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SOME MEASUREMENTS OF THE MICRO-STRUCTURE OF FOG AND STRATUS-CLOUDS IN THE OSLO-AREA

BY

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Summary. A total number of 52 samples of droplets from fog and stratus-clouds in the Oslo-area has been taken. The samples are grouped according to the meteorological conditions. For three of these groups size distributions which are believed to be typical are presented. Interesting features are the existence of a large number of droplets in the diameter range 1μ to 3μ in all the samples, and the minimum at about 7μ diameter in the size distribution of droplets at the base of advection fog.

1. Introduction. During the last two years (1957—1959) an investigation of the micro-structure of fog and stratus-clouds has been undertaken at two different places in the Oslo-area: at the university campus at Blindern (90 m a.s.l.), and on a ridge just outside the city, Tryvannshøgda (500 m a.s.l.). A total number of 52 samples of cloud and fog drops has been taken by means of a "cascade impactor", an instrument consisting essentially of a system of four jets and sampling slides in series (MAY 1945).

Of the 52 samples, 25 were taken in advection type fog at Blindern, 3 in a radiation type fog at the same place, and 24 in stratus-clouds, also of the advection type, at Tryvannshøgda.

2. Sampling method. The cascade impactor is described and tested by MAY (1945). He finds, by laboratory tests, that the instrument is most useful for sampling particles in the size range from 1μ to 50μ diameter. For drops of 50μ diameter orifice wall losses begin to appear and these losses increase with the drop size.

In our investigations the rate of air flow through the instrument was controlled by a flowmeter, and was usually 16 to 17 litres min^{-1}. The sampling time needed to get a proper density of the droplets on the slides varied between 1 and 10 seconds, depending on the type and density of the fog. Hence, the volume of air sampled ranged from about 0,3 to 3 litres, and the estimated total drop numbers could vary between 2000 and 150 000.

The sampling slides were prepared by a dyestuff, Naphtol Green B, contained in a thin film of gelatine (LIDDELL and WOOTTEN, 1957). A droplet impinging upon the film dissolves the dyestuff as it spreads and, upon evaporation, leaves a ring in which the concentration of the dyestuff is increased. When observed through a microscope with normal transmitted illumination, these rings appear dark against a lighter background. The outer diameter of the dark rings were measured by the use of a special eyepiece graticule (MAY, 1945). By using this, the droplet stains were grouped in size intervals of exponentially increasing length. If the spreading factor is known, the sizes of the original droplets are determined. Under laboratory conditions LIDDELL and WOOTTEN found that the ratio of the stain diameter to drop diameter was 2.5 : 1, with a standard deviation of 0.13, and this value is adopted in our measurements.

3. Accuracy of the measurements. A true sample is obtained when all the droplets in a given volume of foggy air are collected on the slides of the impactor. This is unfortunately not the case with this method. As mentioned above, MAY found that a fraction of the drops of 50μ diameter was deposited at the walls of the orifice, and that this fraction increased with increasing drop size. According to our measurements, however, it appears as if the orifice wall losses begin already at drops of 25μ to 30μ diameter. This was found by comparing the maximum drop size collected by the impactor with the maximum size found on a slide held against the wind, or, if calm weather, waved around in the fog. It is generally agreed upon that the "open slide" method is very efficient in sampling the drops in the upper part of the size spectrum, but not very useful for sampling the smallest drop sizes. Furthermore, it gives no possibility of obtaining the concentration of drops or the liquid water content in the fogs and clouds. The impactor method, on the other hand, is most efficient in sampling the drops in the lower part of the size spectrum, and also gives methods of estimating the drop concentration and the liquid water content. A simultaneous operation of the two methods should probably make it possible to calculate the correct distribution for all sizes. Unfortunately, this is not performed with the samples presented here.

Due to the probable loss of a fraction of the largest drops, the liquid water content will be underestimated, and the computed values are therefore not included in the tables. The drop concentration, however, will probably not be seriously affected by this loss, as the largest drops only amount to a small fraction of the total drop number.

WILCOX (1957) has stressed the importance of "isokinetic sampling" of airborne particulates. Isokinetic conditions prevail when there is no divergence of the flow lines around the sampler inlet. The velocities of the sampled and sampling streams must be equal, and the orifice must face directly into the sampled stream in order to minimize or eliminate divergence of the flow lines at the orifice. Sampling under non-isokinetic conditions will give a false sample of the airborne particulates. As to the cascade impactor, with a sampling rate of 17 l/min, MAY (1945) found that for wind speeds less than 11 kts, the requirements of isokinetic conditions were met fairly well. In calm air or very low wind speed an orifice adaptor is used, and the samples are taken with the adaptor facing upwards. From the tables it will be seen that in our measurements there are just a few samples taken in higher wind speed than 11 kts.

In most of the samples, the drops were deposited on the two first slides of the impactor. Only in about 1/5 of the samples drop stains were detected on the third slide. The fourth slide was either blank (as usually was the case at Tryvannshøgda) or contained a narrow streak of very small particles in high concentration, probably smoke and dust particles (at Blindern). In the rapid air flow through the cascade impactor the pressure is lowered and a high degree of supersaturation may occur and cause formation of small droplets. In two occasions when the air was nearly saturated at 10° C, samples of several litres were taken, but no droplets were found. A sample of 8 litres was taken in air with 98 % relative humidity at 28° C. On slide one and two no droplets were found. On the third slide a slight number of droplets in the size groups 1, 2 and 3 were found. The fourth slide was continually covered with droplets. The writers are not able to tell whether these droplets were formed in the instrument or did exist in the air. The number of droplets on the third slide, however, was so small that a possible effect of the pressure drop is thought not to distort the measured size distributions.

In order to obtain a representative size distribution of the collected drops, about two hundred stains were measured on each slide. To test the accuracy of the method, two test countings were performed. In each of these, the drop stains on one slide (slide 1 in the first test, slide 2 in the second) were measured by two different observers. A different number of drops were measured in each case, and the four possible combined histograms of the drops on the two slides drawn. These are shown in Figs. 9a to 9d. As seen from the figures, the histograms show some difference; the maximum value in size group four thus varies between 26 % and 34 %, and the double maximum is slightly marked or does not appear at all. In spite of these differences, however, one may conclude that the counting technique used gives a fairly representative size distribution of the *collected* drops.

Another question is how representative this measured distribution is of the real distribution of the existing droplets in the fog. A test was performed in order to try to obtain an answer to this question. A series of eight samples was taken with 2 to 3 minutes time interval in almost calm weather at Blindern. No drizzle was observed, and it was believed that the weather situation would not favour any major changes to occur between the drop size distributions of the successive samples. The forms of the size-frequency histograms agree very well, taking into account the counting errors that may occur. The two extreme histograms are shown in Figs. 10a and 10b. The estimated drop concentrations ranged from 30 to 70 per cm^3.

It is reasonable to conclude that the measured samples give a true size distribution of the droplets in the diameter range from 1μ to 25μ, and that the measured concentrations are of the right order of magnitude.

4. Results. The results of the measurements are presented in the Tables A to G and in the Figs. 1 to 8. The Tables A to G give some data of the individual samples together with meteorological observations. The cumulative volume distributions are specified by giving the values of the first quartile, volume median and third quartile diameters, and the minimum and maximum diameters. In addition the drop concentrations (number per cm^3) are given. Due to the incompleteness of the sampling method the volume distribution may only be used as a comparative factor. The Figs. 1 to 5 give the mean frequency polygons of the samples listed in Tables A to E respectively. The Figs. 6, 7 and 8 give the frequency histograms of the individual samples listed in Table G.

In all the diagrams the ordinate gives the relative number of drops in the corresponding diameter range. Plotted as abscissae are the drop diameters in microns in a logarithmic scale.

The samples of advection type fog at Blindern are all taken in calm weather. They are separated in the following three groups. *Group A* contains seventeen samples when no precipitation occurred. The samples were taken on six different days. They are tabulated according to the thickness of the fog, to the extent the observations allow to determine this parameter. The differences in the volume distributions are mainly caused by the larger drops, these are relatively few in number, so that the size distributions are essentially equal. The mean size distribution (frequency polygon) of the group is given in Fig. 1. *Group B* contains six samples when light drizzle occurred. Their individual frequency polygons are not quite similar, but they are all essentially of the same form as their mean frequency polygon, Fig. 2. *Group C* contains two samples. The fog was gradually breaking up after a rainfall. The two individual frequency polygons are very similar to their mean frequency polygon, Fig. 3.

The twentyfour samples taken in stratus-clouds at Tryvannshøgda are separated in three groups. *Group D* contains ten samples taken in calm weather when no precipitation occurred. They were taken on five different days. They are tabulated according to the height above the cloud base. The size distributions are rather different. The extreme samples are D5 and D6 with maximum points in the interval around 2,5μ (22 % of the total drop number) and around 9μ (39 %) respectively. All the size distributions are, however, of nearly normal or Gaussian form. Their mean frequency polygon is given in Fig. 4. *Group E* contains eight samples of non-precipitating clouds formed under the influence of wind. They were taken on five different days. The tabulation is done according to the strength of the wind. The individual size distributions are less different than in group D. The extreme samples are E1 and E4 with maximum points in the interval around 3,5μ (44 %) and in the interval around 7μ (46 %) respectively. The size distributions are all close to the normal form. The mean frequency polygon is given in Fig. 5. *Group F* contains six samples when light drizzle occurred. The shape of their frequency polygons varies strongly.

The three samples of the radiation type fog are listed in Table G. Their frequency histograms are given in Figs. 6 to 8. As seen from the figures, the histograms of the individual samples are very different, indicating large fluctuations in the micro-structure of the fog. However, it was not only the micro-structure that changed, the fog as a whole was observed to undergo rapid fluctuations in density, and could disappear and suddenly reform again. Thus, the visibility changed from 50 m to several kilometers in less than a minute, and vice versa. The writers have not been able to find in the literature any other measurements from pure radiation fog, to which our results could be compared.

An interesting feature of the size spectra are the very small droplets found in nearly all the samples, independent of place and cloud type. From the figures it will be seen that in many cases a great number of these smallest droplets, 1μ — 3μ in diameter, were collected. In this connection it should be mentioned that droplets less than 1μ diameter can not be measured and hardly detected in the microscope. The measurements may be compared with one reported by Liddell and Wootten (1957) who, by the same sampling method, found the number median and the volume median diameters in a "country fog" to be $1{,}6\mu$ and 15μ respectively, and the maximum drop size 30μ.

5. Discussion. In the two groups A and E the individual size distributions show such an essential similarity that although the number of independent samples are few, the respective mean distributions are believed to be typical for the area and the prevailing meteorological conditions. Fig. 1 represents the size distribution of the droplets at the base of a non-precipitating advection fog. The distribution function has two maxima, at about $3{,}5\mu$ (23 % of the total drop number) and at about 11μ (8 %), the minimum is close to 7μ (5 %). Only in one of the seventeen samples this minimum does not exist.

The bimodal size distribution could be accounted for if two air masses of different history joined at the sampling place. The sample would then include the two drop size spectra of the two different air masses. Each spectrum would probably have a different modal size, hence the combined spectrum would show two modes. However, it is not likely that this was the cause in our cases. Neiburger and Chien (1959) find that the computed drop size spectrum after a certain time always shows two modes. This should be caused by the separation of the condensation nuclei in two groups, one which is activated during the condensation process and grows to cloud drops, and the other which is not activated. In their computations based on a cloud model of the stratus type the gap in the size distribution appeared at a drop diameter of about 6μ. As the cooling continued the gap moved upwards to include 14μ. If this is the explanation of the bimodal form, a tendency to such a size distribution should also appear in the samples of group D and E. All individual samples in these groups, however, show a unimodal size distribution. The samples in group D and E are taken well above the condensation level, while the fog samples are taken at the condensation level. There is therefore the possibility that the bimodal form observed in group A (and B) is a phenomenon connected to the fog base.

Fig. 5 represents the size distribution of droplets in the middle layer of a non-precipitating stratus cloud (Table E), formed by a combined effect of advection and lifting. The form is close to a normal distribution, with maximum value at 4μ to 5μ (33 %). The maximum of the individual curves varies slightly with the wind speed. From Table E it is seen that in high wind speed there is a relatively large drop concentration, and in low wind speed a small concentration.

The two extreme samples in group D are both taken near the cloud top, where the cloud may be expected to have a cellular structure due to entrainment. The size distributions of the remaining eight samples all have a form close to the curve in Fig. 4. The typical distribution of the droplets at the middle layer of a non-precipitating stratus cloud of the advection type in the Oslo area is therefore believed to be of an approximately normal form with maximum at about 6μ diameter (24 %).

If we assume that the size distribution and the nature of the nuclei on which condensation occurred were quite similar on the different days on which the samples were taken at the same place, the drop concentrations of the different samples may be directly related to the rate of cooling of the air. Now, a high wind velocity will cause the air to ascend rapidly over the ridge Tryvannshøgda, hence the rate of adiabatic cooling will be large. This is followed by a high peak supersaturation (see e.g. MORDY, 1959), so that not only the larger condensation nuclei are activated, but also the smaller ones and a large drop concentration results. When the rate of cooling is small, the peak supersaturation will be low, and this results in a small number of drops per unit volume.

From Tables D and E it is seen that the observations are in good agreement with the condensation theory. In low wind speed, the mean values of the concentration and median volume diameter are 55 cm^{-3} and 9μ respectively, versus 214 cm^{-3} and 7μ in high wind speed.

According to HOCKING (1959), no collisions will occur between freely falling droplets unless the diameter of the largest is at least 36μ. HOCKING, in his computations of the collision efficiency of small drops, is the first to have considered the mutual interaction of the flow patterns around the drops. His values of the collision efficiencies deviate considerably from earlier computations (LANGMUIR, 1948, PEARCEY and HILL, 1957). As seen from Tables D and E, the maximum observed diameters are 26μ or less, and the droplets are therefore likely to have grown by condensation only. Of the seventeen samples in group A, fourteen have observed diameters equal to or larger than 26μ, and since the number of drops larger than 25μ diameter probably is underestimated, coalescence may possibly have occurred. However, the existing coalescence theories are not able to account for the minimum of the size distributions found here. This minimum of drop concentration at about 7μ is to the writers' knowledge not earlier observed.

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Table A: *Samples taken in non-precipitating advection fog at Blindern (for meanings, see table G).*

No.	Date	Time	d_m	d_1	d_2	d_3	d_M	n	Wind	Temp.	Vis.	Thickness of fog layer
1	15/1/58	1130	1	13	15	17	26	9	Calm.	—4	200	150 m
2	-	1150	1	13	14	17	26	10	-	-	150	150 -
3	18/11/58	1100	1	12	15	18	26	30	-	0	60-80	<400 -
4	17/11/58	0950	1	15	20	24	37	4	-	2	200-250	-
5	-	1005	1	13	15	17	18	4	-	-	-	-
6	4/3/58	1035	2	7	10	14	18	3	-	—1	200	>400 -
7	-	1120	2	9	12	16	18	17	S-03	-	150	-
8	18/12/57	1050	1	17	20	24	26	8	Calm.	—4	200	-
9	-	1115	1	10	14	17	26	12	-	-	150	-
10	3/3/59	0945	1	19	25	31	37	71	W-01	2	100-150	-
11	-	0948	1	13	18	22	26	43	-	-	-	-
12	-	0951	1	17	22	24	26	55	-	-	-	-
13	-	0953	1	17	22	25	37	38	-	-	-	-
14	-	0955	1	17	21	23	26	62	-	-	-	-
15	-	1001	1	16	21	23	26	61	-	-	-	-
16	-	1004	2	16	21	23	26	31	-	-	-	-
17	-	1006	2	17	22	24	26	37	-	-	-	-
$\frac{\Sigma}{N}$					18			29				

Table B: *Samples taken in advection fog at Blindern, when light drizzle was observed (for meanings, see table G).*

No.	Date	Time	d_m	d_1	d_2	d_3	d_M	n	Wind	Temp.	Vis.
1	26/11/57	1030	2	16	19	24	37	11	Calm	2	200
2	-	1105	1	16	21	25	37	44	-	-	100
3	-	1135	1	14	19	24	37	16	-	-	-
4	-	1200	1	12	15	20	26	19	-	-	-
5	14/4/59	1127	2	17	23	28	37	21	-	6	200-300
6	-	1137	2	18	24	30	37	3	-	-	-
$\frac{\Sigma}{N}$					20			19			

Table C: *Samples taken at Blindern in advection fog, breaking up after rain (for meanings, see table G).*

No.	Date	Time	d_m	d_1	d_2	d_3	d_M	n	Wind	Temp.	Vis.
1	26/10/57	1105	2	20	29	60	73	14	Var.-02	8	200
2	-	1135	1	14	20	31	37	7	Calm	-	250

Table D: *Samples taken in non-precipitating stratus clouds at Tryvannshøgda. Wind speed < 04 kts. (for meanings, see table G).*

No.	Date	Time	d_m	d_1	d_2	d_3	d_M	n	Wind	Temp.	Vis.	Height above cloud base	Remarks
1	18/9/58	0950	1	9	10	11	13	154	SE-02	10	90	200	
2	-	1000	1	6	8	10	18	115	-	-	-	-	
3	29/1/58	1110	2	9	11	14	18	17	S-02	0	100	250	
4	-	1130	1	6	10	11	18	10	-	-	-	-	
5	28/1/58	1115	1	9	10	18	26	15	SW-02	—1	50	350	near top of cloud
6	-	1135	2	8	10	12	18	33	-	-	-	-	- -
7	29/10/58	1055	1	8	9	11	13	84	S-02	5	60-100	350-400	
8	-	1105	1	7	8	9	13	91	-	-	-	-	
9	3/3/59	1105	2	7	10	12	13	8	Var. -02	—4	200-250	410	
10	-	1120	2	5	8	12	18	20	-	-	200	410	
$\frac{\Sigma}{N}$					9			55					

Table E: *Samples taken in non-precipitating stratus clouds at Tryvannshøgda. Wind speed ≥ 04 kts. (for meanings, see table G).*

No.	Date	Time	d_m	d_1	d_2	d_3	d_M	n	Wind	Temp.	Vis.	Height above cloud base	Remarks
1	27/1/58	1200	1	5	9	13	26	25	SW-04	—3	200-300	250	
2	-	1225	1	5	7	9	18	109	SW-06	-	150	-	
3	19/12/57	1100	1	5	6	7	13	123	SW-08	-	80	-	
4	20/5/58	1025	2	6	7	8	13	302	SE-10	7	60	-	
5	4/1/58	1215	1	5	6	7	13	226	SW-12	—4	150	100	
6	-	1220	1	4	6	8	18	180	-	-	-	-	
7	20/12/57	1130	1	4	5	7	26	427	S-20	4	Var. (50)	-	Gustiness
8	-	1140	1	4	6	7	13	319	-	-	-	-	-
$\frac{\Sigma}{N}$					7			214					

7	20/12/57	1130	1	4	5	7	26	427	S-20	4	Var.(50)	-	Gustiness
8	-	1140	1	4	6	7	13	319	-	-	-	-	-
$\frac{\Sigma}{N}$					7			214					

Table F: *Samples taken in stratus clouds at Tryvannshøgda, when light drizzle was observed (for meanings, see table G).*

No.	Date	Time	d_m	d_1	d_2	d_3	d_M	n	Wind	Temp.	Vis.	Remarks
1	8/10/57	1125	1	11	35	42	52	54	Var.-02	8	100-150	
2	-	1140	1	9	19	40	52	72	-	-	-	
3	-	1155	1	9	11	15	37	90	-	-	80	
4	10/10/57	1020	1	12	17	24	37	154	SW-10	7	50	Cloud top 900 m
5	-	1040	1	15	26	36	52	304	-	-	-	
6	-	1100	1	9	13	20	26	273	-	-	60	
$\frac{\Sigma}{N}$					20			158				

Table G: *Samples taken in radiation fog.*

Symbols: d_m, d_1, d_2, d_3, d_M = *minimum, first quartile, volume median, third quartile and maximum droplet diameters in microns respectively;* n = *concentration of droplets pr. cm*^{3}*; vis. = visibility in meters. The wind speed is given in knots, the temperature in Celsius degrees.*

No.	Date	Time	d_m	d_1	d_2	d_3	d_M	n	Wind	Temp.	Vis.	Remarks
1	22/11/58	2015	1	14	16	19	26	23	Calm	1	100	Near top of fog (150 masl)
2	-	2035	1	14	17	21	26	238	-	-	50	Middle of fog (90 m a. s. l.)
3	-	2045	1	12	15	17	26	43	-	-	70	Fog is breaking up (90 ma.s.l.)

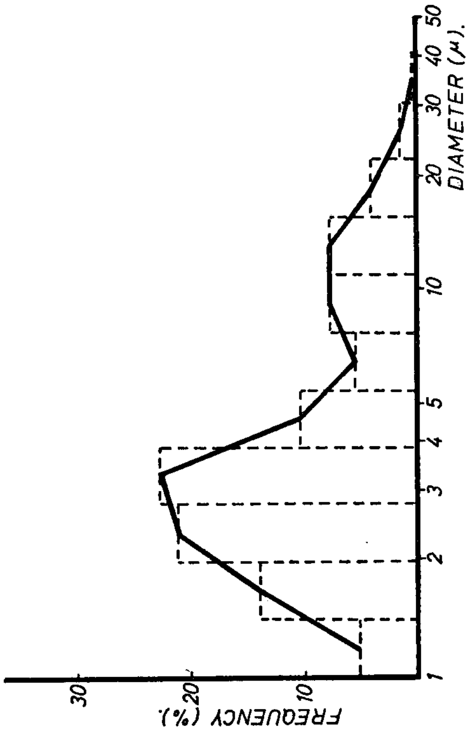

Fig. 1: Mean frequency polygon for the samples listed in table A.

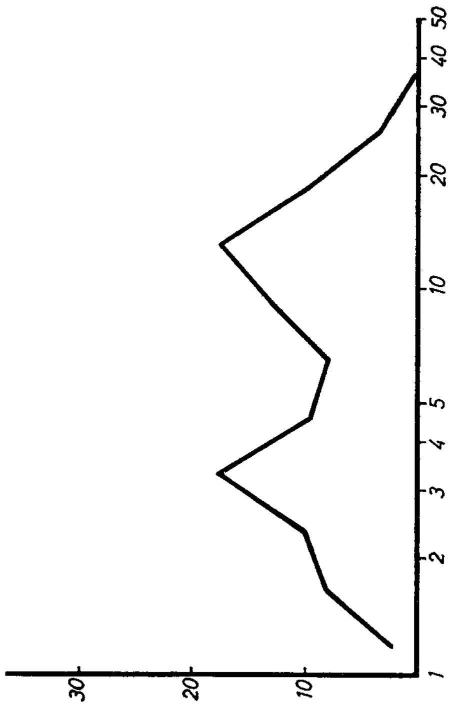

Fig. 2: Mean frequency polygon for the samples listed in table B.

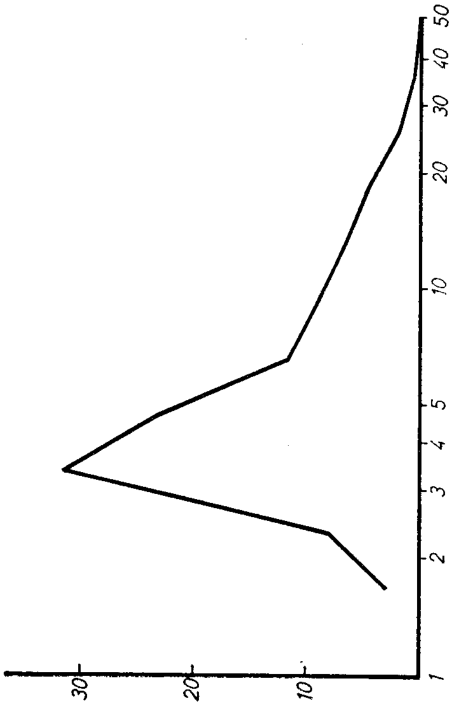

Fig. 3: Mean frequency polygon for the samples listed in table C.

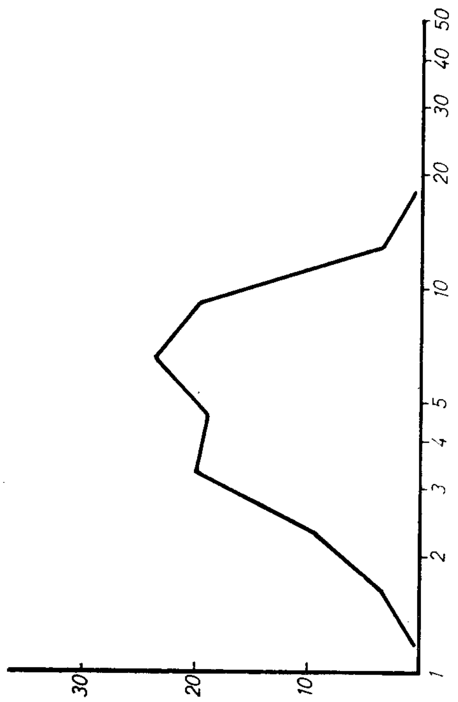

Fig. 4: Mean frequency polygon for the samples listed in table D.

Fig. 3: Mean frequency polygon for the samples listed in table C.

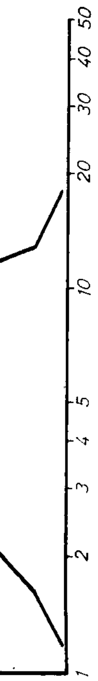

Fig. 4: Mean frequency polygon for the samples listed in table D.

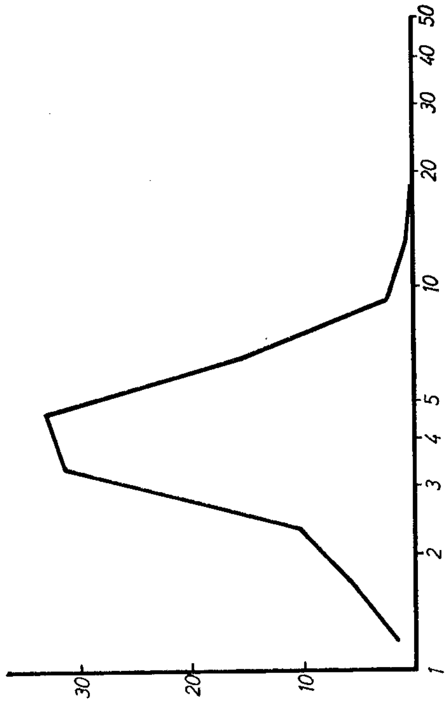

Fig. 5: Mean frequency polygon for the samples listed in table E.

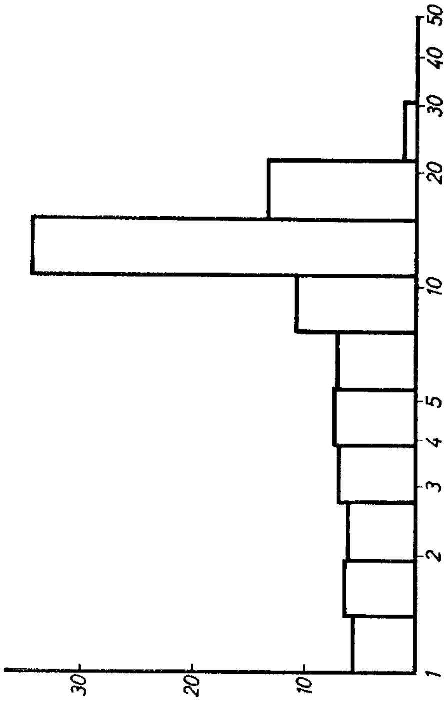

Fig. 6: Frequency histogram for sample G 1.

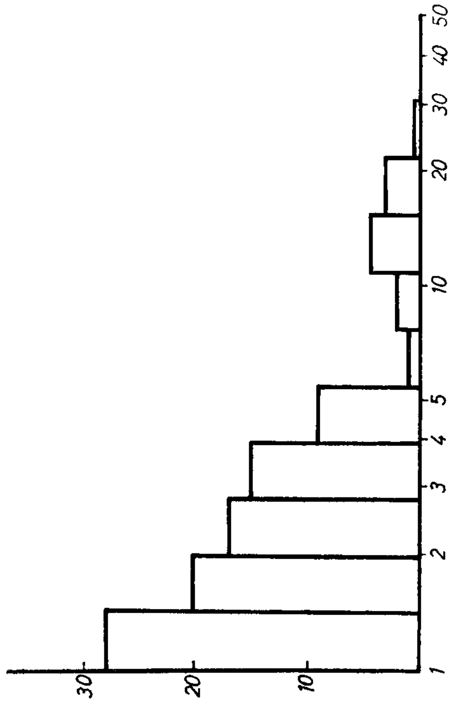

Fig. 7: Frequency histogram for sample G 2.

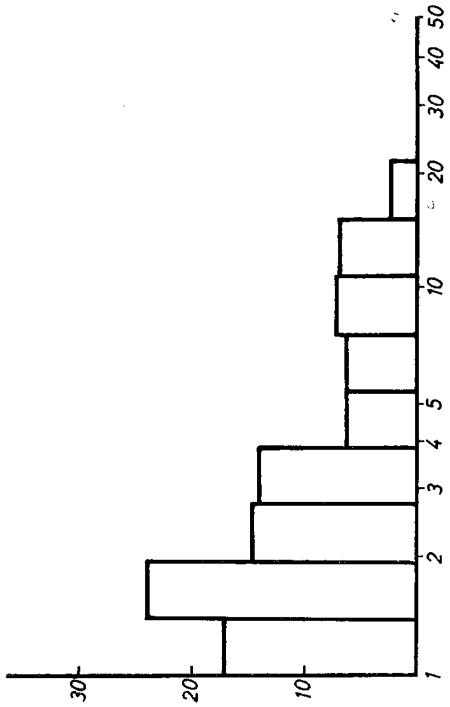

Fig. 8: Frequency histogram for sample G 3.

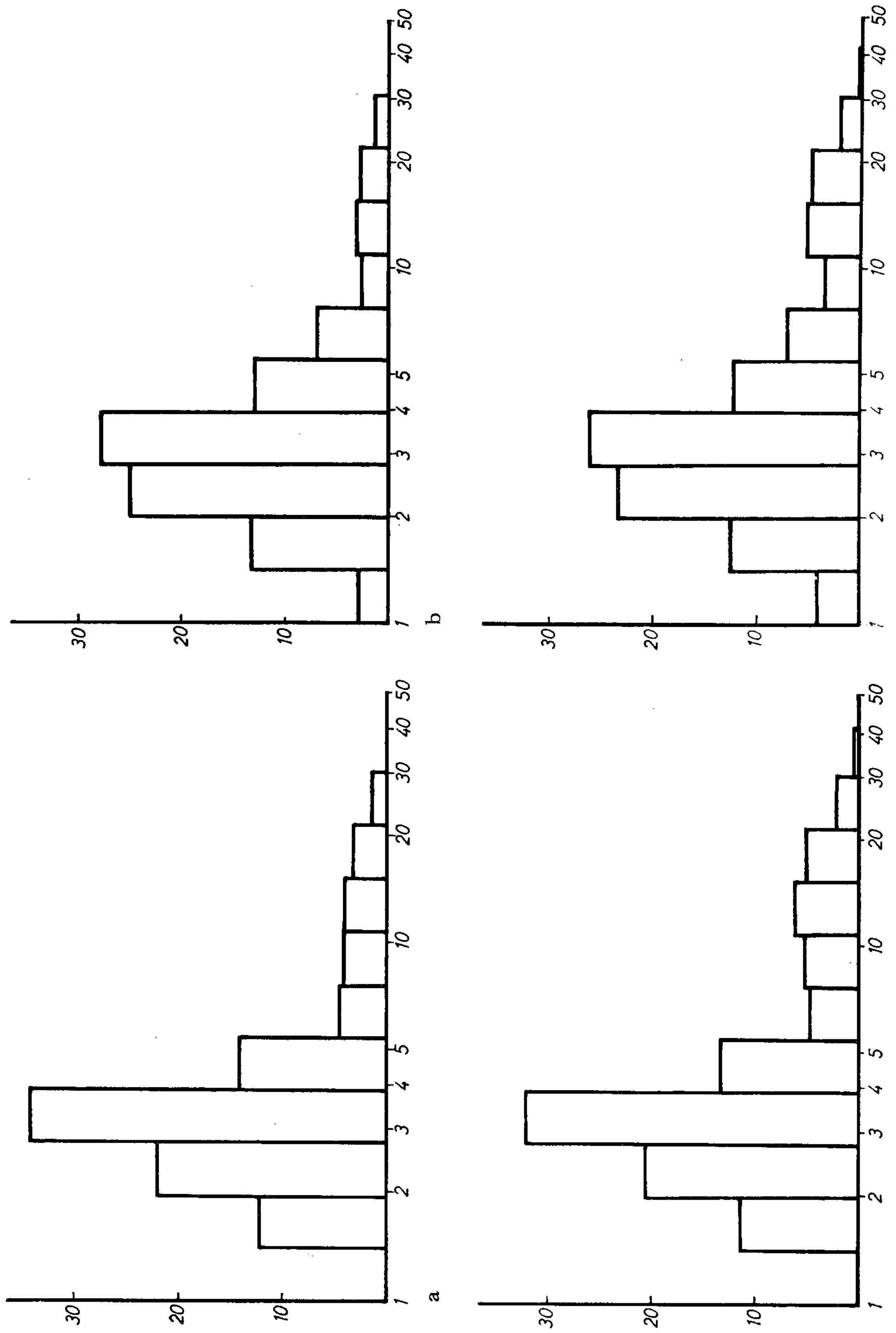

Fig. 9: The figure shows the four possible frequency histograms of the test counting.

Fig. 9: The figure shows the four possible frequency histograms of the test counting.

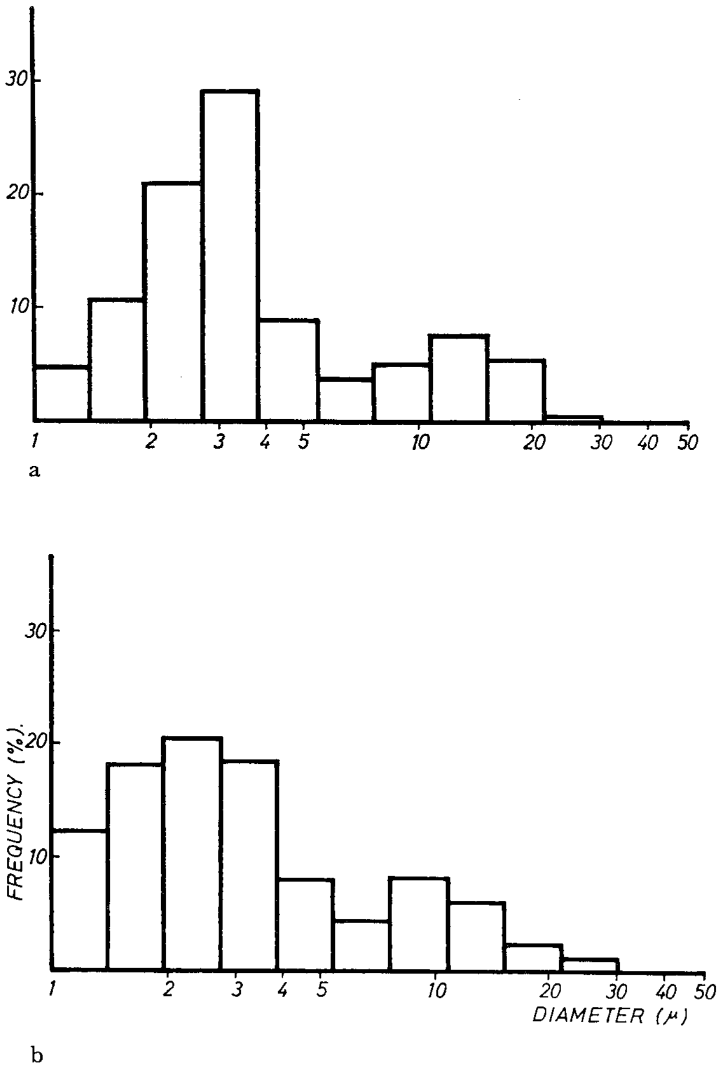

Fig. 10: The figure shows the two extreme frequency histograms of the eight samples A 10 — A 17.