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STATISTICAL EVALUATION OF THE PROCEDURE FOR COUNTING ~~ASBESTOS~~ FIBERS ON MEMBRANE FILTERS

Final Report

Submitted to

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SUMMARY

This report presents the results of a statistical evaluation, performed at this laboratory, of the OSHA procedure for counting asbestos fibers collected on membrane filters. The study addressed itself specifically to the contribution from counter experience, fiber concentration, and fiber distribution to the total variation in the OSHA counting procedure.

Six counters participated in the study. Three were experienced fiber counters; the others, while familiar with the operation of a microscope, had only a half day's familiarization with the rules for fiber counting. Three filters, having fiber concentrations varying from 1 to 5 fibers per Porton field, were investigated. Each observer counted a 1/8 pie-shaped portion of each of the three filters six times. In addition, the entire filters were counted by one of the experienced observers using approximately 4000 randomly selected fields of view per filter.

The fiber concentrations over the entire filters were found to be non-uniform and the distribution of fiber counts was found to be significantly different from the Poisson distribution. For an OSHA fiber count, where the number of fibers counted, N, is approximately 100, the standard deviation of the fiber count distribution appears to be representable by $1.6\sqrt{N}$ rather than $\sqrt{N}$, which is a property of the Poisson distribution. It appears that a high percentage of very fine fibers on a filter can double the variation between counts obtained by different counters. The standard deviation of OSHA counts between counters on a given filter section appears to increase from about 10% to 20% for filters containing very fine fibers. There does not appear to be significant differences in the counts between experienced and inexperienced counters; however, it is important that the inexperienced observers be well acquainted with the fundamentals of fiber counting. Combining variations in fiber concentrations over the entire filter with those for different observers, the standard deviations are estimated as 21% and 25% for filters with and without a high concentration of very fine fibers, respectively. Ninty-five percent confidence intervals are estimated between ±43% and ±50%, depending upon the concentration of fine fibers.

Recommendations, based upon this study, can be found in the last section of this report.

ABSTRACT

The effects of counter experience and fiber concentration upon the precision of the current OSHA asbestos fiber counting procedure were investigated. Variations between two experienced counters and three inexperienced counters were not significant. Concentration interaction effects were significant for two of the five counters. Two σ confidence intervals on a single OSHA count were estimated at 43%. The fiber count data were more disperse than the commonly accepted Poisson distribution.

INTRODUCTION

The precision of the OSHA approved asbestos counting procedure is not well known, particularly as it is effected by observer experience and the average number of fibers per Porton field (F/f) on the filter. Many sources of error are possible, such as variations between observer's visual acuities, difficulties in estimating the five μm cutoff length of the fibers, statistical errors associated with counting, observer experience, and concentration dependence. Experience has shown it to be necessary that even experienced microscopists be pre-tested and specially instructed before they can perform precise counts. The goal of this research performed for AIA/NA was to quantify these effects through the statistical analysis of appropriately acquired data.

The study was divided into two phases.

The purpose of Phase I was to evaluate sources of variation and interaction in fiber counting data obtained utilizing the OSHA technique. The factors to be analyzed were observer and concentration. Specifically, six observers, three experienced asbestos dust counters and three inexperienced counters, counted fibers present on 1/8 filter sections from three filters containing 1, 2.5, and 5 asbestos fibers per Porton field, respectively. The OSHA technique was used for all counting, and the experiment was replicated six times. These data were reduced using standard statistical analytical techniques. The uniformity of the fiber distribution and the approximate concentration was determined for each filter section by an experienced observer prior to the OSHA counting. This evaluation was accomplished utilizing a totally random, yet completely biasable method of sampling. Approximately 500 fibers per filter section were counted for this evaluation.

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The purpose of Phase II of the study was to determine whether or not the average F/f determined by using the OSHA technique on a randomly selected 1/8 filter fraction differs significantly from the population mean and to investigate the fiber distribution on the filters. To accomplish this, the remaining 7/8 of each of the three filters used in Phase I was counted by the same experienced counter used for the evaluation of Phase I sections and utilizing the same technique of sampling. These data were combined with the original evaluation counts from Phase I. The data were examined and reduced to disclose any radial or angular dependence of F/f and to determine the population mean and standard error. Variation from the OSHA measurements were tested for each concentration.

EXPERIMENTAL PROCEDURES

Three representative filters were supplied by Johns-Manville Environmental Control Systems Division for analysis. They were collected so as to contain a nominal 1 (sample 8), 2.5 (sample 11), and 5 (sample 2C) asbestos fibers per Porton field of view (F/f). The samples were prepared using 37 mm, 0.8 μm Millipore AA filters in conjunction with the NIOSH approved MSA-G personal pumps without dampeners. Each membrane filter was to have its orientation with respect to the employee's body identified by a mark on the outer edge. Only two samples, 8 and 11, were so marked. The following procedures were used on all samples.

Sample Mounting

Portions to be counted were placed dust side up on a drop or two of mounting solution on a standard microscope slide. A clean cover slip was placed over the sample and a very slight pressure exerted to make contact with the mounting medium. The mounting solution was prepared by dissolving 50 mg of membrane filter per ml of 1:1 solution of dimethyl phthalate and diethyloxalate. The samples clarified and were ready for counting in approximately two hours.

Counting Instrumentation

All fiber counting was done on one microscope equipped with phase contrast optics. The system used was a Leitz Labolux II with inclined binocular containing paired GF 10X periplanatic widefield eyepieces, one with an adjustable eyelens and Porton reticle. The phase contrast accessories consisted of PHACO No. 402a L phase contrast condenser and a PHACO 40 X/0.65 achromatic dr-phase objective. Focusing of the phase ring was accomplished using the PHADS magnifier. Illumination was provided by a 6 volt/5 amp regulating transformer. Field identification and location was accomplished through the use of a No. 42 mechanical stage with x-y graduated verniers reading to 0.1 mm.

OSHA Ground Rules for Fiber Counting

The left half of the Porton field served as the count area. All particles longer than 5 μm and having length to width ratios equal to or greater than 3 were countable and termed fibers. All fibers contained within the counting area and not touching any of the four sides were counted. Fibers which intersected or touched a side of the counting area were counted for the top and left sides and not counted for the right and bottom sides. Fibers intersecting both the left and bottom sides or the top and right sides were counted only if the greater length was outside the left and top sides, respectively. Fibers which crossed the entire field of view were not counted if they intersected both the top and bottom sides or the top and right sides. These rules are summarized below in Figure 1.

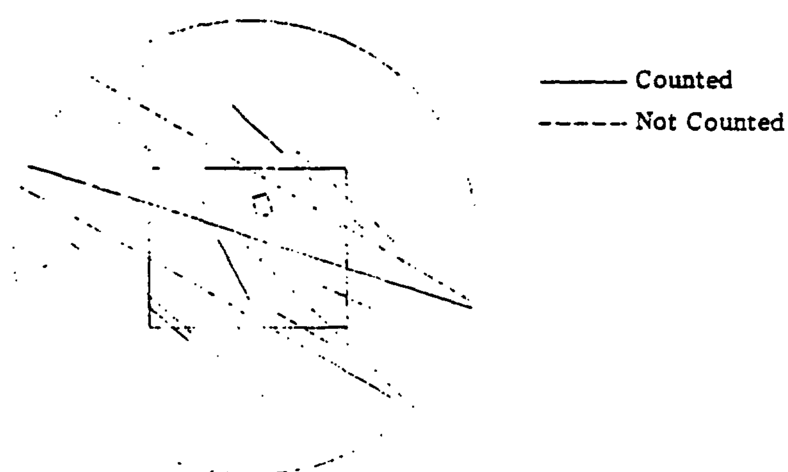

Figure 1

SUMMARY OF FIBER COUNTING RULES

The circular area represents the total field of view and the rectangular area the Porton counting area. Any other fiber configuration which touched the counting area was counted.

Fibers which interesect were counted as being separate only if segments of each were clearly identifiable on both sides of the point of intersection. Fiber intersections of a "Y" configuration were counted as single fibers regardless of the number of branches. For cases where a fiber touched a particle, the particle volumes were ignored and the total fiber length taken as particle diameter plus fiber length.

Fields were selected for counting in the following manner. The microscope was focused at the apex of the wedge shaped filter section no closer to the tip or either edge than two fields of view. The counter then removed his eyes from the binocular and moved the stage a short distance along the bisecting radius toward the circumferential edge. The fibers contained in the Porton counting area were then counted using a mechanical accumulator. This process was repeated until the specified number of fields had been counted. If the outer edge was reached prior to counting the required number of fields, the process was continued using a line parallel to the bisecting radius but removed from it by at least two fields of view. No counts were made within two fields of view of any edge.

Filter Handling and Data Acquisition

A 1/8 pie shaped, fraction was removed from a given filter and mounted. The angular position of one of the fraction's radii relative to the body orientation mark (if present) was noted. From the assumed fiber concentration, a sufficient number of random stage coordinates were generated to yield a total fiber count of approximately 500 on the fraction. The coordinates were generated by a specially written program utilizing an IBM supplied uniform random number generating routine, RANDU. The filter fraction was then counted by an experienced observe and the data tested for goodness of fit to the Poisson distribution using the X^2 statistic. None of the 1/8 fractions so counted resulted in a significant X^2 test at the 5% level and were, therefore, deemed acceptable for the OSHA counting experiment (Phase I).

By making use of the mean F/f determined from the above data, the number of fields to be counted in Phase I to yield a total fiber count of about 100 was determined. It is to be noted that this is a slight, but insignificant, modification to the OSHA procedure. It was done to eliminate one of the variables from the problem.

The six counters then ~~counted~~ the fraction and recorded the total number of fibers counted in the specified number of fields using the OSHA sanctioned technique described above. Each counter counted a given fraction six (6) times. The counter order was selected randomly, but, due to the impracticality of randomizing the replicative counts, they were done consecutively.

The remaining 7/8 of the filter was mounted in 2-7 fractions, depending upon fiber concentration. A suitable number of random coordinates were generated to yield a total filter fiber count of approximately 4000. The same experienced observer which counted the original 1/8 fraction for evaluation counted the remaining 7/8.

STATISTICAL ANALYSIS

The following data in Tables 1-3 are the individual fiber counts of the various observers accumulated using the OSHA sanctioned procedure, modified in that all observers counted the same number of fields on a given filter. Observers 1-3 had previous fiber counting experience and are designated through the use of an asterisk (*). Observers 4-6 had no previous fiber counting experience, but were familiar with the ground rules and were familiar with the use of the microscope.

TABLE 1

OSHA FIBER COUNT DATA ON FILTER 8

Replication	Observer 1*	2*	3*	4	5	6
1	100	86	125	121	89	165
2	112	111	129	123	98	144
3	98	90	132	97	89	117
4	112	96	129	118	86	173
5	115	105	128	103	94	171
6	103	95	126	109	90	131
Mean ($\overline{X}$)	106	97	128	112	91	150
Standard Deviation (s)	7	9	2	10	4	23

Fields Counted: 110 Filter Average: 112 ± 2 (F/110 fields)

Many fibers on filter 8 were extremely fine. A question which arises is if the rather wide spread in means correlates with the counter's visual acuity. This question was not investigated for this report.

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TABLE 2

OSHA FIBER COUNT DATA ON FILTER 11

Replication	Observer 1*	2*	3*	4	5	6
1	129	87	125	125	120	93
2	131	80	131	94	120	93
3	117	99	130	128	110	110
4	113	93	133	127	93	108
5	135	109	130	118	105	123
6	110	106	127	138	120	91
Mean ($\overline{X}$)	122	96	129	122	111	103
Standard Deviation (s)	10	11	3	15	11	13

Fields Counted: 56

Filter Average: 90 ± 2
(F/56 fields)

TABLE 3

OSHA FIBER COUNT DATA ON FILTER 2C

Replication	Observer 1*	2*	3*	4	5	6
1	118	95	98	83	107	140
2	106	79	101	93	65	87
3	107	114	95	80	91	90
4	93	115	104	82	103	97
5	108	95	90	80	99	83
6	95	92	93	89	88	97
Mean ($\overline{X}$)	104	98	97	84	92	99
Standard Deviation (s)	9	14	5	5	15	21

Fields Counted: 20

Filter Average: 94 ± 2
(F/20 fields)

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All statistical tests are conducted at the 5% level of significance.

Homogeneity of Variances

Variance estimates derived from the data presented in Tables 1-3 are presented below in Table 4. These values are the common mean square deviations with N-1 degrees of freedom.

TABLE 4

OSHA FIBER COUNT VARIANCE ESTIMATES (s^2)

	Observer					
Filter	1*	2*	3*	4	5	6
8	51.87	86.97	6.17	110.6	18.40	536.2
11	109.5	124.7	8.27	225.1	120.7	163.6
2C	85.10	191.9	26.97	28.30	228.2	434.0

In order to perform variance analysis, one must demonstrate that the variances to be analyzed are homogeneous. If, for a given filter, it is assumed that each of the observers' counts if drawn randomly from a normal population, the M statistic may be used to test the hypothesis that the 6 populations have the same variance. M is calculated from the relation

$$M = 5\,k \ln \frac{\sum_{1}^{k} 5\, s_i^2}{5k} - \sum_{1}^{k} 5 \ln s_i^2$$

where k is the number of populations being tested.

The results of these tests for all observers taken as a group are presented below in Table 5. The tests were repeated for each filter by dividing the observers into two groups, experienced and inexperienced. The results of these tests are presented in Table 6.

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TABLE 5

M TEST - POOLED OBSERVER DATA

Filter	M	Critical Value	Significance
8	26.5	13.1	Significant - reject
11	10.2	11.1	Cannot reject
2C	14.1	13.1	Significant - reject

TABLE 6

M TEST - GROUPED OBSERVER DATA

Filter	Qualification	M	Critical Value	Significance (at 5%)
8	Experienced	7.00	6.47	Significant - reject
	Inexperienced	11.5	6.47	Significant - reject
11	Experienced	7.71	6.47	Significant - reject
	Inexperienced	0.48	6.22	Cannot reject
2C	Experienced	4.30	6.22	Cannot reject
	Inexperienced	7.35	6.47	Significant - reject

It can be readily seen that most of the populations do not have common variance.

Analysis of Variance

A basic assumption of this type of analysis is homogeneity of variance. A few transformations were attempted to homogenize the variances without success. For this reason, only the means of sample 11 are compared here by this procedure. The results of the single factor analysis are presented below in Table 7.

TABLE 7

SINGLE FACTOR ANALYSIS OF VARIANCE FOR SAMPLE 11

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Among observers	4981.92	5	996.4	7.952
Within observers	3758.83	30	125.3	
Total	8740.75	35		

To test the null hypothesis that the 6 observer means are equal, one compares F, above, with $F_{0.05}$ (30,5) = 2.69. Since an F value of 7.9 is highly improbable we conclude the data is inconsistent with the null hypothesis and that there are significant differences in observer means. Since the observers were not selected at random one cannot rigorously extend the method to include components of variance analysis. Should the reader want to play the game of make believe, however, an estimate of the between - observers variance is 145., and an estimate of the total variance in fiber counts in the population of counters is 270., or a standard deviation of 14%.

Other Tests of μ and σ

The t test of the null hypothesis μ = a on the basis of a random sample was performed on the OSHA counting data for all filters. The F test for σ_1/σ_2 equal to unity was also performed for these samples. The results of these tests are presented below in Tables 8 and 9. The means were tested against the values obtained from the total filter counts and the standard deviations against the theoretical values one obtains if it is assumed that the count data were Poisson distributed.

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TABLE 8

t Test of $\overline{X}$ = Whole Filter Average

(t_{crit} = 2.571)

Sample (μ)	Test	Observer 1*	2*	3*	4	5	6
8	t	1.701	3.940	15.98	0	11.99	4.040
(112)	Significant	no	yes	yes	no	yes	yes
11	t	7.608	1.250	33.47	5.175	4.479	2.499
(90)	Significant	yes	no	yes	yes	yes	no
2C	t	2.788	0.766	1.321	4.374	0.297	0.588
(94)	Significant	yes	no	no	yes	no	no

The OSHA means are significantly different from those determined from the counting of the entire filter. The tests of observer 1* are particularly interesting since this is the individual who counted the entire filters.

TABLE 9

F Test for σ (experimental)/σ (Poisson) = 1

($F_{0.05}$ (5,5) = 5.05)

Sample	Test	Observer 1*	2*	3*	4*	5*	6*
8	F	2.06	1.12	20.8	1.01	4.95	3.57
	Significant	no	no	yes	no	no	no
11	F	1.12	1.30	15.63	1.85	1.08	1.59
	Significant	no	no	yes	no	no	no
2C	F	1.23	1.95	3.59	2.99	2.48	4.38
	Significant	no	no	no	no	no	no

One could not conclude from this data that the fiber counts are not Poisson distributed, however see Tables 15-17 for the whole filter counting.

Data Rejection

After performing measurements of the first filter fraction (sample 11), we became suspicious of counter number 3's data because of the extremely low value of the variance of his measurements (8.27). When this was repeated on the second fraction counted (sample 8), it became obvious that he may, indeed, have been biasing his data. For counting of the third fraction, his procedure was monitored for three replications and opaque tape placed over the fiber count window of the count accumulator until the total of 20 fields had been counted on a given replication. The F test results of Table 9 tended to confirm the suspicion and it was decided to repeat the M test for homogeneity of variances without including his data. The results are presented below in Table 10.

TABLE 10

M TEST - COUNTER 3 REJECTED

Filter	M	Critical Value	Significance
8	15.4	10.24	Significant - reject
11	0.91	9.80	Cannot reject
2C	8.90	9.80	Cannot reject

The above results allow a two-factor analysis of variance for filters 11 and 2C, providing the two filters have common variance. Since it is known that the data on these filters (Tables 2 and 3) do not have the same mean and it is known that the means are approximately proportional to the variances it is clear, a priori, that the two filter count populations will not have common variance. For this case, the transformation $Z = \sqrt{X} + \sqrt{X+1}$ will approximately stabilize the variance at unity for $\overline{X} > 0.8$. The transformed data are presented below in Tables 11 and 12.

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TABLE 11

TRANSFORMED OSHA FIBER COUNT DATA ON FILTER 11

Replication	Observer 1*	2*	4	5	6
1	22.76	18.71	22.41	21.95	19.34
2	22.93	17.94	19.44	21.95	19.34
3	21.67	19.95	22.67	21.02	21.02
4	21.31	19.34	22.58	19.34	20.83
5	23.28	20.92	21.77	20.54	22.23
6	21.02	20.64	23.54	21.95	19.13
ΣX	132.99	117.51	132.41	126.77	121.89
$\overline{X}$	22.16	19.58	22.07	21.13	20.31
s	0.945	1.15	1.41	1.06	1.24
s^2	0.8930	1.314	1.977	1.121	1.546

TABLE 12

TRANSFORMED OSHA FIBER COUNT DATA ON FILTER 2C

Replication	Observer 1*	2*	4	5	6
1	21.77	19.54	18.28	20.74	23.71
2	20.64	17.83	19.34	16.19	18.71
3	20.74	21.40	17.94	19.13	19.03
4	19.34	21.49	18.17	20.35	19.74
5	20.83	19.54	17.94	19.95	18.28
6	19.54	19.23	18.92	18.31	19.75
ΣX	122.86	119.05	110.59	115.17	119.21
$\overline{X}$	20.48	19.84	18.43	19.19	19.87
s	0.901	1.40	0.571	1.64	1.97
s^2	0.8120	1.949	0.3265	2.695	3.870

The M test performed on the 10 variances yields a value of $M = 9.67$ which is less than the critical value. The null hypotheses of homogeneous variances, therefore, cannot be rejected. The results of the two factor variance analysis of the transformed data are presented below in Table 13. F values are compared with the critical values listed under the table in a manner identical to that described for Table 7.

TABLE 13

TWO FACTOR ANALYSIS OF VARIANCE FOR SAMPLES 11 AND 2C
(Transformed Data)

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Among filters	33.2866	1	33.287	20.17
Among observers	17.4124	4	4.3531	2.640
Interaction	26.9503	4	6.7376	4.086
Sub Total	77.6494	9		
Within observations	82.4462	50	1.649	
Total	160.0956	59		

$F_{0.05}(1,50) = 4.04$ $F_{0.05}(4,50) = 2.57$

The significant variations among filters and among observers are not particularly interesting since the former was anticipated from the method of counting and the latter simply confirms the results summarized in Table 7. The fact that the interaction variation is significant, however, implies that there may be an effect due to fiber concentration upon the ability of an observer to accurately count an asbestos sample. On the other hand, it should be kept in mind that significant interactions will occur with a 5% probability due to random fluctuations alone, or may be due to important variables being left out of the analysis (perhaps improper sampling).

Individual Comparison

Tests for individual contrasts among the means in Tables 11 and 12 were conducted using the 97.5 percentile of the t distribution with the "within observations" root-mean square from Table 13 as the best estimate of the common standard deviation. Coefficient determination was based upon the usual model of

$$X_{ij} = \mu + r_i + C_j + I_{ij} \text{ where } \sum_i r_i = \sum_j C_j = \sum_i I_{ij} = \sum_j I_{ij} = 0$$

Results of these individual contrasts are presented in Table 14. Results are significant which do not include zero. Analogous simultaneous group comparisons using the q distribution were insignificant.

Precision of OSHA Method

An estimate of the preciscion of an individual OSHA count, including variations due to observer and fiber concentration was obtained from the data of Table 13 assuming that components of variance analysis was applicable, omitting the unusable among filter variation, and assuming $\sigma_x^2 = \left(\frac{\partial Z}{\partial X}\right)_{\bar{x}}^{-2} \sigma_z^2$

where $Z = \sqrt{x} + \sqrt{x+1}$

The result is $\sigma_{\bar{x}}$ (%) = 16.2. Of this variation, 78% is attributable to variability in the OSHA procedure, the balance (22%) to variation among counters and interaction.

Whole Filter Data

Fiber counts from the entire filters were tested for goodness of fit to the Poisson distribution using the Chi Squared statistic. All three tests were significant indicating the hypothesis that the fibers are distributed according to the Poisson distribution should be rejected. Results of the X^2 tests are presented below in Tables 15-17, together with histograms of the count data in Figures 2-4.

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TABLE 14

INDIVIDUAL CONTRASTS IN TRANSFORMED DATA
(Filters 11 and 2C)

No.	Coefficients (a_{ij})										$\Sigma a_{ij}\overline{X}_{ij} \pm t_{\alpha/2}\, s\sqrt{\frac{\Sigma a_{ij}^2}{n}}$ **	Estimate of:
	$\overline{X}_{11}$* 22.16	$\overline{X}_{12}$* 19.58	$\overline{X}_{13}$ 22.07	$\overline{X}_{14}$ 21.13	$\overline{X}_{15}$ 20.31	$\overline{X}_{21}$* 20.48	$\overline{X}_{22}$* 19.84	$\overline{X}_{23}$ 18.43	$\overline{X}_{24}$ 19.19	$\overline{X}_{25}$ 19.87		
1	1/2	-1/2	0	0	0	1/2	-1/2	0	0	0	1.61 ± 0.74	* Difference between experienced observer
2	1/4	1/4	-1/2	0	0	1/4	1/4	-1/2	0	0	0.26 ± 0.65	Difference between experienced observers and observer 4
3	1/4	1/4	0	-1/2	0	1/4	1/4	0	-1/2	0	0.35 ± 0.65	Difference between experienced observers and observer 5
4	1/4	1/4	0	0	-1/2	1/4	1/4	0	0	-1/2	0.42 ± 0.65	Difference between experienced observers and observer 6
5	1/2	-1/8	-1/8	-1/8	-1/8	-1/2	1/8	1/8	1/8	1/8	0.12 ± 0.59	Interaction effect - observer 1*
6	-1/8	1/2	-1/8	-1/8	-1/8	1/8	-1/2	1/8	1/8	1/8	-1.09 ± 0.59	* Interaction effect - observer 2*
7	-1/8	-1/8	1/2	-1/8	-1/8	1/8	1/8	-1/2	1/8	1/8	1.34 ± 0.59	* Interaction effect - observer 4
8	-1/8	-1/8	-1/8	1/2	-1/8	1/8	1/8	1/8	-1/2	1/8	0.28 ± 0.59	Interaction effect - observer 5
9	-1/8	-1/8	-1/8	-1/8	1/2	1/8	1/8	1/8	1/8	-1/2	-0.66 ± 0.59	* Interaction effect - observer 6
10	1/5	1/5	1/5	1/5	1/5	-1/5	-1/5	-1/5	-1/5	-1/5	1.49 ± 0.47	* Difference between filters

*Significant contrast **$t_{\alpha/2} = 2.010$, $s = 1.284$, $n = 6$

TABLE 15

CHI SQUARE TEST OF SAMPLE 8 WHOLE FILTER DATA

Value	Experimental Frequency	Cumulative Frequency	Theoretical Frequency	Cumulative Theoretical	Category
0	1419	1419	1308.64	1308.64	1
1	1236	1236	1343.39	1343.39	2
2	623	623	689.53	689.53	3
3	264	264	235.94	235.94	4
4	88	88	60.55	60.55	5
5	16	16	12.43	12.43	6
6	6	6	2.12	2.12	7
7	0	6	0.31	2.43	7
8	1	7	0.04	2.47	7

Degrees of Freedom	7	Mean (F/f)	1.02
CHISQ (0.050,5)	11.070	Poisson Standard Deviation	1.6 percent
CHISQ (calculated)	49.355	Standard Error	1.7 percent

FIGURE 2

FIBER COUNTING HISTOGRAM FROM FILTER 8 DATA

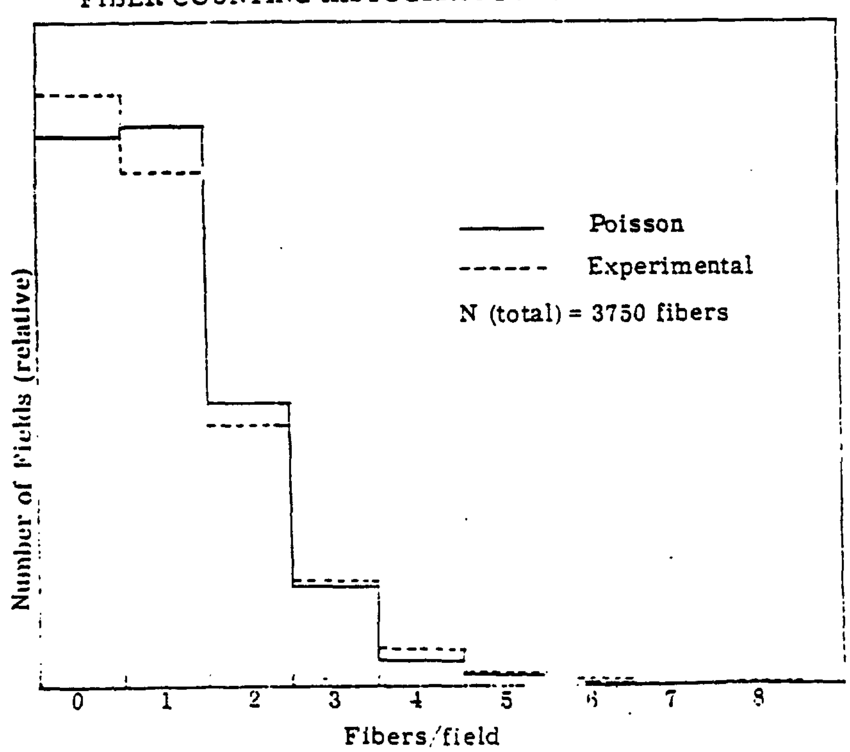

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TABLE 16

CHI SQUARE TEST OF SAMPLE 11 WHOLE FILTER DATA

Value	Experimental Frequency	Cumulative Frequency	Theoretical Frequency	Cumulative Theoretical	Category
0	504	504	398.25	398.25	1
1	583	583	645.09	645.09	2
2	463	463	522.45	522.45	3
3	245	245	282.08	282.08	4
4	117	117	114.22	114.22	5
5	67	67	37.00	37.00	6
6	24	24	9.99	9.99	7
7	6	6	2.31	2.31	8
8	2	2	0.46	0.46	9
9	0	2	0.08	0.55	9
10	1	3	0.01	0.56	9
**	***	9	******	2.87	8

Degrees of Freedom	8	Mean (F/f)	1.61
CHISQ (0.050, 6)	12.590	Poisson Standard Deviation	1.7 percent
CHISQ (calculated)	102.745	Standard Error	2.0 percent

FIGURE 3

FIBER COUNTING HISTOGRAM FROM FILTER 11 DATA

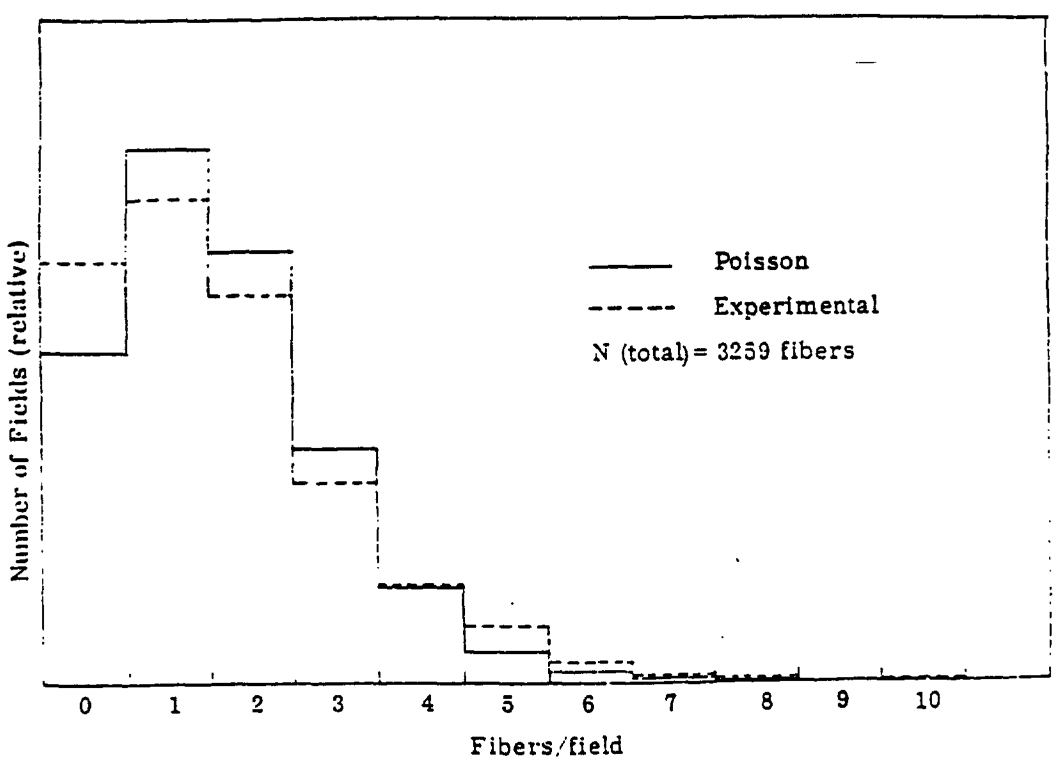

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TABLE 17

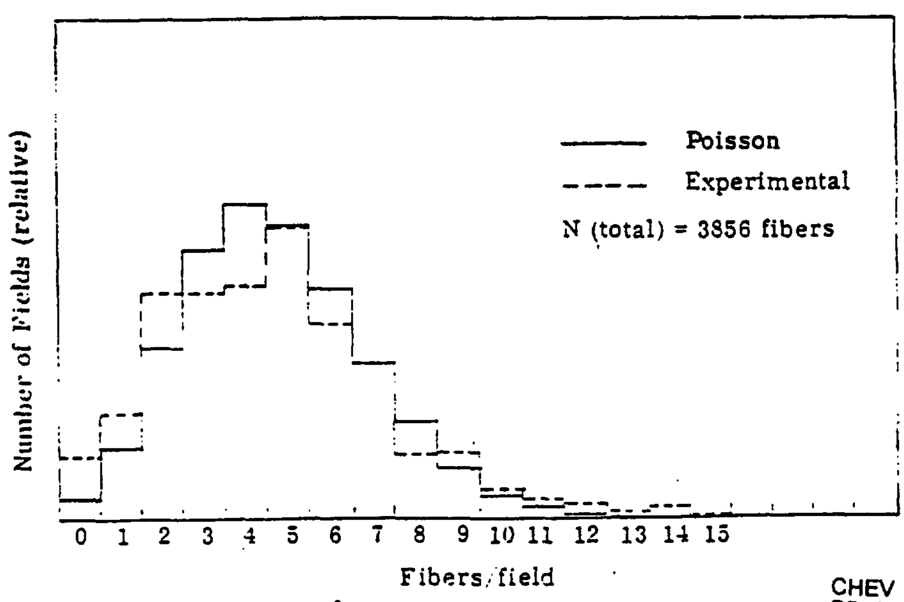
CHI SQUARE TEST OF SAMPLE 2C WHOLE FILTER DATA

Value	Experimental Frequency	Cumulative Frequency	Theoretical Frequency	Cumulative Theoretical	Category
0	30	30	7.43	7.43	1
1	48	48	34.98	34.98	2
2	107	107	82.25	82.25	3
3	107	107	128.94	128.94	4
4	110	110	151.58	151.58	5
5	140	140	142.56	142.56	6
6	93	93	111.73	111.73	7
7	76	76	75.05	75.05	8
8	32	32	44.11	44.11	9
9	38	38	23.05	23.05	10
10	14	14	10.84	10.84	11
11	10	10	4.63	4.63	12
12	7	17	1.81	6.45	12
13	2	2	0.65	0.65	13
14	5	7	0.22	0.87	13
15	1	8	0.06	0.94	13

Degrees of Freedom	13	Mean (F/f)	4.70
CHISQ (0.050, 11)	19.680	Poisson Standard Deviation	1.6 percent
CHISQ (Calculated)	182.777	Standard Error	1.9 percent

FIGURE 4

FIBER COUNTING HISTOGRAM FROM FILTER 2C DATA



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Linear regression analysis was performed on $\ln(s^2)$ vs $\ln(\overline{N})$ values obtained from the whole filter counting data. The values used are tabulated below in Table 18.

TABLE 18

VALUES USED FOR s^2 vs $\overline{N}$ REGRESSION ANALYSIS
(Model: $\ln(s^2) = m \ln(\overline{N}) + \alpha$)

Filter	$\overline{N}$	s^2	$\ln(\overline{N})$	$\ln(s^2)$
8	1.02	1.189	0.0198	0.1729
11	1.61	2.135	0.4762	0.7585
2C	4.70	7.231	1.5476	1.9789

The results of the analyses may be expressed in the form

$$\mathrm{Var}(\overline{N}) = 1.18\,\overline{N}^{(1.17 \pm 0.03)}$$

The value of the regression correlation coefficient is: 0.9996. The above relation may be compared with $\mathrm{Var}(\overline{N}) = \overline{N}$ which is applicable to the Poisson distribution. It is to be noted that this relation implies a minimum 16 fiber standard deviation in a 100 fiber OSHA count due mainly to the lack of uniformity of the fiber distribution and the method in which it is sampled.

It was planned originally to quantify the fiber distributions on the filters. Preliminary graphical treatment of the whole paper data, however, indicated that if the functional form of the distributions is desired the experiment should be replanned to include non-random sampling, many more observations, and the development of an appropriate model making use of the physics involved both in air flow and filter vibration. The necessity for this will become clear upon examining Figures 5-8. Each point in the figures represents an equal area average for the radial section indicated and the angular arc specified at the left. The horizontal "mean line" represents radial position with r = o at the left of the line. The position of a point is its average position within its area. The values under "N" are the extreme fibers/area encountered within the arc. Error bars are Poisson standard deviation estimates. Deviations from 360° for the whole filters are due to random errors in sectioning the filters and measuring the key coordinates on each section.

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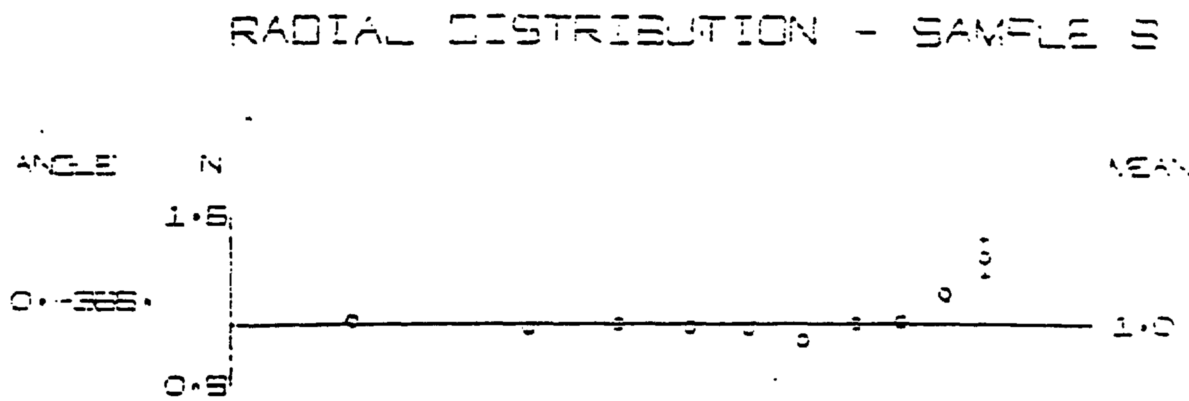
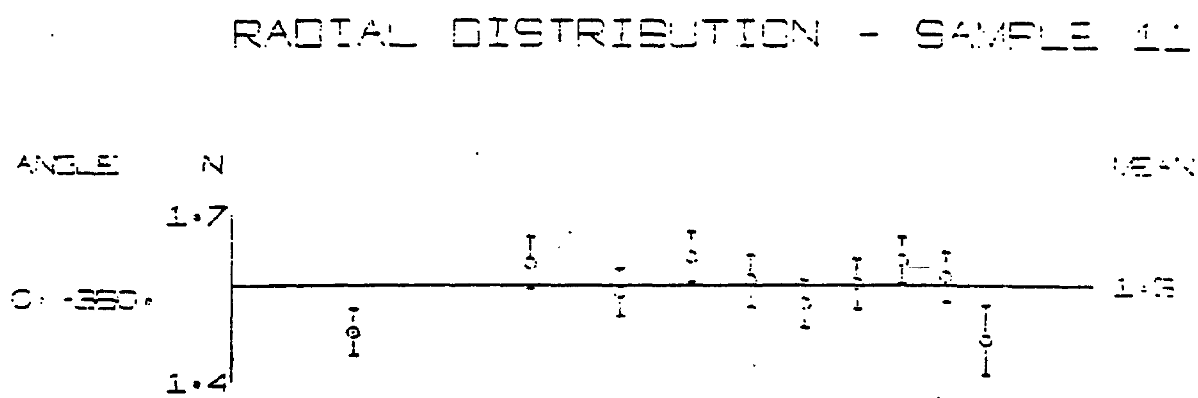
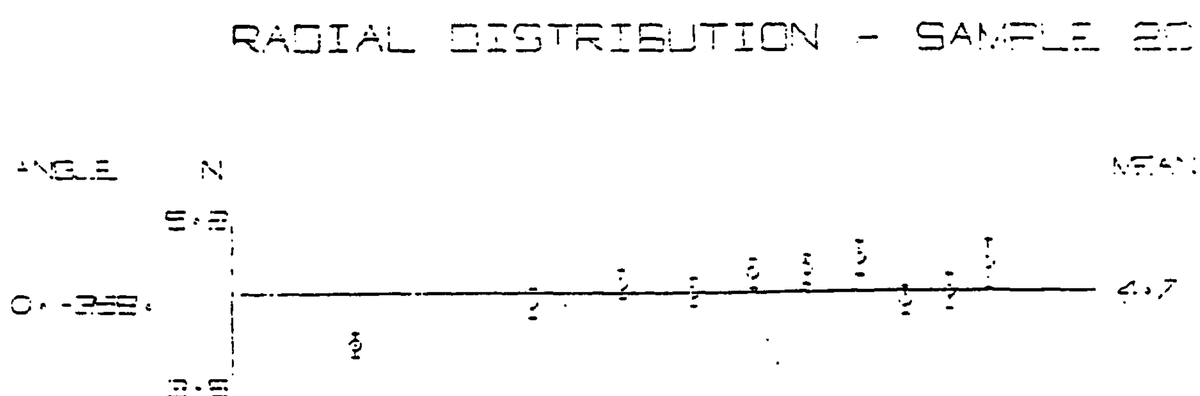
FIGURE 5

TOTAL FILTER AVERAGES







(Explanation of figure on page 20)

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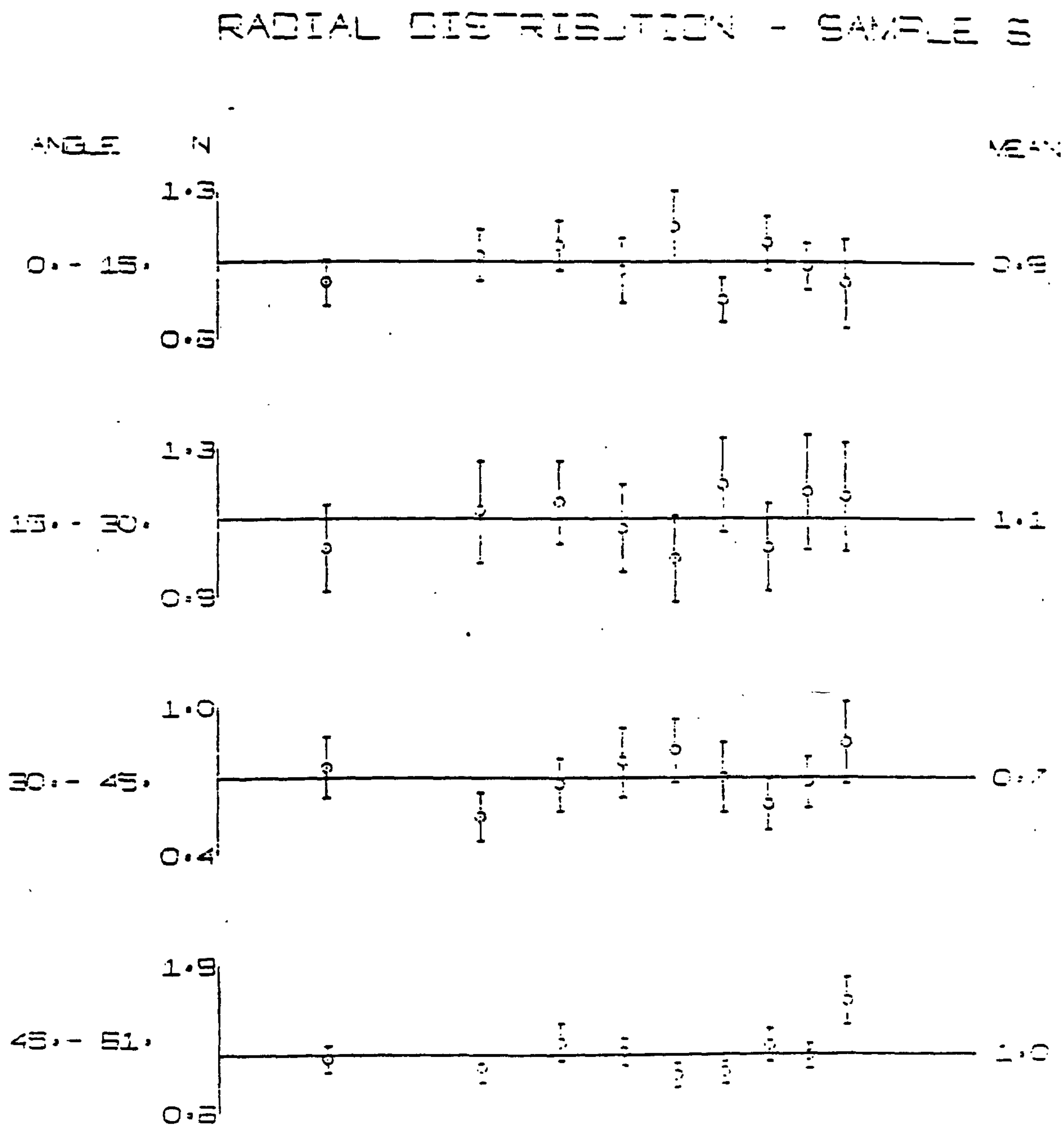
FIGURE 6

ANGULAR VARIATION OF RADIAL DISTRIBUTIONS



(Explanation of figure on page 20)

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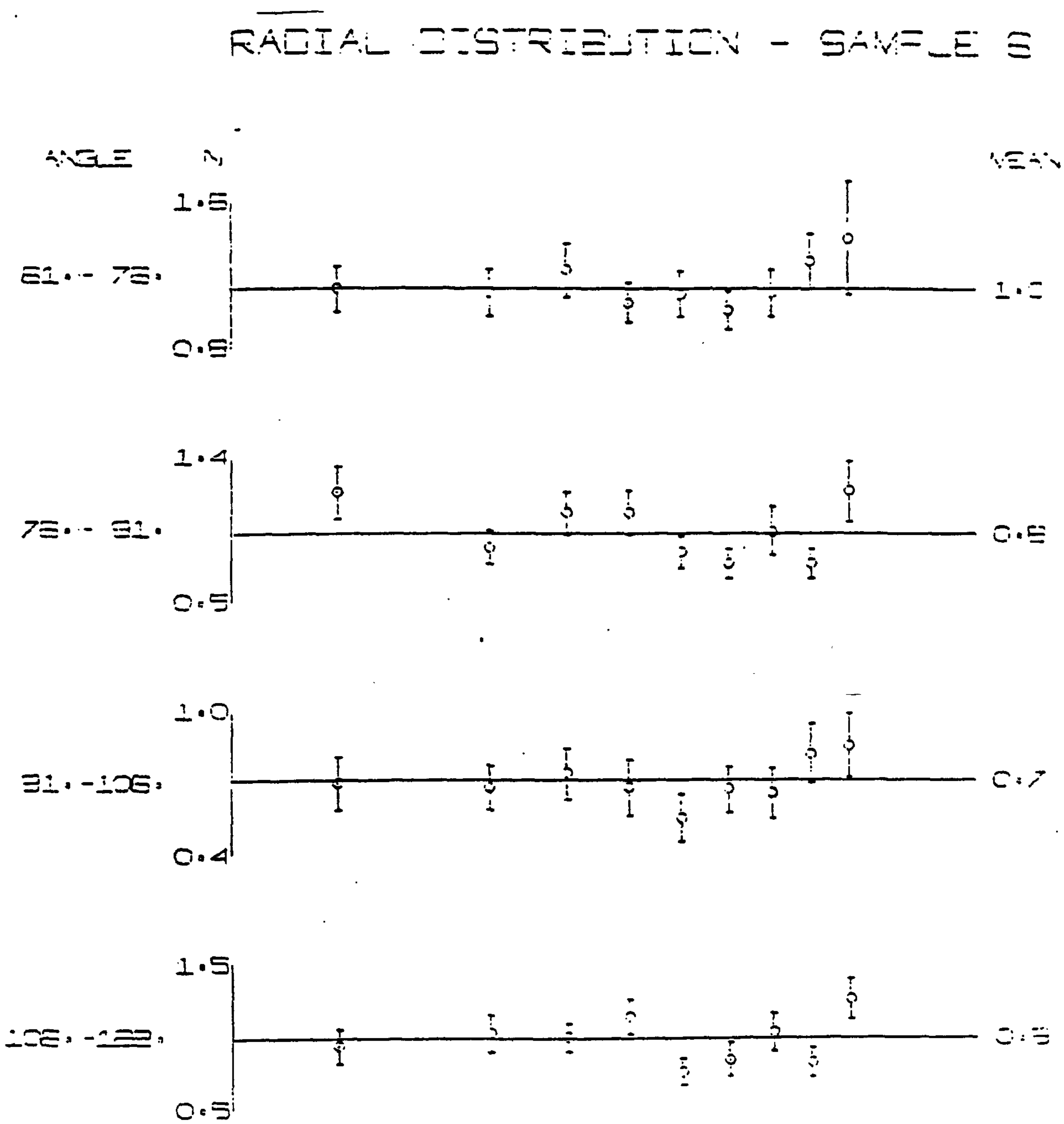

Figure 6 - Angular Variation of Radial Distributions (cont'd)

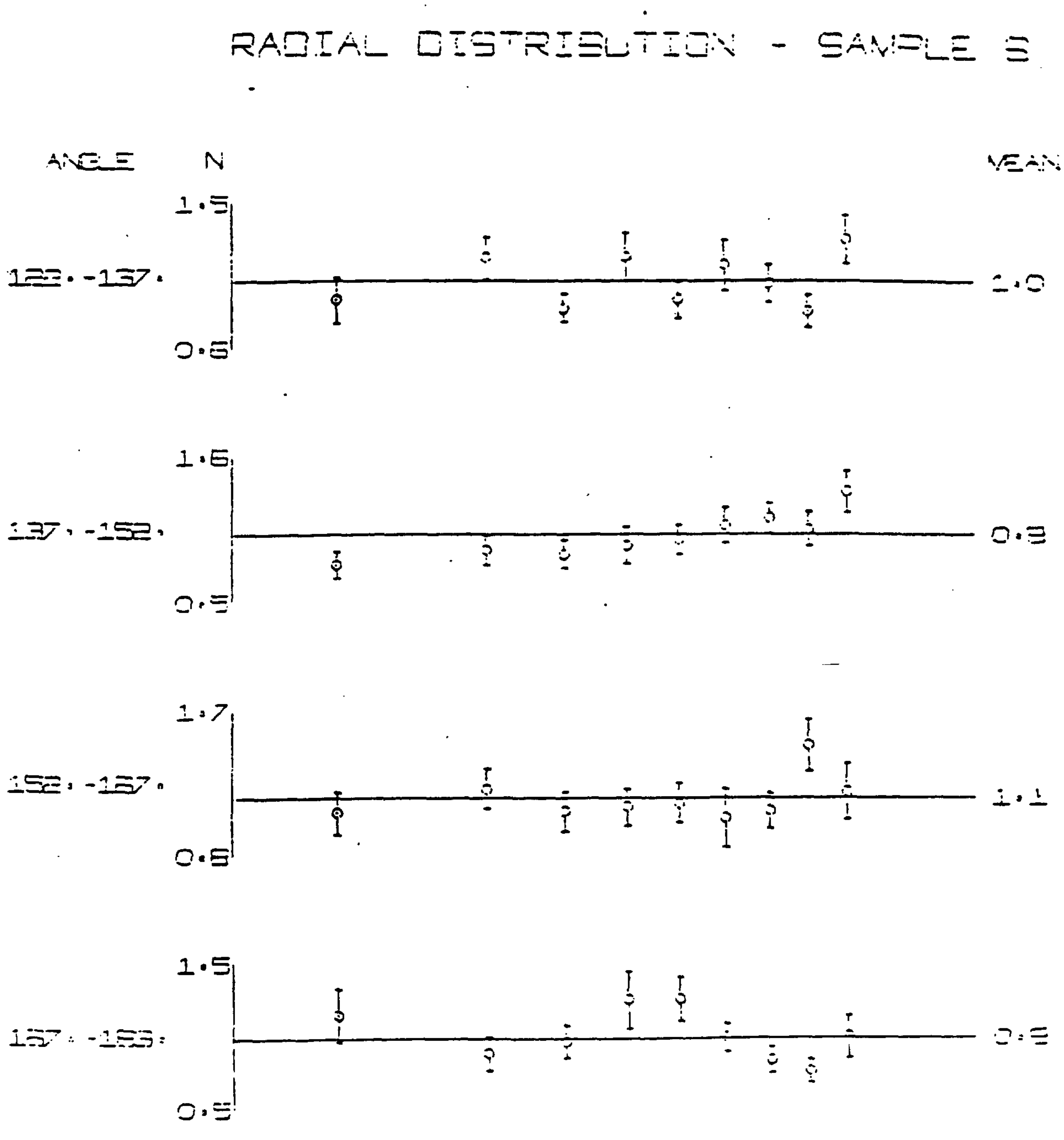

Figure 6 - Angular Variation of Radial Distributions (cont'd)

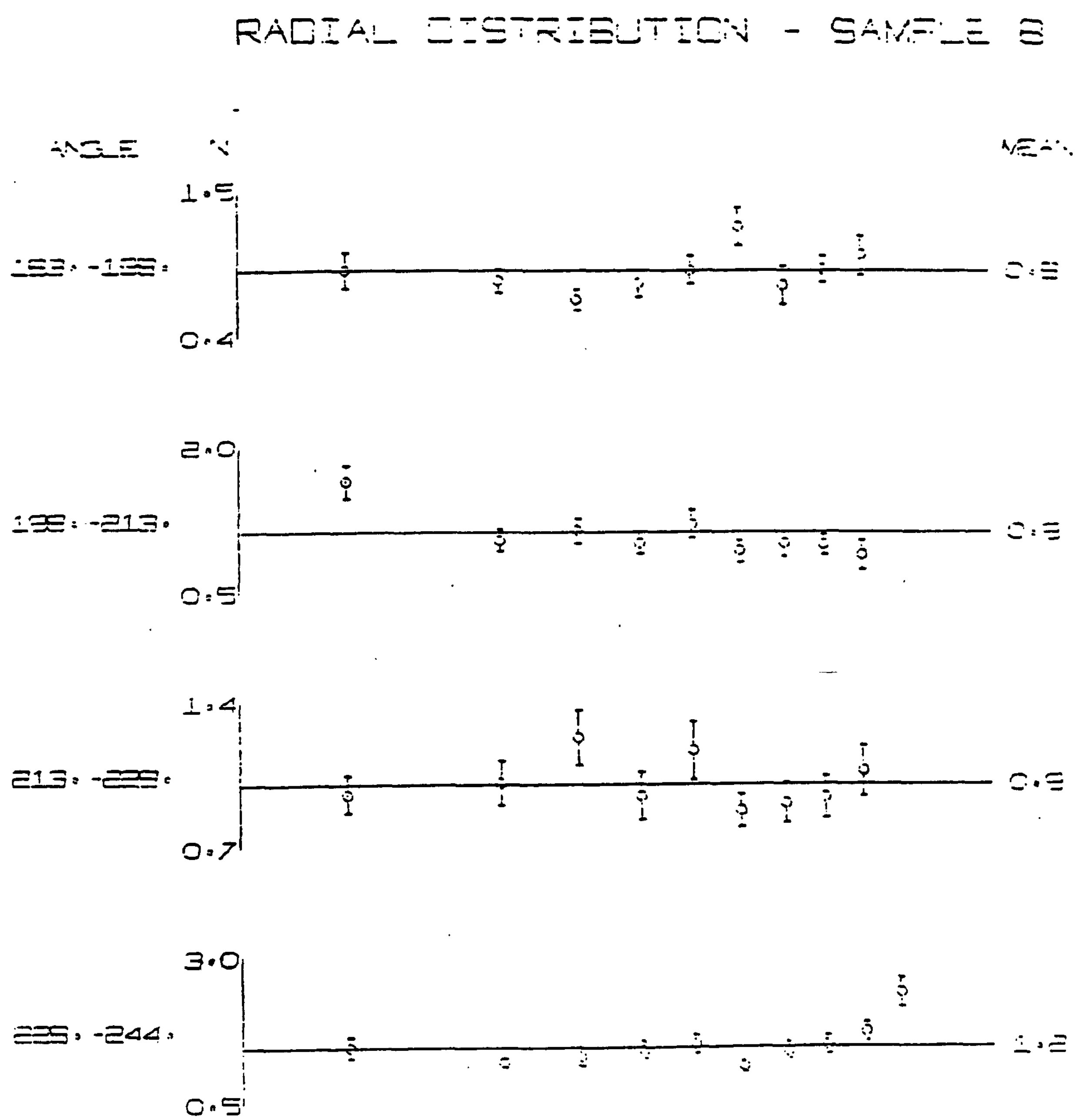

Figure 6 - Angular Variation of Radial Distributions (cont'd)

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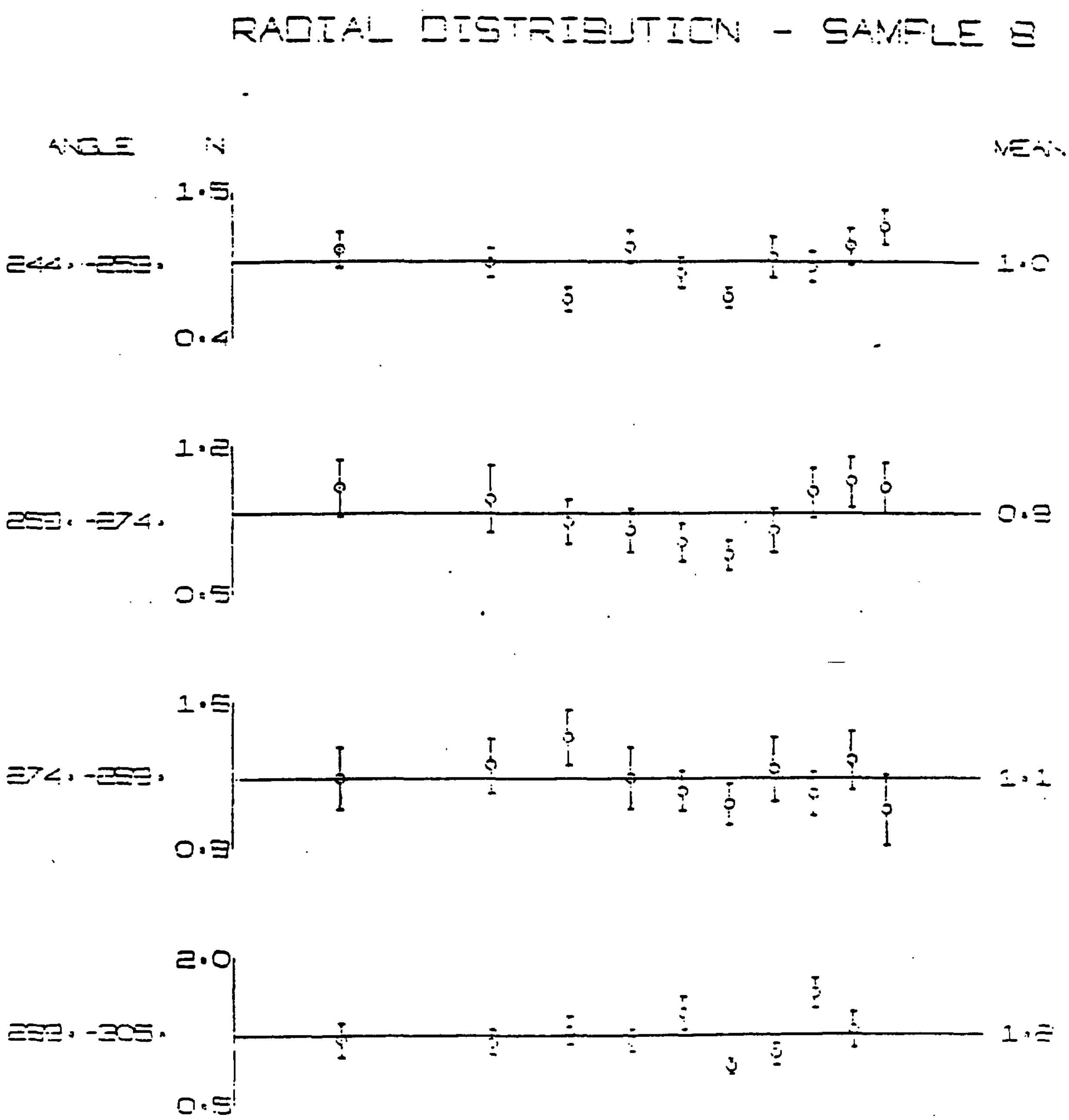

Figure 6 - Angular Variation of Radial Distributions (cont'd)

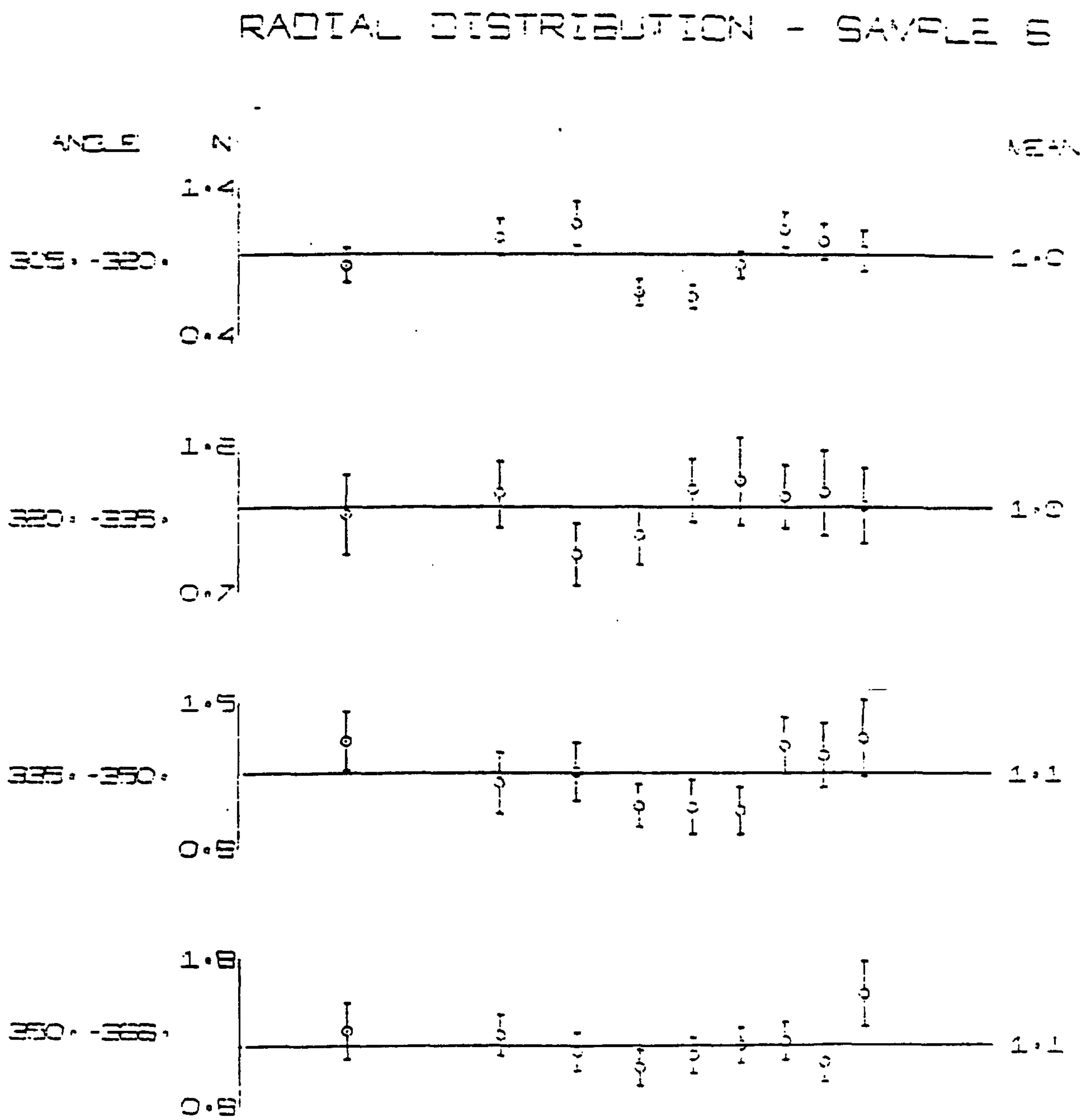

Figure 6 - Angular Variation of Radial Distributions (cont'd)

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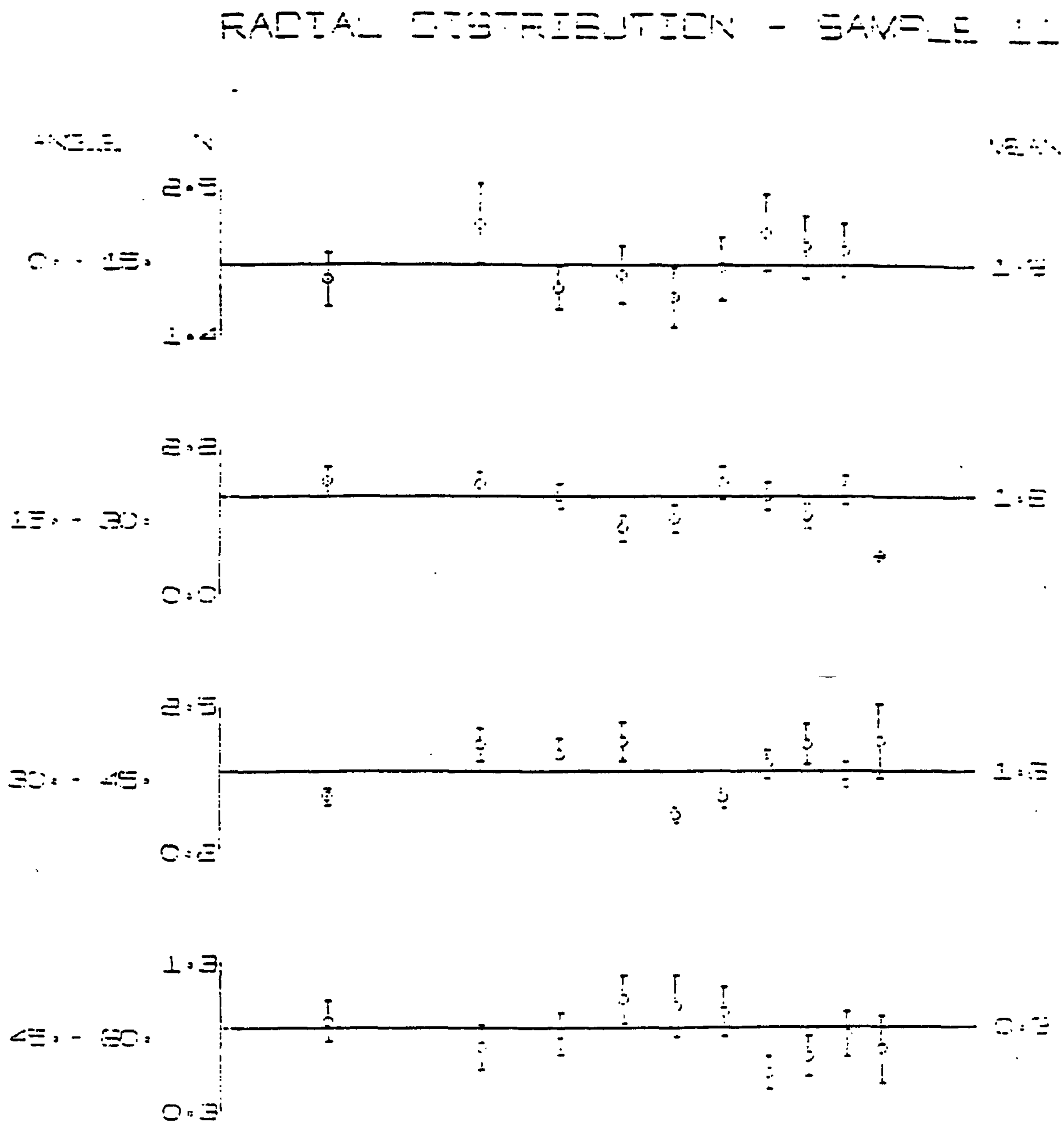
FIGURE 7

ANGULAR VARIATION OF RADIAL DISTRIBUTIONS



(Explanation of figure on page 20)

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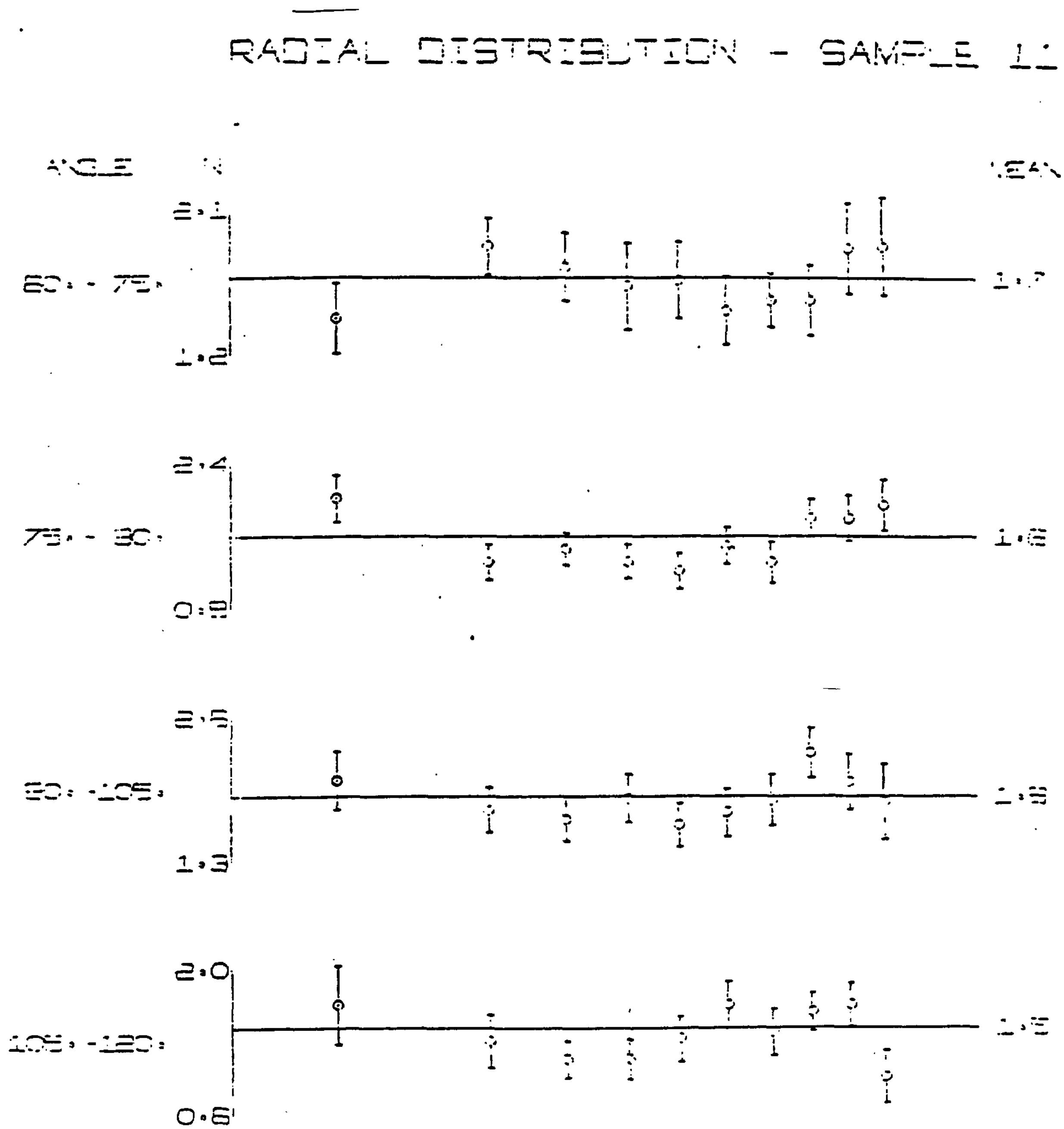

Figure 7 - Angular Variaition of Radial Distributions (cont'd)

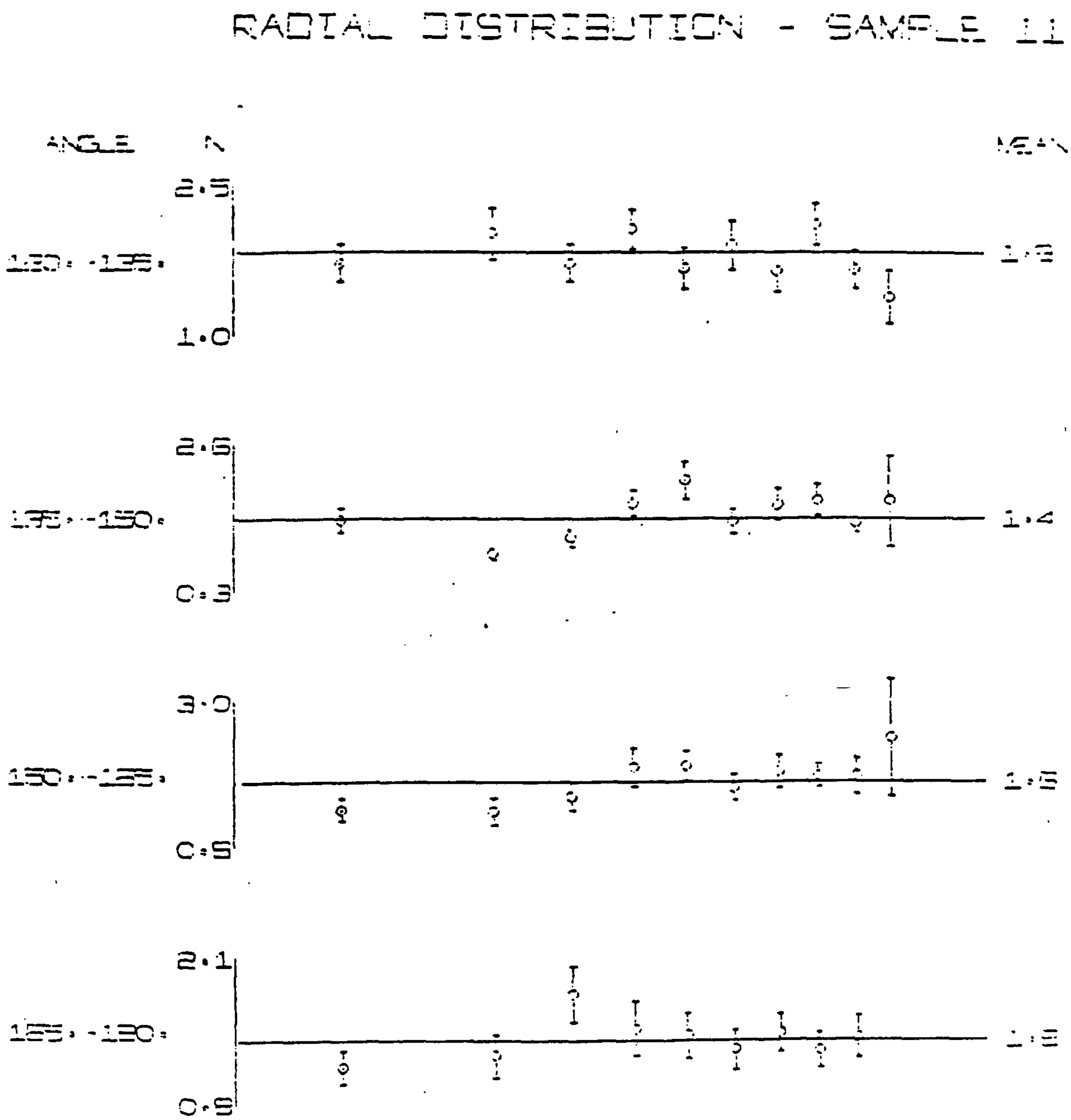

Figure 7 - Angular Variation of Radial Distributions (cont'd)

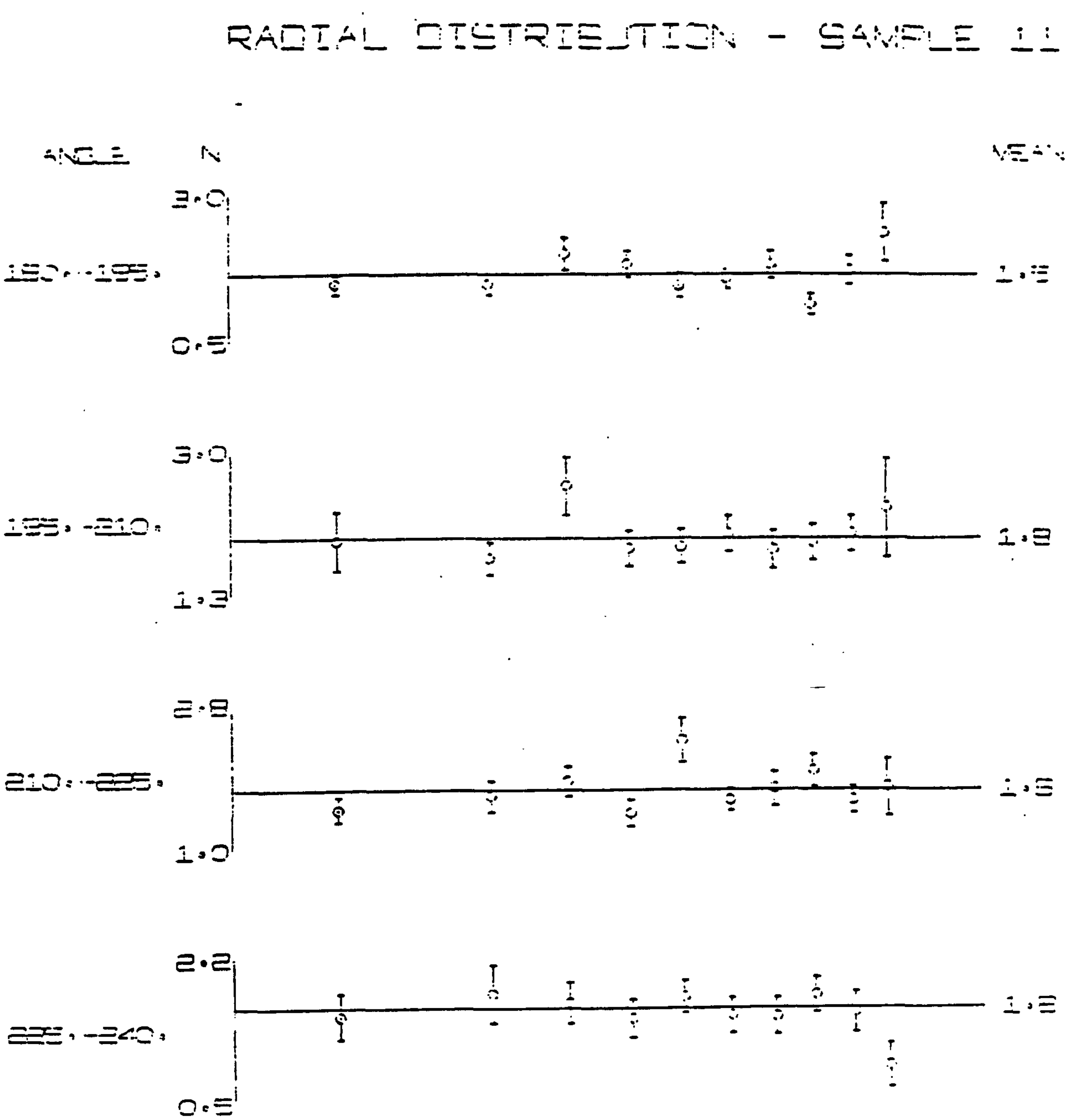

Figure 7 - Angular Variation of Radial Distributions (cont'd)

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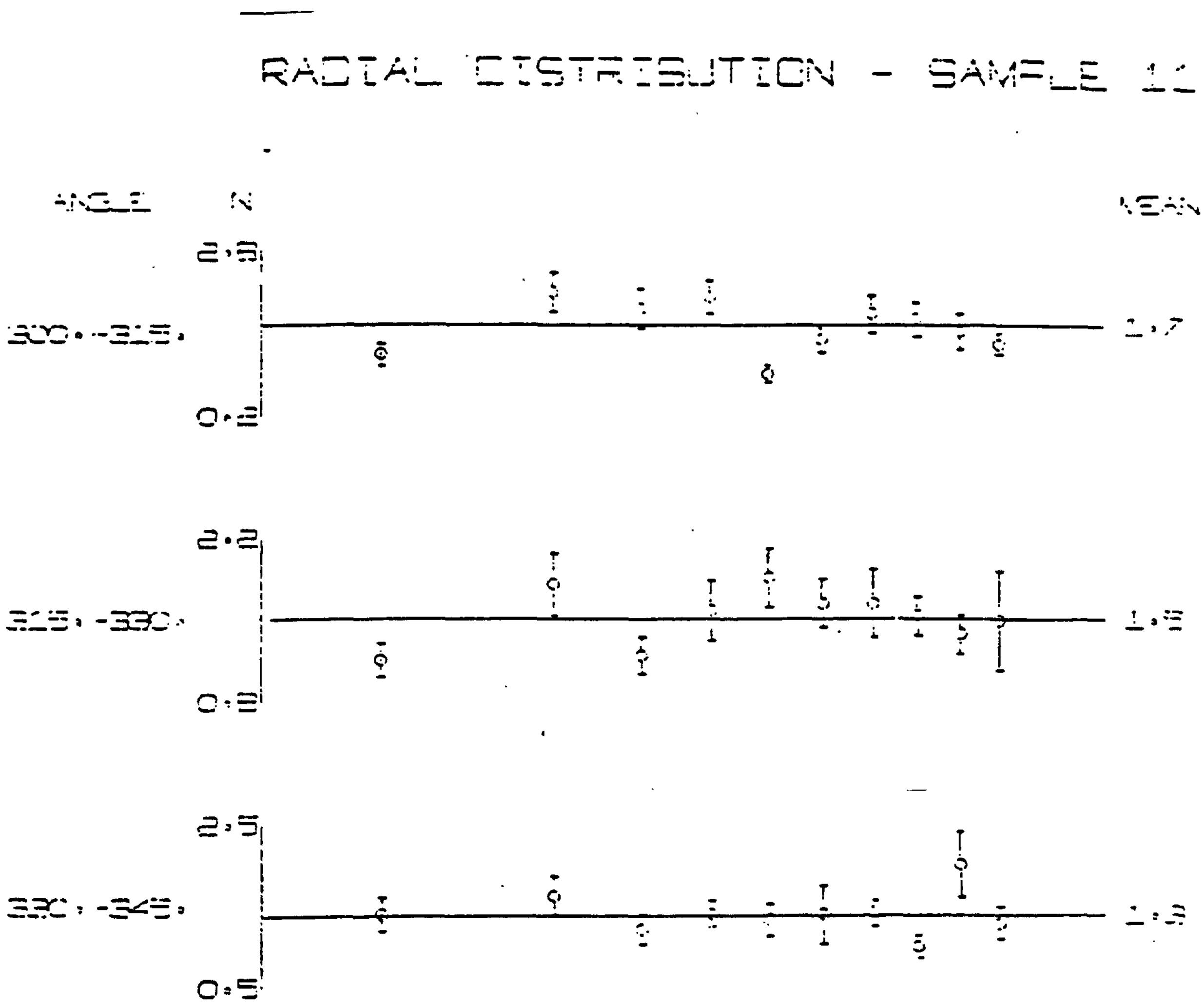

Figure 7 - Angular Variation of Radial Distributions (cont'd)

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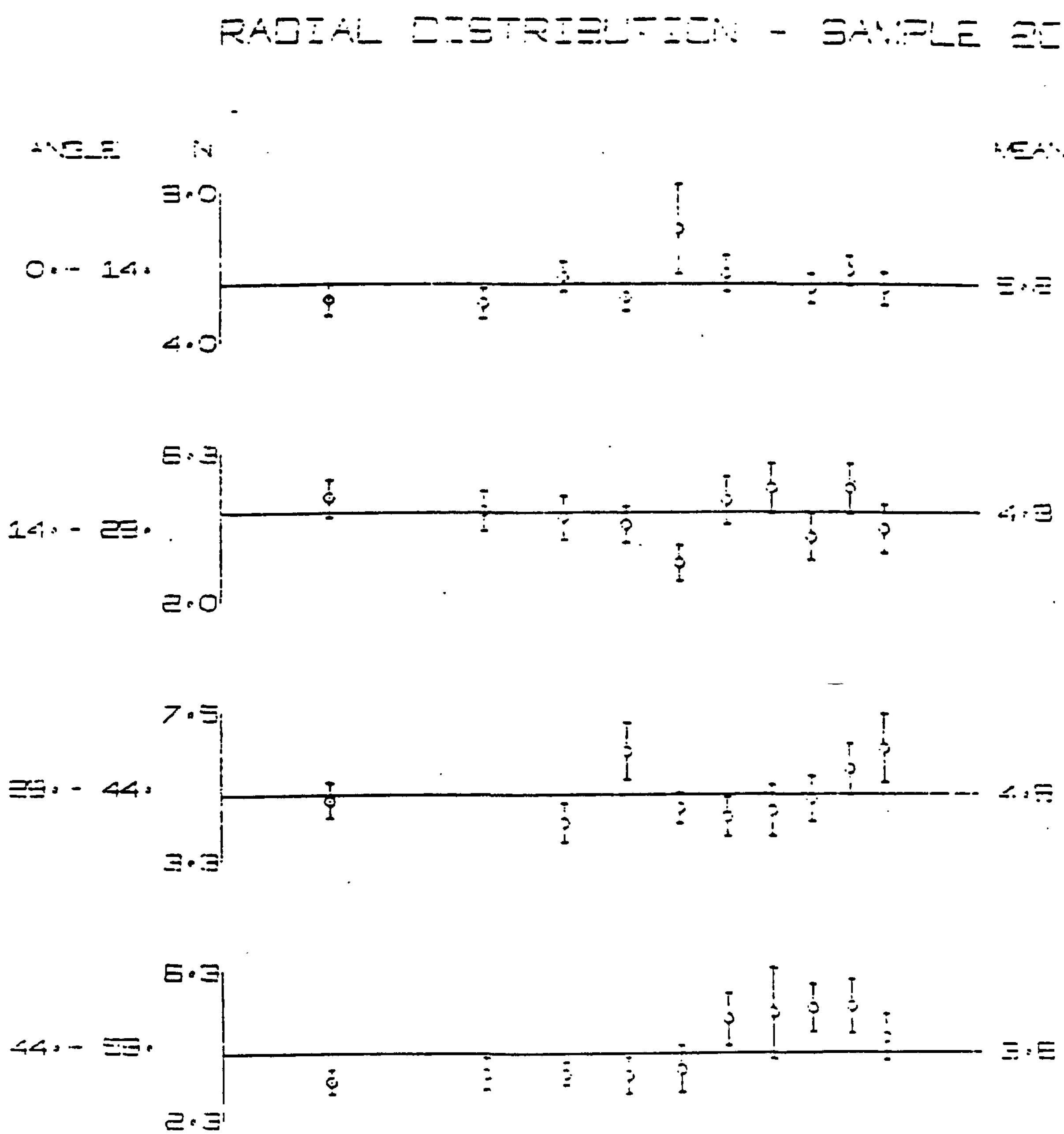
FIGURE 8

ANGULAR VARIATION OF RADIAL DISTRIBUTIONS



(Explanation of figure on page 20)

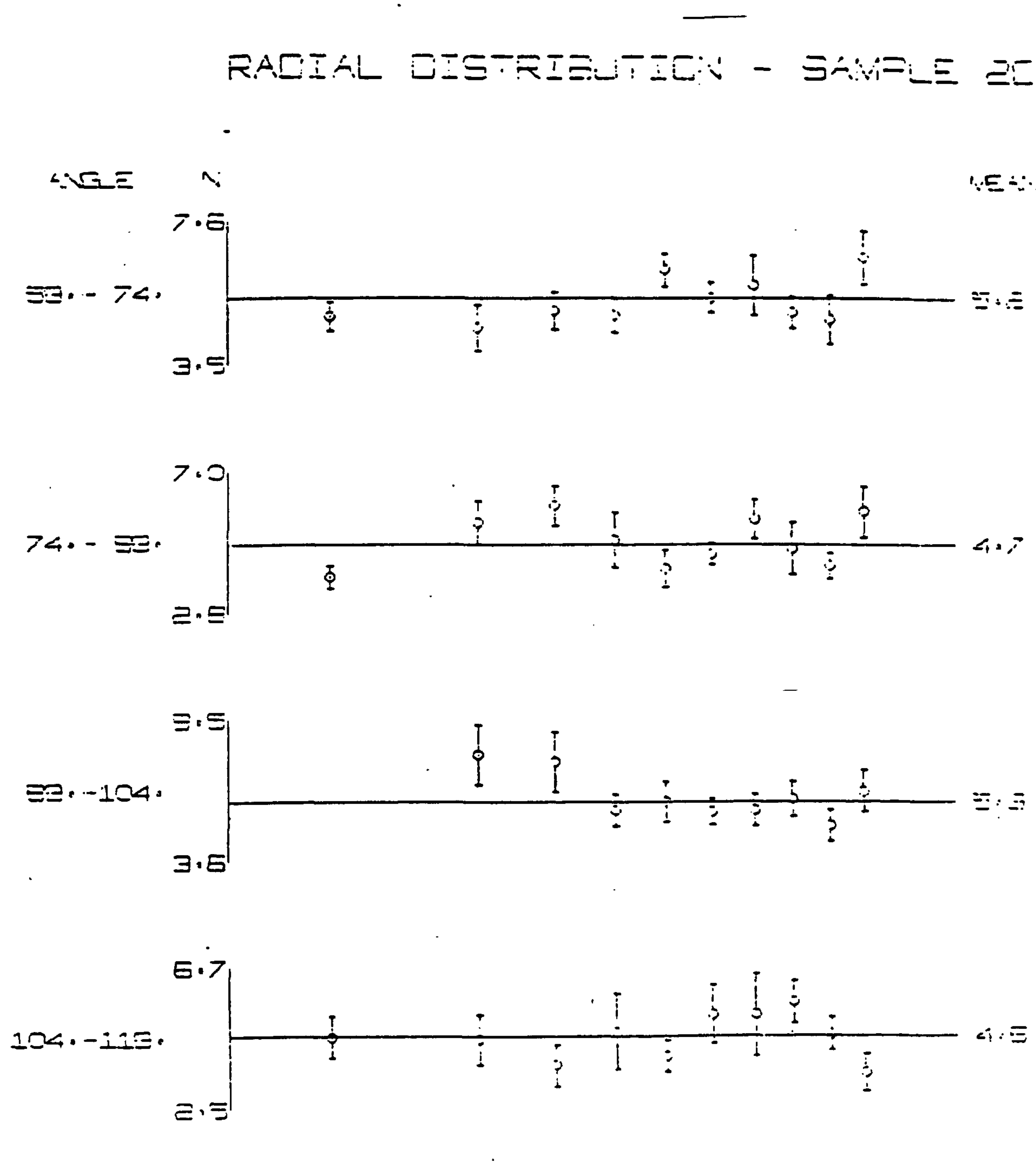


Figure 8 - Angular Variation of Radial Distributions (cont'd)

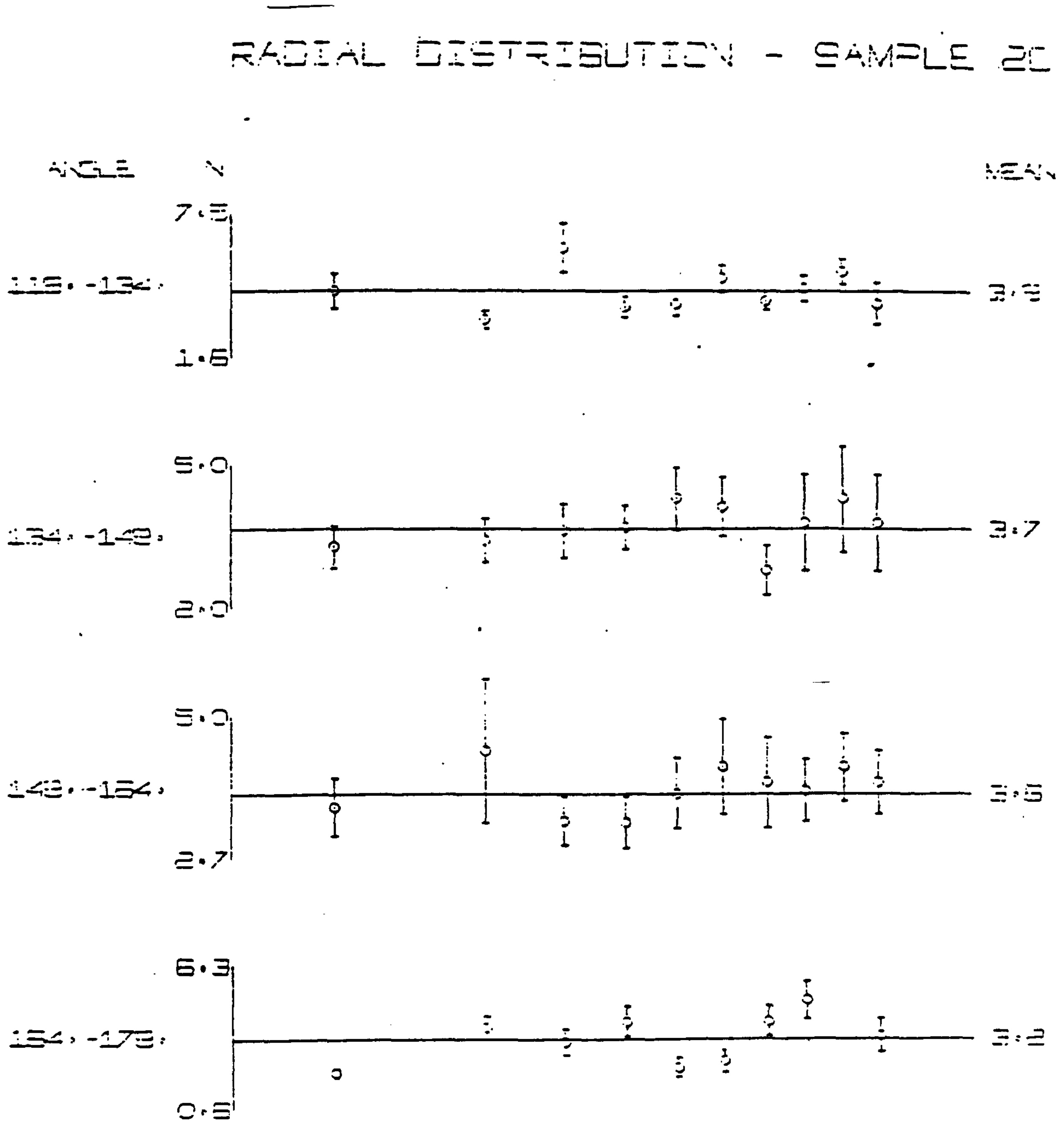


Figure 8 - Angular Variation of Radial Distributions (cont'd)

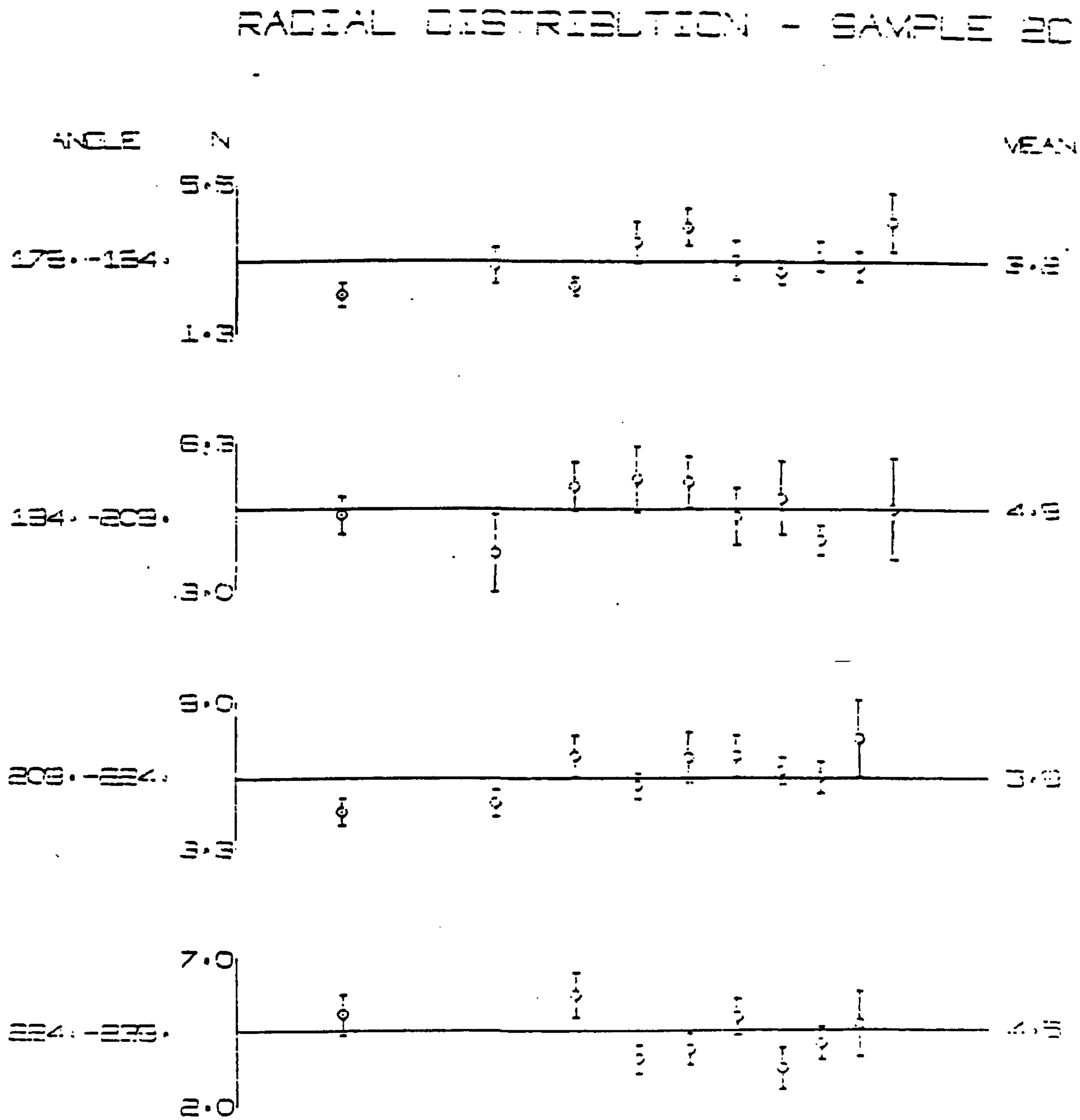


Figure 8 - Angular Variation of Radial Distributions (cont'd)

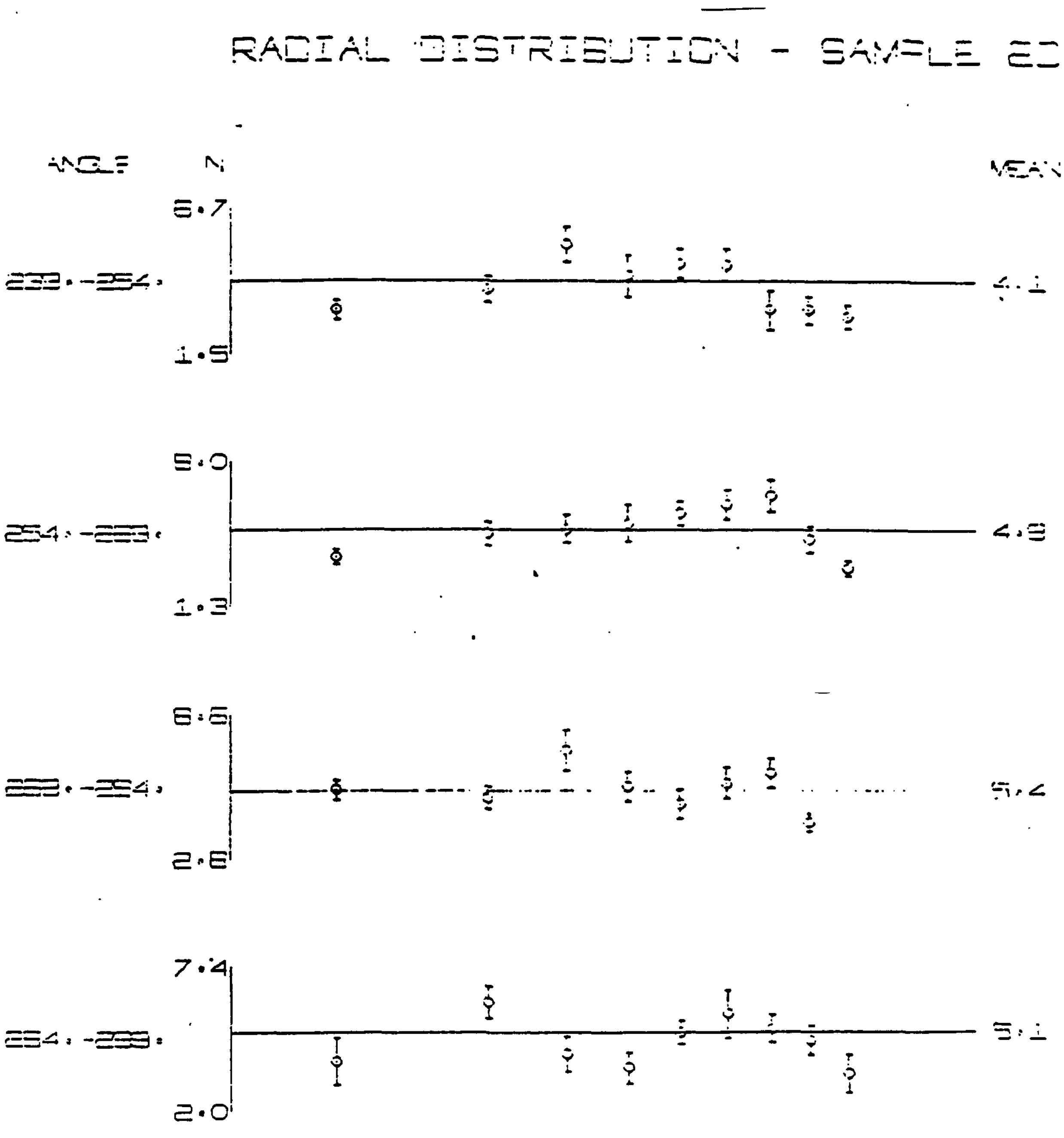


Figure 8 - Angular Variation of Radial Distributions (cont'd)

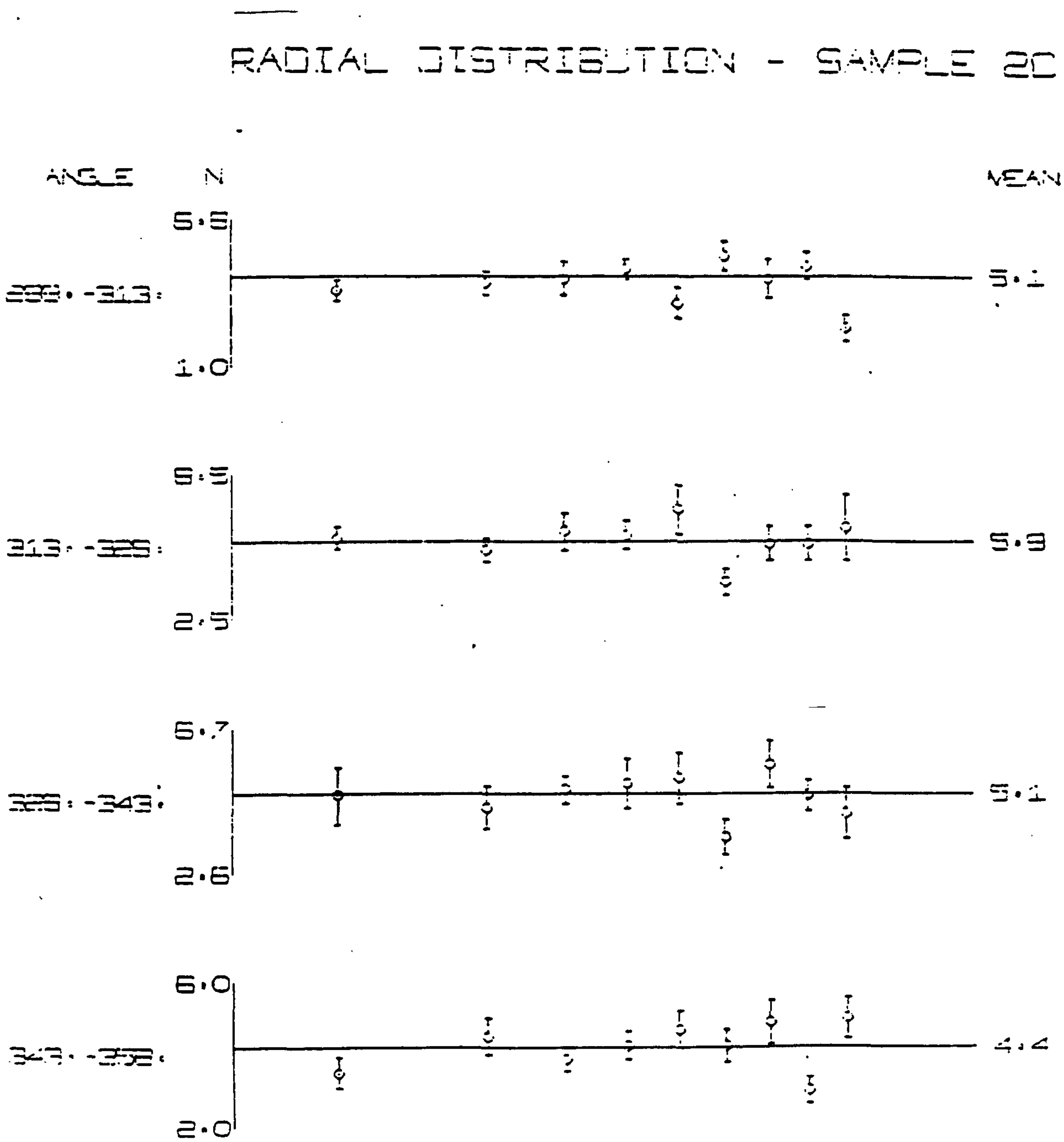


Figure 8 - Angular Variation of Radial Distributions (cont'd)

It is clear from each figure that most of the sub-populations associated with each area overlap but that there are systematic variations, not only for the filters as a whole (Figure 4), but within angular sectors as well (Figures 5-7). Numerical data relating to Figures 5-7 are summarized in Tables 19-21. Standard error estimates are included with each sector mean F/f.

TABLE 19

SECTOR MEAN FIBERS/FIELD (FILTER 8)

Sector (°)	Fields	Mean ± $s_{\bar{x}}$	Sector (°)	Fields	Mean ± $s_{\bar{x}}$
0-15	148	0.98±0.08	183-198	154	0.85±0.08
15-30	157	1.15±0.08	198-213	124	0.96±0.09
30-45	148	0.74±0.07	213-228	170	0.97±0.08
45-61	161	1.02±0.08	228-244	145	1.21±0.11
61-76	174	1.09±0.08	244-259	155	1.03±0.07
76-91	130	0.88±0.10	259-274	148	0.95±0.09
91-106	149	0.77±0.07	274-289	148	1.17±0.09
106-122	164	0.98±0.07	289-305	157	1.20±0.10
122-137	151	1.03±0.08	305-320	152	1.02±0.09
137-152	153	0.99±0.08	320-335	148	1.06±0.08
152-167*	171	1.10±0.07	335-350	146	1.17±0.09
167-183	133	0.98±0.09	350-366	166	1.16±0.09

*Body mark indicator

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TABLE 20

SECTOR MEAN FIBERS/FIELD (FILTER 11)

Sector (°)	Fields	Mean ± $s_{\bar{x}}$	Sector (°)	Fields	Mean ± $s_{\bar{x}}$
0-15	83	1.93±0.15	180-195	80	1.56±0.17
15-30	99	1.80±0.15	195-210	89	1.80±0.15
30-45	87	1.62±0.17	210-225	102	1.60±0.13
45-60	85	0.97±0.12	225-240	85	1.87±0.14
60-75	94	1.77±0.14	240-255	72	1.25±0.17
75-90	76	1.60±0.16	255-270	98	1.54±0.13
90-105	90	1.84±0.14	270-285	96	1.86±0.16
105-120	84	1.57±0.16	285-300*	89	1.43±0.13
120-135	95	1.97±0.16	300-315	71	1.78±0.19
135-150	98	1.45±0.14	315-330	83	1.51±0.13
150-165	84	1.71±0.18	330-345	91	1.31±0.15
165-180	80	1.28±0.13			

*Body mark indicator

TABLE 21

SECTOR MEAN FIBERS/FIELD (FILTER 2C)

Sector (°)	Fields	Mean ± $s_{\bar{x}}$	Sector (°)	Fields	Mean ± $s_{\bar{x}}$
0-14	39	5.25±0.42	179-194	41	3.21±0.31
14-29	31	4.96±0.33	194-209	35	5.00±0.43
29-44	30	4.90±0.52	209-224	32	5.96±0.50
44-59	37	3.83±0.48	224-239	21	4.57±0.63
59-74	43	5.20±0.41	239-254	28	4.10±0.46
74-89	46	4.76±0.39	254-269	33	5.00±0.45
89-104	31	5.35±0.46	269-284	39	5.43±0.53
104-119	26	4.69±0.36	284-299	29	5.10±0.59
119-134	34	3.97±0.38	299-313	38	5.13±0.37
134-149	27	3.74±0.41	313-328	32	5.90±0.51
149-164	33	3.63±0.33	328-343	36	5.11±0.36
164-179	28	3.28±0.55	343-358	50	4.44±0.42

The approximate 15° of each sector was chosen so that each sector would approximate an OSHA count fiber total. Some indicators of the overall fiber variability are presented below in Table 22. Range percents are calculated relative to the whole filter means given in Tables 15-17.

TABLE 22

WHOLE FILTER VARIATION INDICATORS

Filter	Sector Mean F/f			Sector Standard Error	
	Range	Dispersion	df	Mean	Range
8	46%	12%	23	8.6%	50%
11	62%	15%	22	9.7%	63%
2C	59%	16%	23	9.7%	100%

Percent values calculated relative to filter means.

When converted to the same total fiber count per sector, there are no significant differences between the mean standard errors for filters 11 and 2C and the within observations root mean square estimates determined by variance analysis and given in Tables 7 and 13. On the other hand, the extreme sector mean F/f values on all filters are significantly different; i.e., the mean F/f range percents presented in Table 22 are significant. The large range of standard errors are indicators of the variable fiber uniformity from sector to sector.

Accuracy of the OSHA Method

An estimate of the accuracy of the OSHA procedure may be obtained by assuming that all contributions to the total variance are additive. One can approach this from two directions; both assume an OSHA count of 100 fibers.

The first approach combines the results of the two factor variance analysis given in Table 13, which accounts for variation due to differences among counter, interaction, and the statistics involved in the counting of the fiber distribution on 1/8 of the total filter, with the mean F/f dispersion listed in Table 22, which accounts for variation over the entire filter. The result is a standard deviation estimate of 21.6%.

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The second approach is to make use of the result Var $(\overline{N}) = 1.18\ \overline{N}^{1.17}$, which accounts for variation due to the statistics of counting the fiber distribution over the entire filter for one counter, with the among observers and interaction components estimated from the data in Table 13, which account for the additional indicated variation. The result is a standard deviation estimate of 19.2%.

The F test for (21.6/19.2) = 1 is not significant using $F_{0.05}$ (125,9) = 2.97. Pooling the two variances results in a standard deviation estimate of 21.4%.

95% Confidence Interval on the OSHA Standard Error

Assuming that the standard deviation of the population of 100 fiber OSHA counts may be estimated by the within observations root mean square from Table 13, 95% confidence intervals on a given 100 fiber OSHA count standard error may be calculated from this estimate, the assumption that an "average" OSHA count contains 29 degrees of freedom, and the 0.975 percentile of the F distribution. Expressed as percents the result is:

$$12.7^{+4.8}_{-3.7}$$

In the same manner, the upper 99.5% confidence limit is 19.3%. This value may be used as an absolute rejection criterion.

CONCLUSIONS AND DISCUSSION

The following conclusions have been drawn from the data and analyses presented in this report.

1. The precision of the OSHA procedure for filters not containing an abundance of extremely fine fibers can be estimated by a standard deviation of 16.2%. This value includes variation among counters and observed interaction effects. The accuracy of the OSHA procedure for similar filters may be estimated by assuming that the contribution of the overall variance from the non-uniform fiber distribution is additive and making use of the data in Tables 13 and 22. For a 100 fiber OSHA count the result is a standard deviation of 21.4%. Ninty-five percent confidence intervals are most easily estimated as $\pm 2\sigma$ or about ± 43%. For filters with a large number of fine fibers, the 95% conf9dence intervals are about ±50%.

2. The means of experienced counters are significantly different. Contrasts between counters 1* or 2* and each of the inexperienced counters, not shown in Table 14 but easily calculable, indicate that experience as a fiber counter is not a significant parameter. It is, of course, important that the individual counter be familiar with the use of the microscope and understand thoroughly the counting ground rules.

3. Concentration interaction effects can be significant but are individual in nature and not related to experience. This effect may be due to the method of sampling. If real, however, it can cause significant error and its presence should be analyzed for as a routine quality control measure.

4. Filter 8 contained an abundance of extremely fine fibers. This is believed to account for the widened dispersion in OSHA means (Table 1). With the exception of counter 3* whose data was rejected, all variances are not significantly different from Poisson estimates, and it seems improbable that the filter 8 data dispersion is due to random fluctuations.

5. The distribution of the fibers on the filters is not uniform and the distribution of fiber counts is more disperse than Poisson. Regression analysis of the count data obtained on the whole filter suggests the relation

$$s(N) = 1.6 \sqrt{N}$$

is appropriate for estimating the minimum standard deviation in the OSHA procedure where N is approximately 100. The fiber concentration varies significantly between angular sectors on a given filter, varying as much as 50-60% of the estimated mean. There is also considerable variation in uniformity. These conditions appreciably limit the accuracy of the OSHA procedure.

6. Significant differences exist between the OSHA procedure means and estimates of the means based upon whole filter data as measured by counter 1*. It is felt that most of this variation is introduced through inappropriate data acquisition and mean calculation. Both the OSHA method and that used to count the entire filter samples area randomly and will give accurate mean estimates only if the distribution is uniform. Since this is not the case, the distribution must be sampled randomly or appropriate weighting factors used with random area sampling. Unfortunately, to do either, the distribution must first be determined. To do this for every filter is obviously impractical and the OSHA method must be lived with.

7. Regression of the data in Table 20 on the data in Table 19 relative to the body mark indicator did not result in a significant correlation It does not appear, therefore, that the positioning of the filter cassette on the wearer was a significant factor in determining the fiber distribution on the filters analyzed.

One thing which has not been mentioned and must be stressed is the following: All of the preceding statements apply only to the fiber concentration on the filters, not to the concentration of fibers per volume of air and then only to the filters which we analyzed. To apply to other filters one must assume that those filters analyzed are truely representative of all asbestos samples collected. To apply to the concentration in air, one must assume that all collection systems are accurately calibrated and not significantly different in operation than those used to collect the analyzed filters. These are not trivial points; the analyses are invalidated if the filters supplied are non-representative.

RECOMMENDATIONS

The following recommendations are made to improve the accuracy of the OSHA procedure and to provide additional necessary information relating to the problem of determining airborne asbestos concentrations.

1. Make certain that all fiber counters are properly trained. This is an obvious point but must be mentioned. In addition to being thoroughly familiar with the ground rules for counting and field selection and the use of the microscope, the counter must be made fully aware of the importance of not biasing data; that every number of fibers counted in a given field is the best number for that field. Much valuable information is lost by well-intentioned technicians trying to "look good". One of the experienced counters used for this investigation appears to have fallen into this trap.

2. While performing an OSHA count, insure that the entire radius is uniformly sampled, consistent with the requirement of remaining two fields of view inside any edge of the filter. This will eliminate any apparent concentration effect caused by the counter remaining in regions of relatively low or high concentration.

3. The following procedure is suggested as an aid to the rejection of non-representative data. It can be accomplished with a desk calculator in less than 15 minutes per sample.

a. Record individual field counts as a function of radial position when counting a filter.

b. From the recorded field counts calculate the standard error.

c. Note whether each individual measurement is larger or smaller than the mean by a "+" or "—". The occurrence of "+'s" and "—'s" should be randomly distributed along the radius, i.e., there should be no long series of one sign followed by a long series of the other or no obvious oscillation.

d. If the "+'s" and "—'s" do not look random and the standard error is larger than 0.175 times the mean reject the sample as being non-representative.

e. If the standard error is larger than 0.193 times the mean reject the sample as being non-representative.

4. It is recommended that counters 1*, 2*, 4, 5, and 6 be tested for visual acuity to determine the presence or absence of a significant correlation. It appears that this additional analytical effort is important since the dispersion of Filter 8's data is 21% whereas the dispersions of Filter 11 and $\overline{2}$C's data are only 10% and 8%, respectively.

5. The variation of fiber concentrations over individual filters should be evaluated for filters exposed with the Bendix personal pump.

6. The variation of fiber concentrations over individual filters should be evaluated for the MSA personal pump with a vibration damper.

7. An intercalibration study should be performed to determine variations of counting results among AIA/NA members.

8. The European and Asian techniques for analyzing asbestos fibers should be compared with ours.