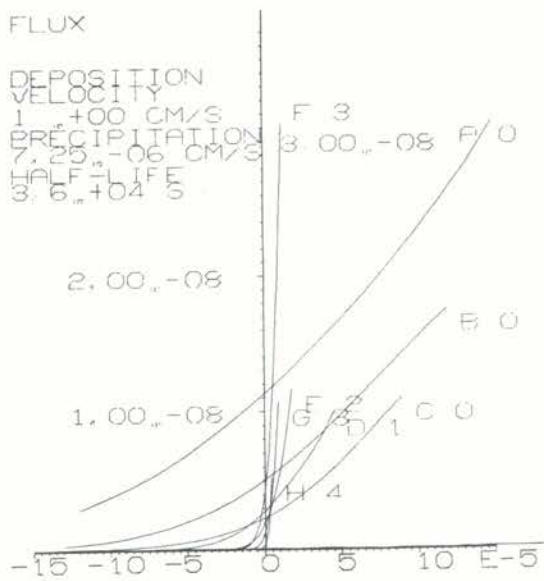
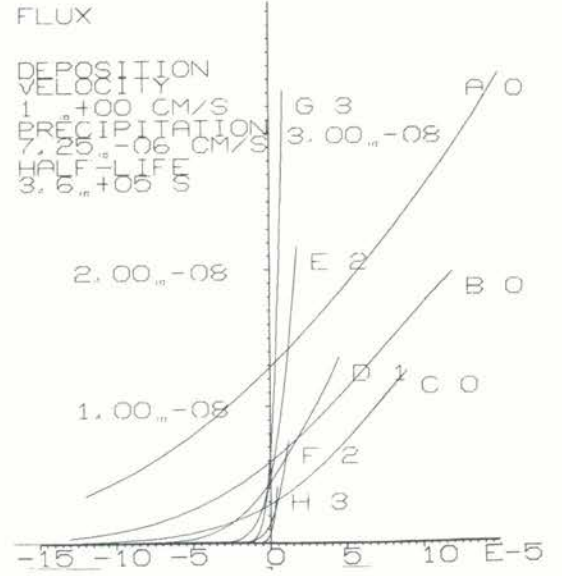
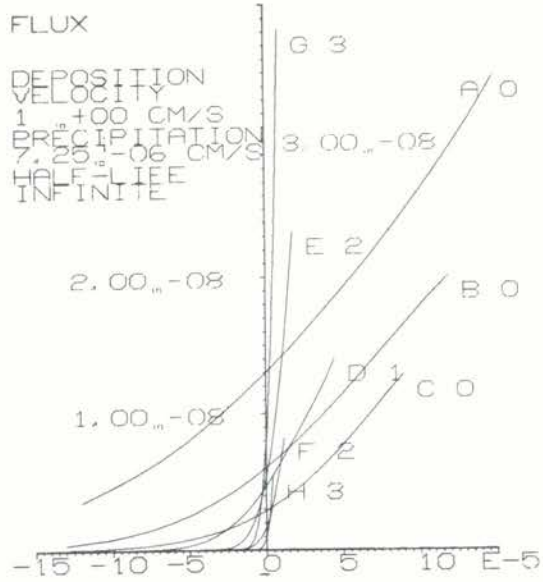


Fig. 13—cont.

FL-4-4



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