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DIGITAL COMPUTER ANALYSIS OF PARTICLE SIZE DISTRIBUTION IN DUSTS AND POWDERS

George A. Klingler

Aerospace Research Laboratories
Wright-Patterson Air Force Base, Ohio

August 1972

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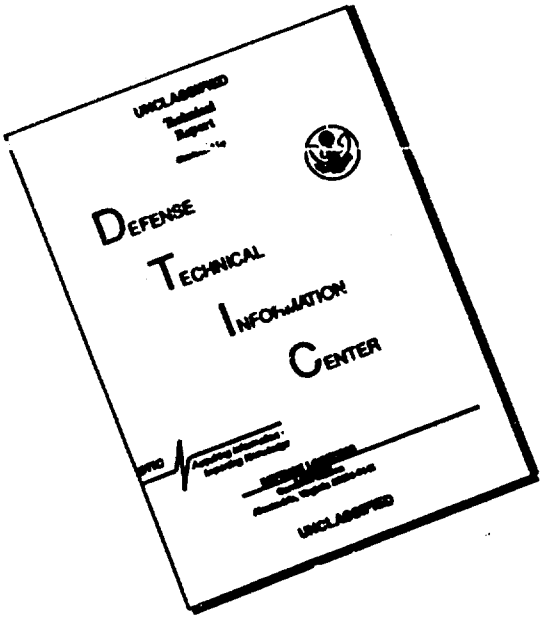

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ENERGY CONVERSION RESEARCH LABORATORY

PROJECT 7116

AIR FORCE SYSTEMS COMMAND
United States Air Force

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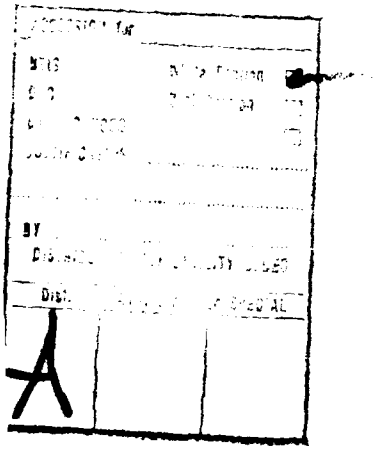

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13. ABSTRACT

Particle size distribution measurements of a variety of materials over a range from 0.1 to 150 microns are presented. Computer data analysis provides plots of the cumulative weight-size distribution and the mass frequency distribution. The size range covered was accomplished by two sedimentation methods both yielding the Stokesian diameter. Centrifugal photosedimentation was used for fine particles and gravity sedimentation for coarse particles. The useful range of particle concentrations in dispersions for conducting repeatable measurements was determined for both methods of sedimentation. Results of supplementary investigations by microscope on the particle shape of the materials analyzed and other pertinent data are listed in the appendix.

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14 KEY WORDS	LINK A		LINK B		LINK C	
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Cumulative Distribution Function						
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Dust and Powder Characteristics						
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Homogeneous Suspensions						
Layer Suspensions						
Mass Concentration of Suspensions						
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Streaming in Suspensions						
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AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

I-C

FOREWORD

This report represents experimental investigations of particle characteristics carried out as a part of the multi-component flow research program in the Energy Conversion Research Laboratory under Project 7116, entitled "Energy Conversion Research".

The report covers work performed during the period from 1 June 1970 to 30 May 1972. Under the same project, ARL Report 71-0134 was issued describing methods and techniques of particle size analysis by sedimentation.

Acknowledgement is made to J. William Snelnutt, Capt, USAF, who was instrumental in initiating the sedimentation program, and who wrote the computer programs prior to his separation from service in June 1971.

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I. INTRODUCTION

Particle size analysis by sedimentation is a form of data acquisition that allows derivation of the particle size distribution on a mass or number basis. Both data collection and determination of the size distribution from the raw data is ordinarily tedious and very time consuming. However, data acquisition can be automated and computation time considerably shortened by use of computers. Application of computers in particle analysis work basically requires only some changes in the routine of data acquisition in order to utilize computer programs effectively. Once this is realized, computer data reduction can increase the scope of particle size analysis tremendously. The results of experiments which are the subject of this report were obtained by computer analysis.

The particle size distributions reported here were the result of investigations made on dusts and powders in support of ARL's in-house research program in multicomponent flow with emphasis on research relevant to the colloid core reactor (Ref. 1). The experiments in the particle size analysis program were carried out on a sedimentation balance and a photosedimentometer.

Concurrently with these experiments in an effort to expedite data reduction, computer programs were developed for both methods of sedimentation and were the subject of an

earlier report (Ref. 2). These programs, after minor changes to afford flexibility, were used in analysis of the present data.

In Section II, results of experiments on the sedimentation balance are presented followed by Section III showing results of experiments on the photosedimentometer carried out with and without a buffer layer. The appendices contain listings of factual data on each experiment and other pertinent information regarding the materials analyzed.

II. EXPERIMENTS CONDUCTED ON THE SEDIMENTATION BALANCE

Investigations of particle characteristics were initially started in conjunction with experimental investigations of particle-gas behavior in flows and studies of erosion associated with particle laden flows (Ref. 3). The particle size of the materials used in these studies falls within the capabilities of the two instruments used in the present particle size analysis effort (Ref. 4). However, in most experiments coarse powders were used and emphasis was put on finding out more about the influence of the larger size particles on the flow behavior and their abrasive effect on walls containing the flow. For these reasons and because of the size range of some of the powder materials used and the somewhat better utility of the Cahn balance in its range, more experiments were conducted on the Cahn sedimentation balance. Since the methods used in these experiments were already reported elsewhere (Ref. 2), only additional information is presented. This information is supplemented by explanations regarding particular aspects of the investigations and comments on the results of the experiments.

Prior to sedimentation experiments on a particular powder, tests using a microscope were made to determine the particle shape and in particular to find the approximate particle size range of the material to be analyzed. These preliminary

investigations were supplemented by tests to determine the proper wetting agent and sedimentation fluid. In the data analysis, the weight of the sample actually in suspension in the sedimentation column at the onset of the experiment is used. At times this weight may be different from the weight used in preparing the basic dispersion. Weight differences may be due to a combination of factors and may depend upon the material to be analyzed, the amount of fluid used, the way the dispersion is introduced into the column and other experimental factors, and essentially will affect the accuracy and quality of the final results.

In all experiments made on the Cahn Unit the sedimentation fluid was replaced after each experiment. In most experiments the powder material initially dispersed in the sedimentation fluid was recovered after settling. Usually the material accumulated on the collecting pan was recovered. In many cases for complete recovery, the powder that had settled on the bottom of the sedimentation bath was also recovered after sufficient settling time or, when necessary, after prolonged settling in an auxiliary vessel.

Since the sedimentation cylinder was provided with a mechanism affording a positive seal between cylinder and collecting pan, the difference between the initial weight in suspension and the weight of the sediment recovered from the collecting pan represents

the weight fraction of material still in suspension. A portion of this weight fraction, however, may have escaped into the bath surrounding the settling column by diffusion, hence a fractional recovery of this portion can be made from the bottom of the bath.

Strong diffusion was only observed in the exploratory experiments conducted on boron powder. However, after completion of a powder recovery effort made on boron as received it was found that only 3.6% of the mass initially in suspension was lost, e.g., was still in suspension after 72 hours of settling at the time the experiment was terminated and the weight of the sediment was determined.

In conducting weight recoveries great care must be exercised in manipulating the bath and in particular the collecting pan in order to succeed not only in a nearly complete powder recovery, but at the same time assure accuracy of the individual weight fractions recovered comprising the sediment. Essentially the same care is necessary in conducting routine particle size distribution measurements in order to come up with meaningful results.

In the procedure adapted for weight recovery the flow rate was such that it took approximately two hours to syphon off the liquid from the bath to the level below the collecting pan. The pan was then carefully removed and the powder washed

from the pan and collected in a beaker where it was further diluted and left to settle again. After the powder had settled out, the liquid was syphoned off to a level where syphoning would not disturb the sediment. The beaker was then put in an oven and the remaining water evaporated and the weight of the sediment determined by weighing the beaker first with the powder and then without. The powder recovery from the bottom of the bath was carried out in a similar fashion. In the experiments where glycerin-water sedimentation fluid was used, larger beakers were used in order to reduce the amount of glycerin associated with the sediment to a level that would have little or negligible affect on the weight of the sediment.

In all the powder recoveries made, discrepancies were only found for 0.5 - 5 micron zinc powder and titanium metal powder. For zinc the discrepancy was small, but the titanium powder appeared to be still strongly associated with glycerin after being highly diluted and washed in distilled water and the weight recovered was far in excess of the weight initially in suspension. The mass concentration in the sedimentation column in these experiments ranged from approximately 2×10^{-4} gm/cc to 2×10^{-3} gm/cc.

The results of experiments conducted on the sedimentation balance illustrating this section of the report are self-explanatory. In most cases the data was obtained from fresh samples

and the particle size distribution is representative of the bulk. Others represent samples obtained in conjunction with flow experiments and indicate changes in the distribution brought about by specific tests. Some experiments were repeated in order to find out how well the measurements could be duplicated. In some measurements the initial weight in suspension was changed in repeated measurements to find the conditions under which consistent measurements could be obtained and to get an idea on the limitations of both the instrument and methods.

Evaluation of the experiments conducted indicates, and the data presented here bears this out, that over the useful range of the instrument, and for the range of concentrations used in the dispersions, particle size distributions are obtained that are fairly representative of the samples analyzed. While this is true in general, a critical examination of the results may, at times, reveal differences between repetitive runs in particular if the experimental conditions are not kept exactly the same. Experiments carried out on the same powder under different settling conditions are shown in Figs. 35-38. These experiments are the results of consecutive runs conducted on aluminum oxide powder. Disregarding the differences in mass concentration as the cause of the discrepancy, the difference in the size frequency distribution indicated in

these two measurements may well be due to the irregular chip-like particle shape of the aluminum oxide powder in conjunction with settling conditions brought on by the sedimentation fluid, which was distilled water in the former and glycerin-water in the latter, both with Liqui-Nox as a wetting agent.

When materials of unknown size range were to be analyzed or when the approximate size distribution could not easily be assessed by microscope because of agglomeration or the fineness of the powder, exploratory runs were conducted. These runs gave a good indication of the size distribution on the basis of which more accurate experiments were subsequently conducted on the photosedimentometer. When the size range was not completely covered by an analysis, as for example for fine Arizona road dust and boron powder as shown in Figures 39-46, additional or supplementary experiments were conducted on the photosedimentometer in order to obtain a better or more complete particle analysis.

Although exploratory runs made on Arizona dust and boron produced repeatable results, the Cahn Unit favored the larger particle size for both materials when compared with results obtained by the photosedimentometer for the same powder and dust. This indicates that repeatability by itself is no assurance for correctness of measurements. For boron this was

to be expected, but the reason for the discrepancy for fine Arizona dust is not known. The discrepancy may be due to a combination of factors since a large fraction of fines of Arizona dust is in the area of the lower size limit of the Cahn Unit and the settling in this region may be strongly affected by the mass frequency distribution of the dust because of the long settling times involved. On the basis of GM specifications for fine Arizona dust, the size distribution obtained by the photosedimentometer represents the more accurate data.

III. EXPERIMENTS CONDUCTED ON THE PHOTOSEDIMENTOMETER

Experiments involving the photosedimentometer are more difficult to carry out than on the sedimentation balance. The utility of this method is not great but once a procedure has been worked out, excellent results can be obtained. The time involved in conducting measurements on the present photosedimentometer is extensive, but since the unit runs around the clock, measurements can be programmed where both day and nighttime are utilized, thus making the time element involved more acceptable.

For a successful analysis using this method the sedimentation must start from a layer and the particles must settle at low Reynolds numbers. The latter requirement can usually be met easily for most substances, however, the greatest difficulty encountered by this method of sedimentation is streaming. This perhaps eliminates many materials from analysis by this method since layer suspensions and uniform settling from layers are difficult to achieve by suspensions of particles that have a tendency to form clusters.

In these experiments, fine Arizona dust was analyzed, both with and without a buffer layer, and repeatable results were obtained. The range found for concentrations of suspensions where consistent measurements could be obtained was very

much the same for experiments with or without a buffer layer. For Arizona dust the lower concentration limit for suspensions was 4×10^{-4} gm/cc and the upper limit was 1×10^{-2} gm/cc. For these limits the total mass injected and initially in suspension ran from 20 to 80 mg. On the basis of these experiments, measurements on boron powder were conducted.

The results of measurements on Arizona dust made with and without buffer layer for these concentrations are shown in Figures 47 - 60. Measurements on amorphous boron powders were all conducted with a buffer layer and the size distributions are shown in Figures 61 - 64. The sedimentation fluid in these experiments was distilled water with Liqui-Nox as a wetting agent and the buffer layer was isobutyl alcohol. Conical 200 ml Erlenmeyer flasks with initially 150 ml sedimentation fluid were used in preparing the suspensions. Ultrasonic agitation was used in preparing the suspensions of boron prior to injection. A 10 cc Multifit syringe was used for the fluid injections. The boron suspensions were injected with a blunt 3 inch long #17 needle. Arizona dust suspensions were injected from a vertically held syringe. A nonconventional 90 degree #17 needle having a straight 4 inch portion for insertion was used in conjunction with these injections. The sedimentation drum speed was 900 RPM in the measurements on Arizona dust and 2200 RPM in the measurements on boron. In

the data analysis of all experiments conducted on the photo-sedimentometer, Rose's extinction coefficient was applied.

The lower limit of the mass concentration in these experiments was primarily due to instrument parameters such as sensitivity, stability and proneness to extraneous signals and factors dependent on general environmental conditions. Successive injections of increasing mass concentrations much beyond the upper limit, in particular for the runs made without a buffer layer, resulted in increasing deviations from the average particle size distribution and were less and less repeatable. This trend observed for measurements made with increasing concentrations was accompanied by an initial negative recorder response which started two or three seconds after injection and was indicative of higher transmissivity in the detection zone. The trace after going negative for a number of seconds reversed direction and after 20 to 25 seconds from the time of injection, crossed the base line and assumed the regular response. This abnormal behavior was observed in experiments on Arizona dust made with and without a buffer layer and apparently was dependent only on the mass concentration injected and occurred only upon injection of two to five times the mass of what was determined to be the approximate upper concentration limit. This irregularity was ascribed to particle interactions, e.g., large particles interacting with

very fine ones that stayed in suspension for a long time and the concentration of which increased by each successive injection and in time resulted in a suspension of very fine particles, or background, of sufficient concentration to cause detectable interactions at the onset of a new experiment.

On the basis of these observations it was decided to use successive injections only for a series of exploratory runs, rinse the drum and start out with fresh sedimentation fluid for conducting final measurements in order to avoid influence of the results by residual particles.

The level of the background represented by the base line on the recorder was also influenced by a small usually continuous change in signal level. This change in signal, or drift, originated in the illuminating system and was taken into account in the final data analysis.

In the absence of an indicator, the temperature of the sedimentation fluid was derived from temperature measurements of the sedimentation drum axle area and the drum enclosure. Temperature readings were taken at intervals throughout the time the photosedimentometer was in operation. The data gathered was supplemented by actual temperature readings of the sedimentation fluid taken when the drum was briefly stopped at times when it did not interfere with the actual experiments. Correlation of the data collected for both drum speeds produced

plots from which the effective temperature of the sedimentation fluid for each run was determined.

IV. ILLUSTRATIONS OF PARTICLE SIZE DISTRIBUTIONS OBTAINED BY COMPUTER ANALYSIS

A. RESULTS OF EXPERIMENTS CONDUCTED ON THE SEDIMENTATION BALANCE

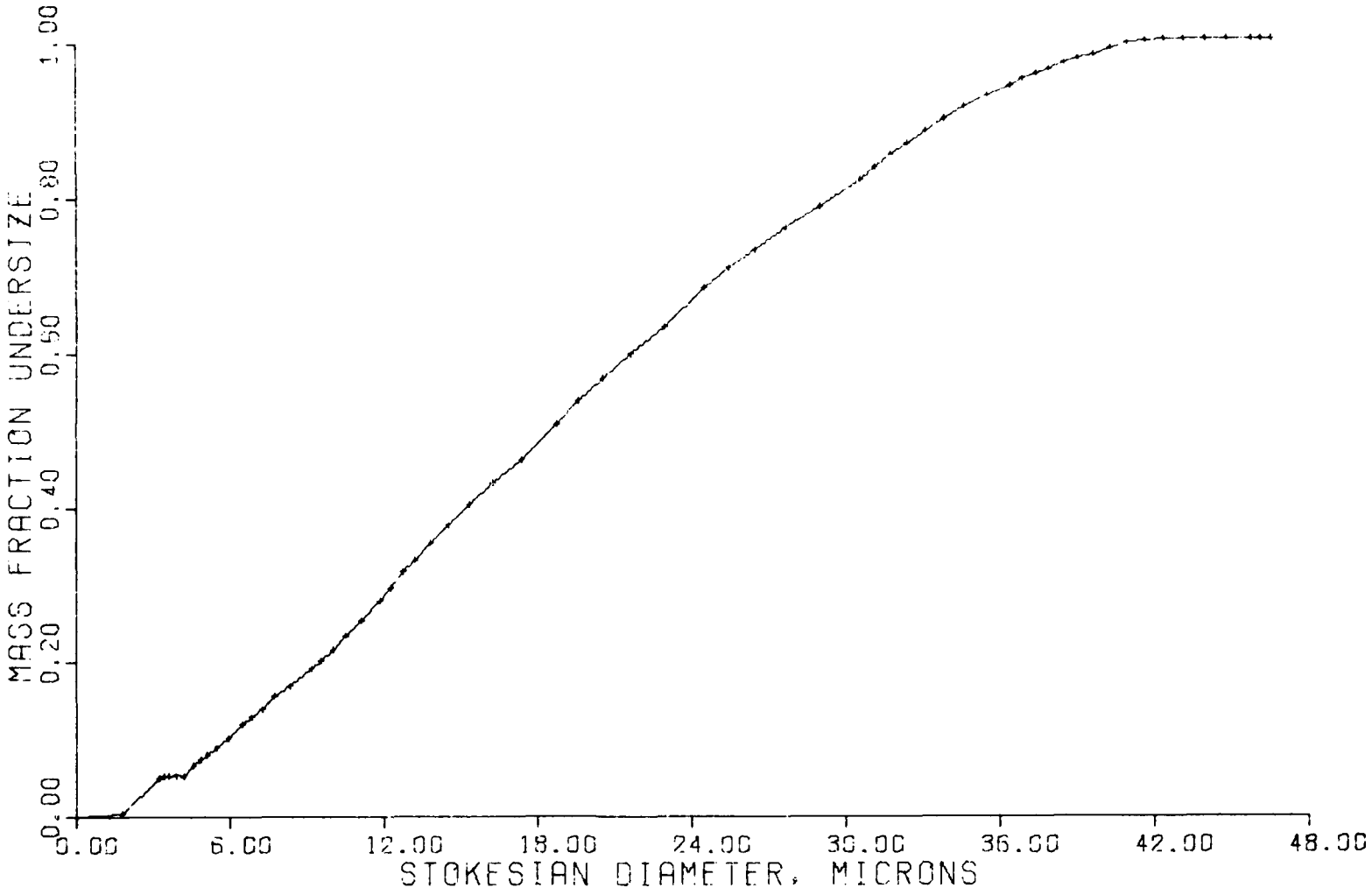

Figure 1. Experiment No. 1 Cumulative Particle Size Distribution of Johnson Baby Powder. Mass Concentration 1.02 mg/cc.

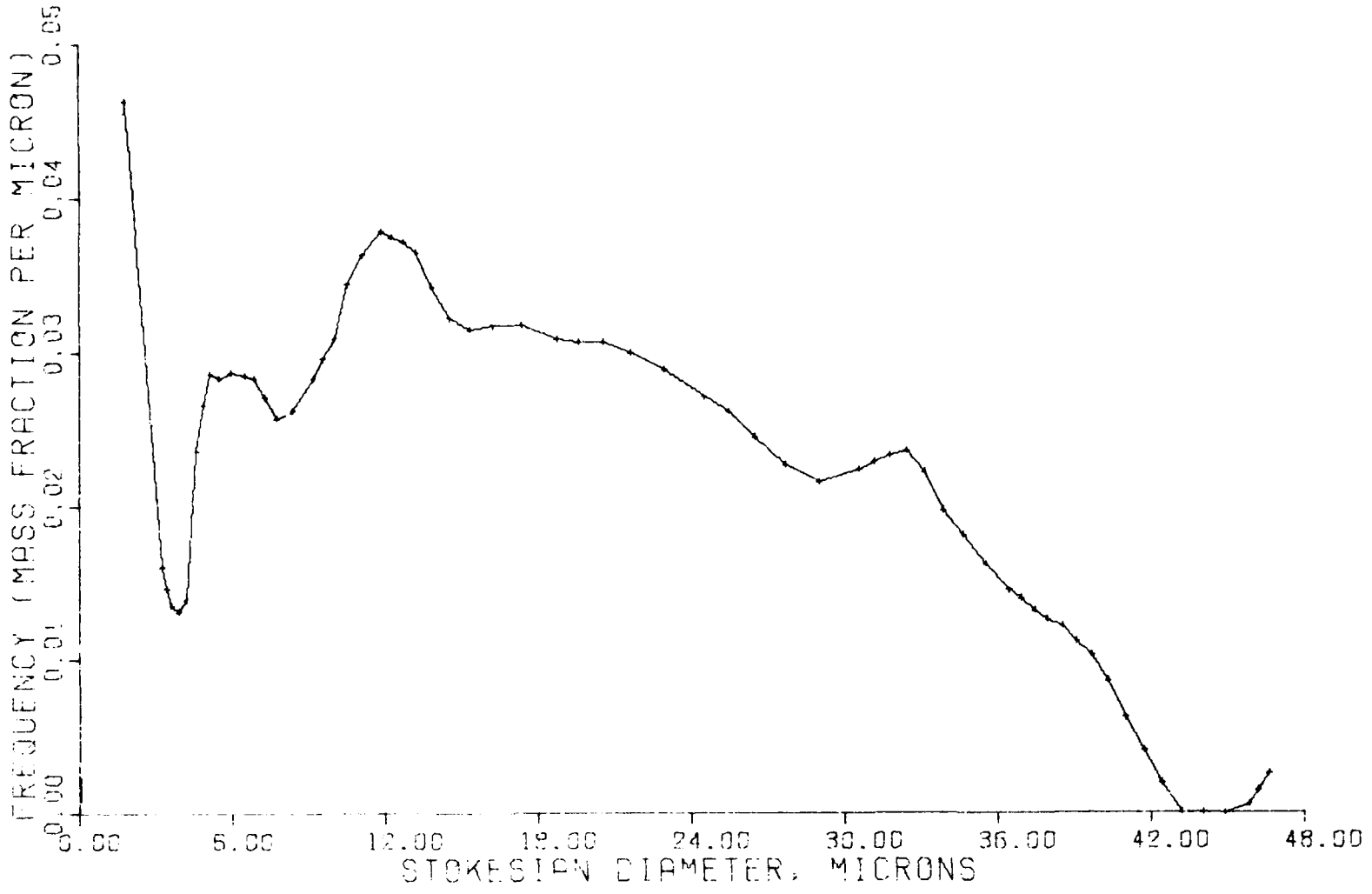

Figure 2. Experiment No. 1 Particle Size Frequency Distribution of Johnson Baby Powder. Mass Concentration 1.02 mg/cc.

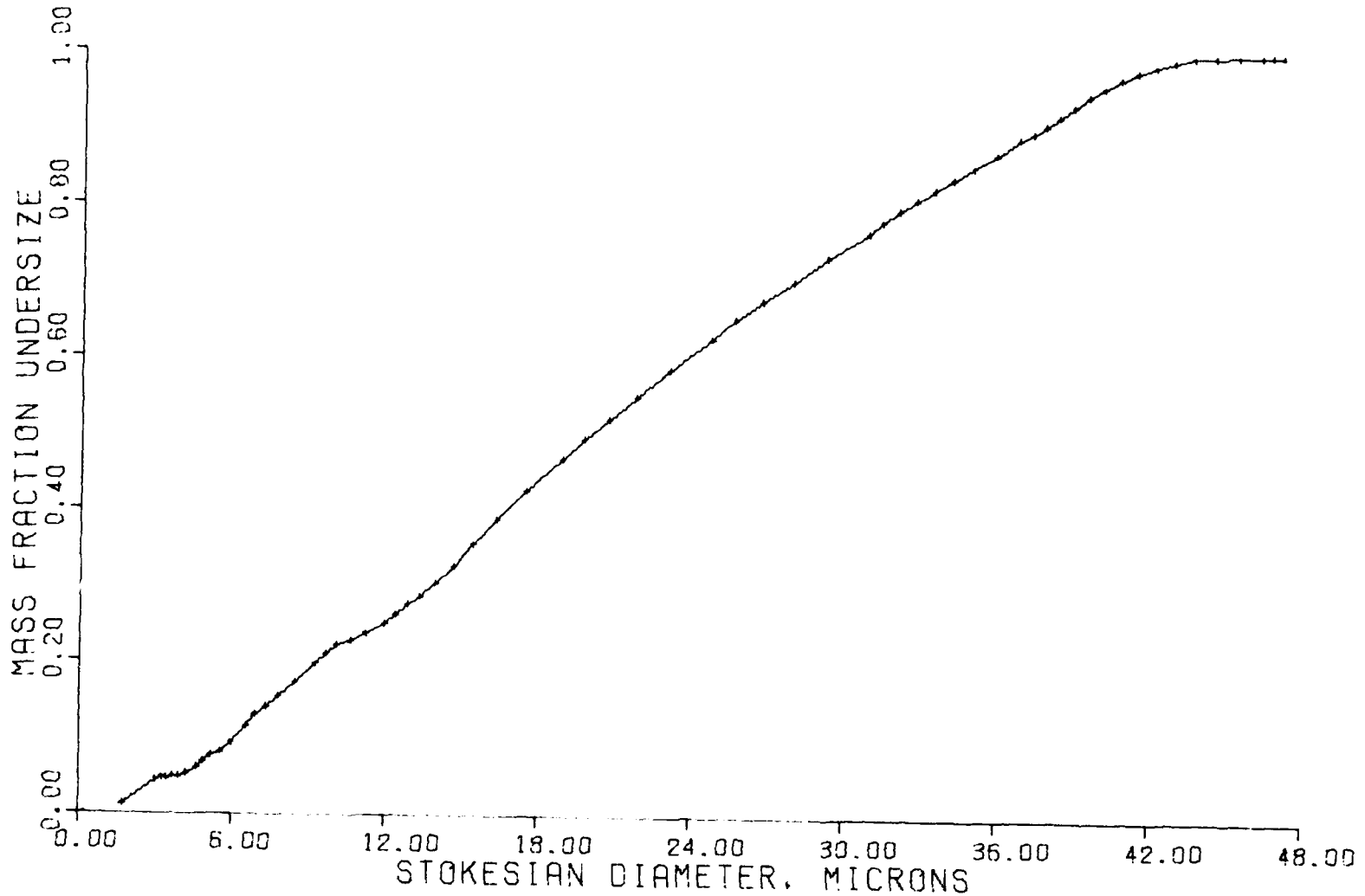

Figure 3. Experiment No. 2 Cumulative Particle Size Distribution of Johnson Baby Powder. Mass Concentration 1.97 mg/cc.

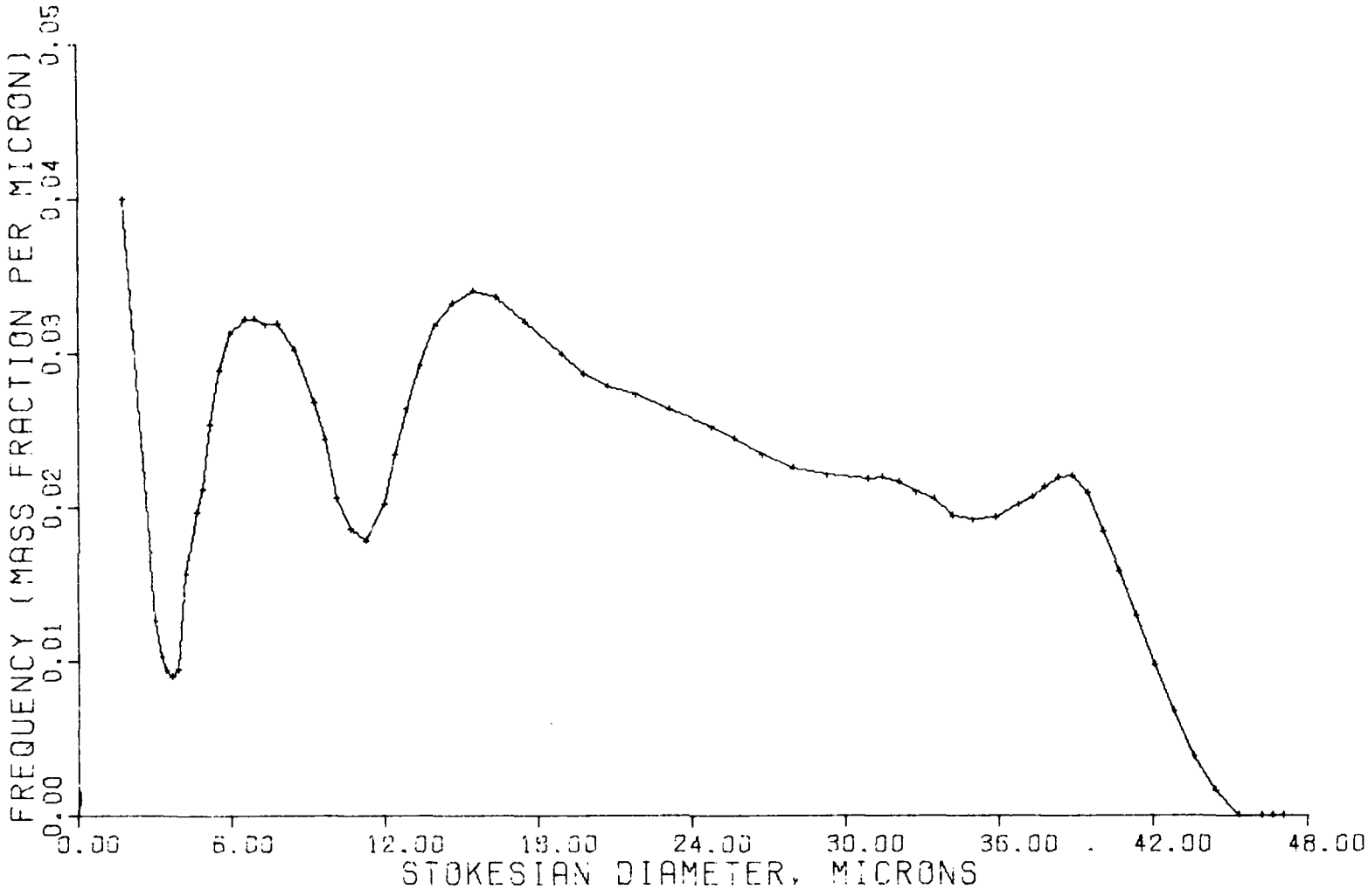

Figure 4. Experiment No. 2 Particle Size Frequency Distribution of Johnson Baby Powder. Mass Concentration 1.97 mg/cc.

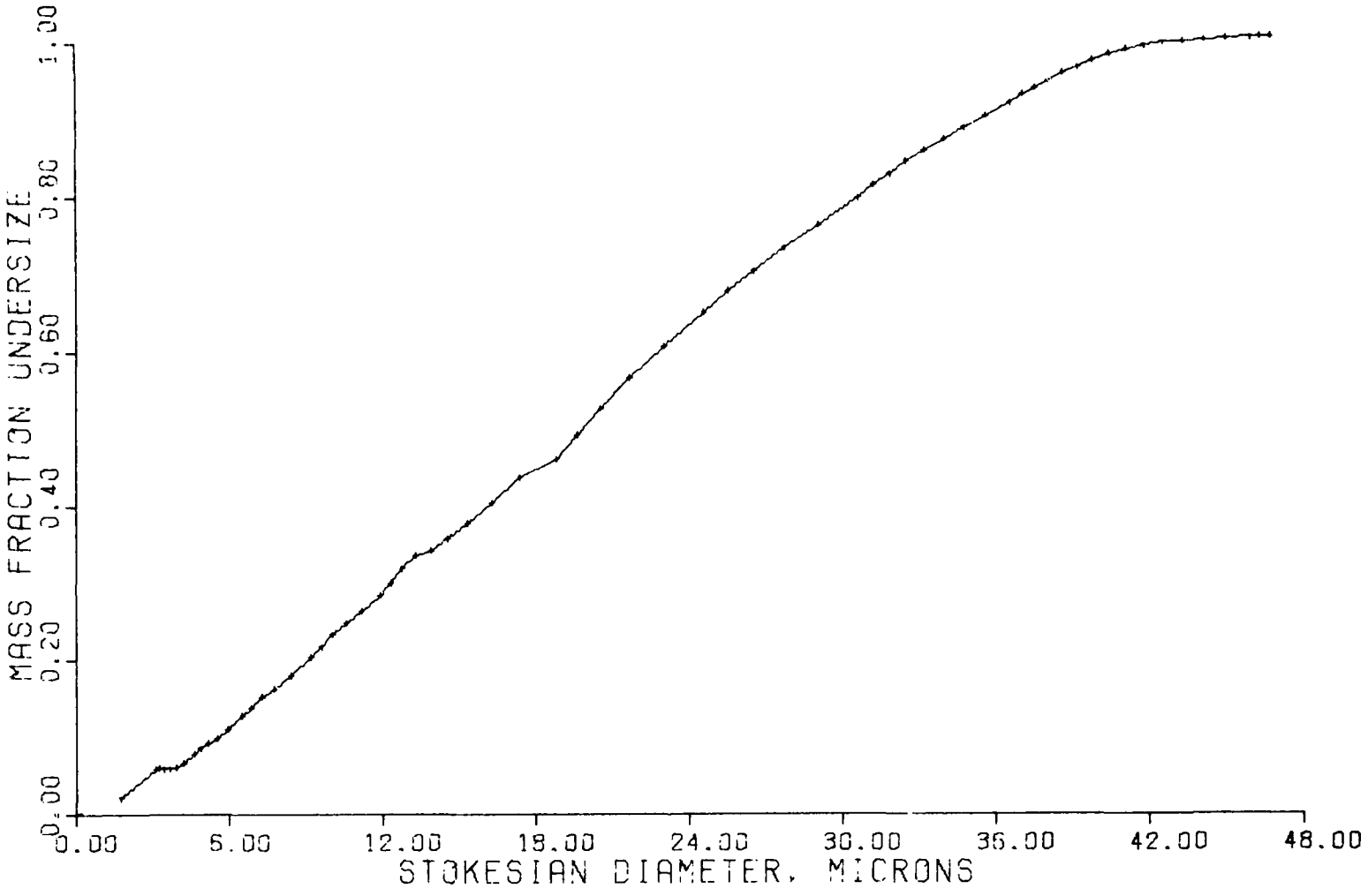

Figure 5. Experiment No. 3 Cumulative Particle Size Distribution of Johnson Baby Powder. Mass Concentration 2.21 mg/cc.

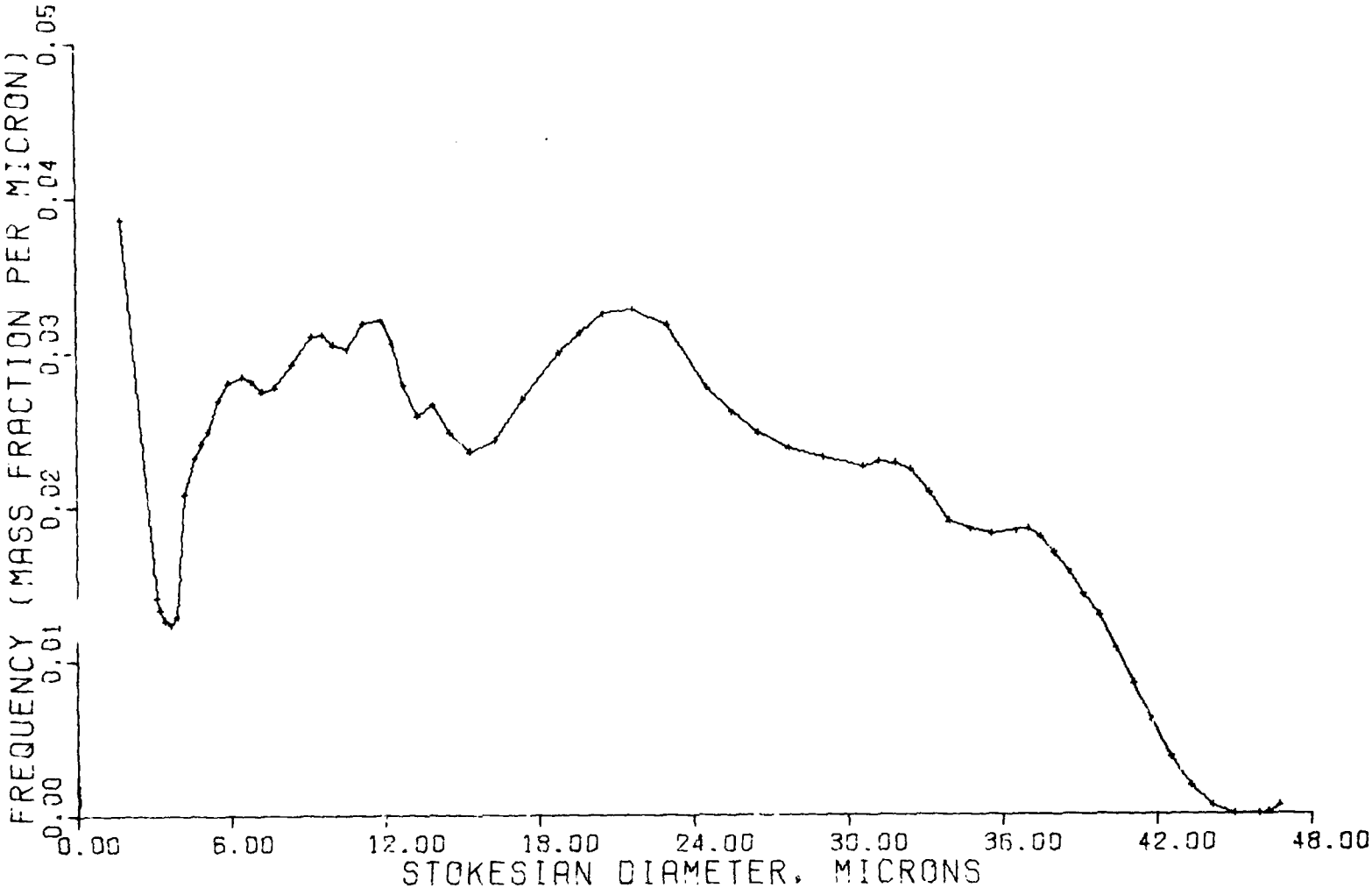

Figure 6. Experiment No. 3 Particle Size Frequency Distribution of Johnson Baby Powder. Mass Concentration 2.21 mg/cc.

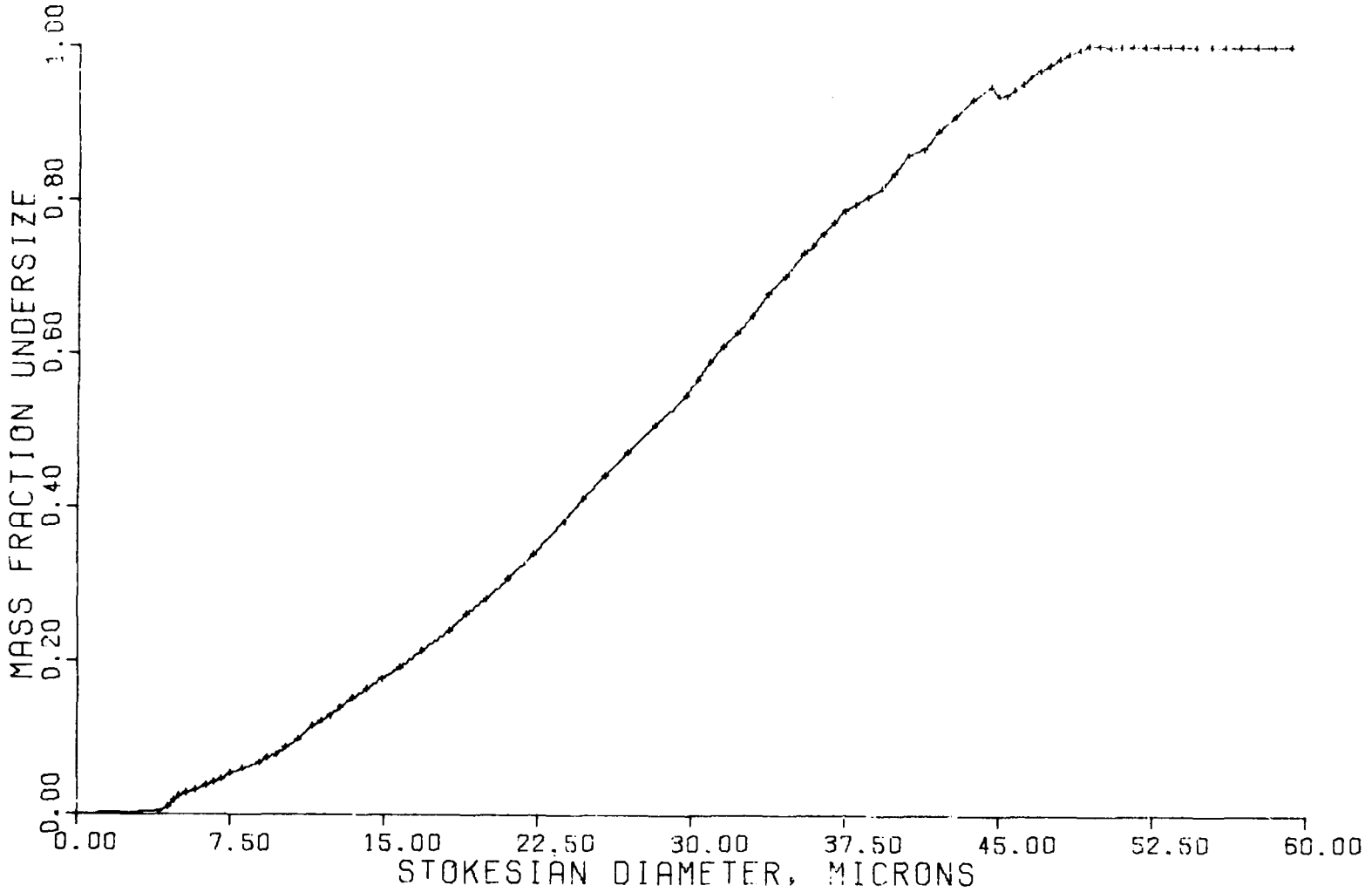

Figure 7. Experiment No. 4 Cumulative Particle Size Distribution of Modified Johnson Baby Powder. Mass Concentration 1.0 mg/cc.

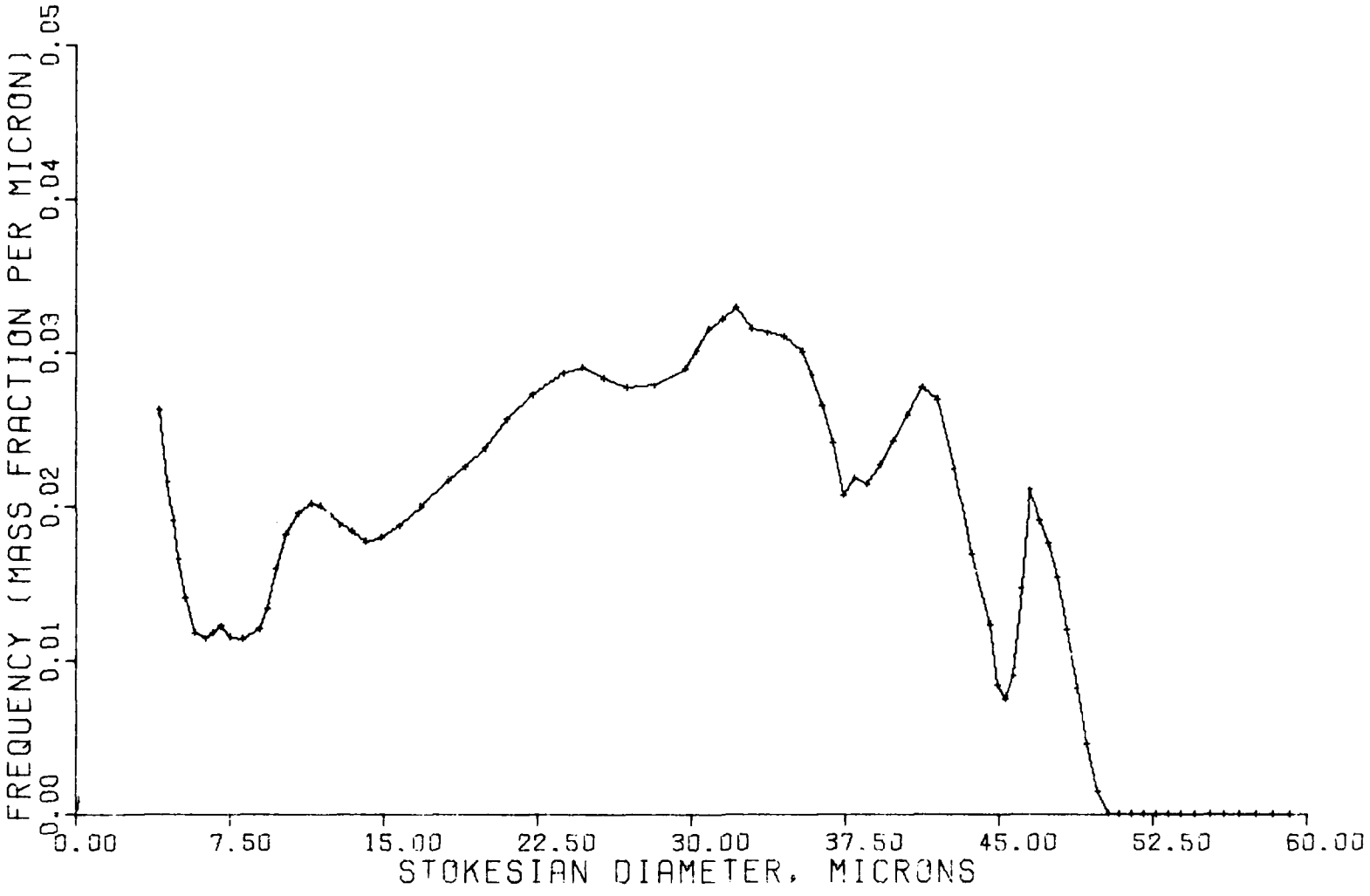

Figure 8. Experiment No. 4 Particle Size Frequency Distribution of Modified Johnson Baby Powder. Mass Concentration 1.0 mg/cc.

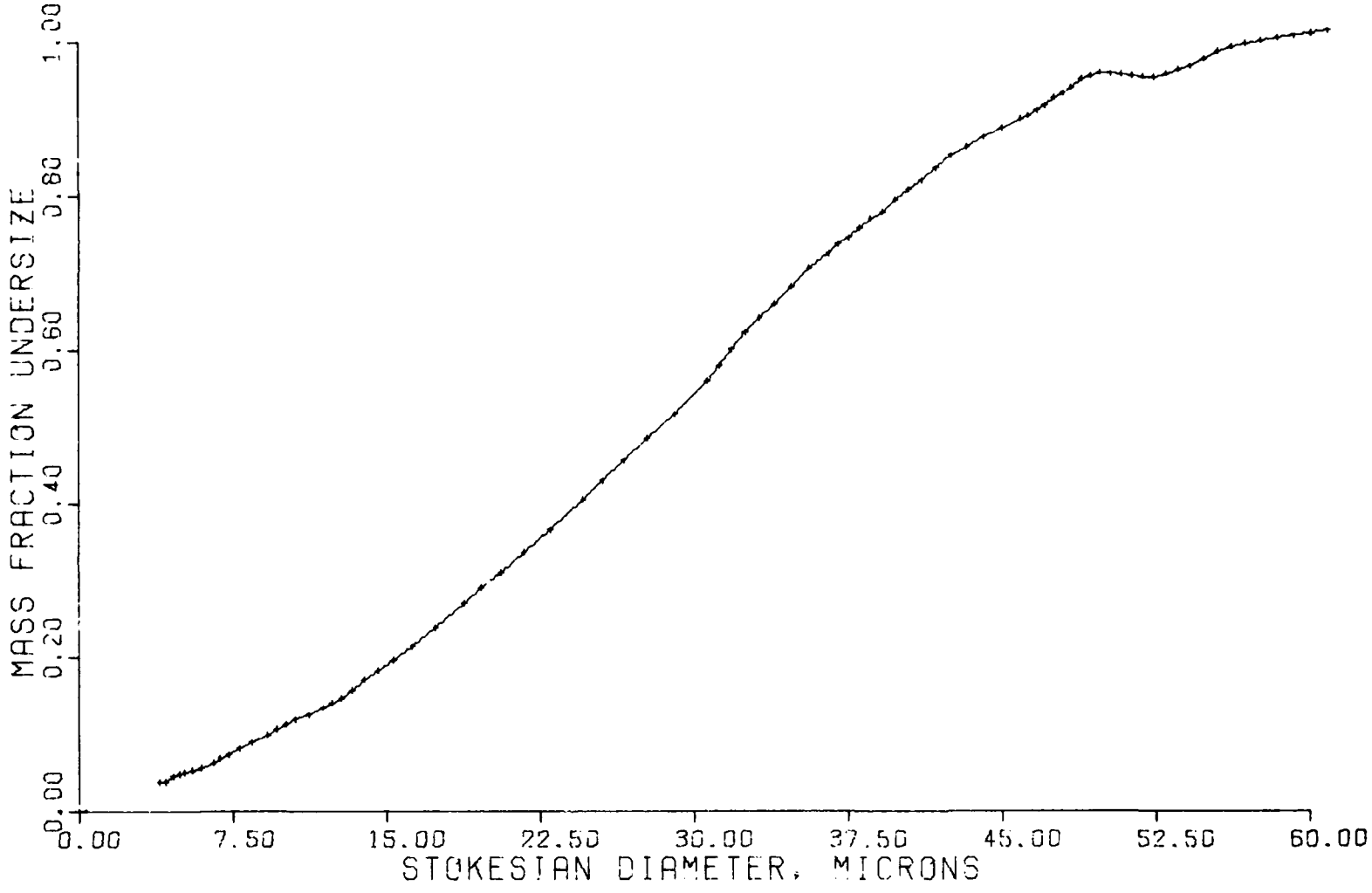

Figure 9. Experiment No. 5 Cumulative Particle Size Distribution of Modified Johnson Baby Powder. Mass Concentration 1.33 mg/cc.

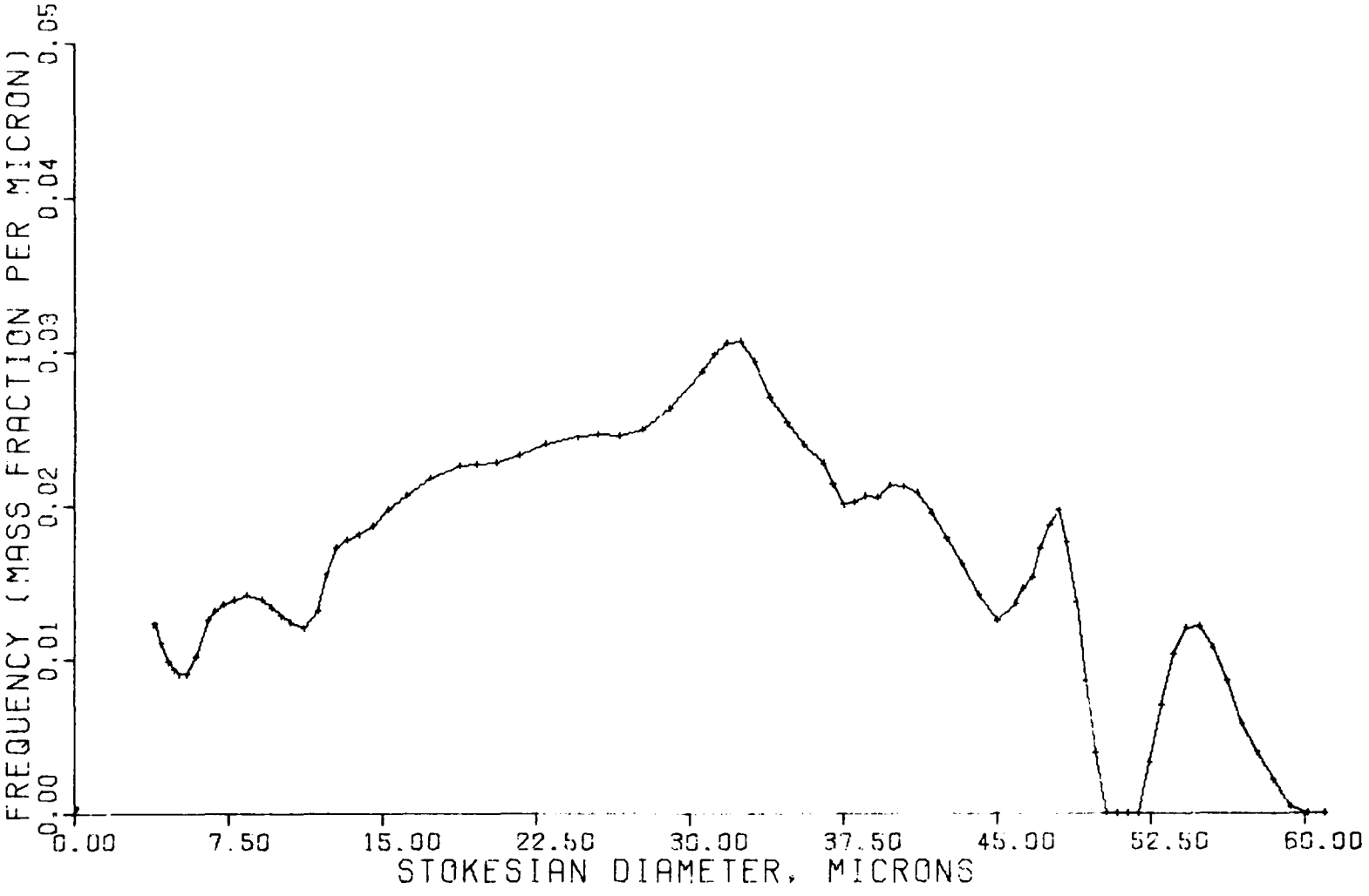

Figure 10. Experiment No. 5 Particle Size Frequency Distribution of Modified Johnson Baby Powder. Mass Concentration 1.33 mg/cc.

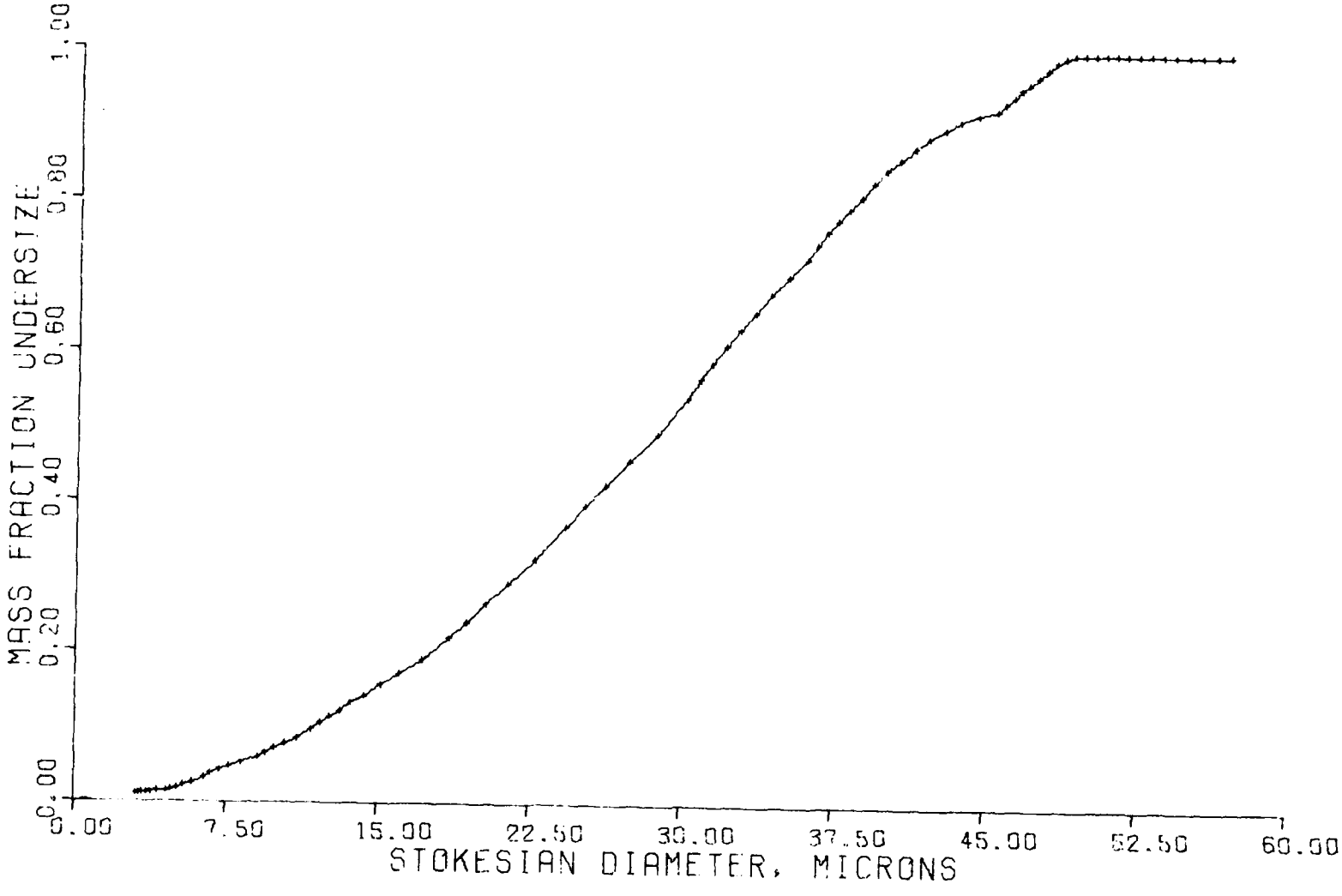

Figure 11. Experiment No. 6 Cumulative Particle Size Distribution of Modified Johnson Baby Powder. Mass Concentration 1.94 mg/cc.

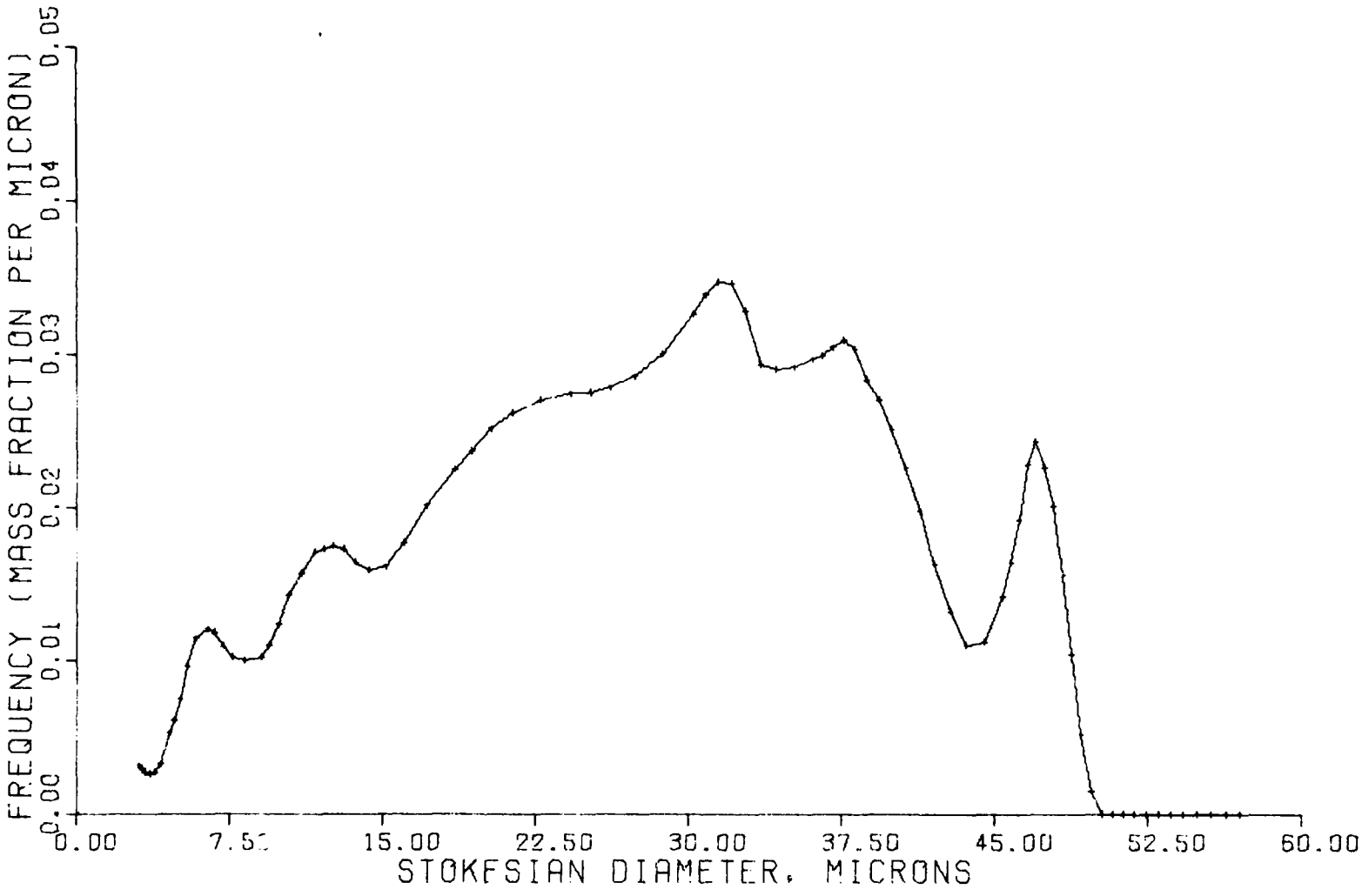

Figure 12. Experiment No. 6 Particle Size Frequency Distribution of Modified Johnson Baby Powder. Mass Concentration of 1.94 mg/cc.

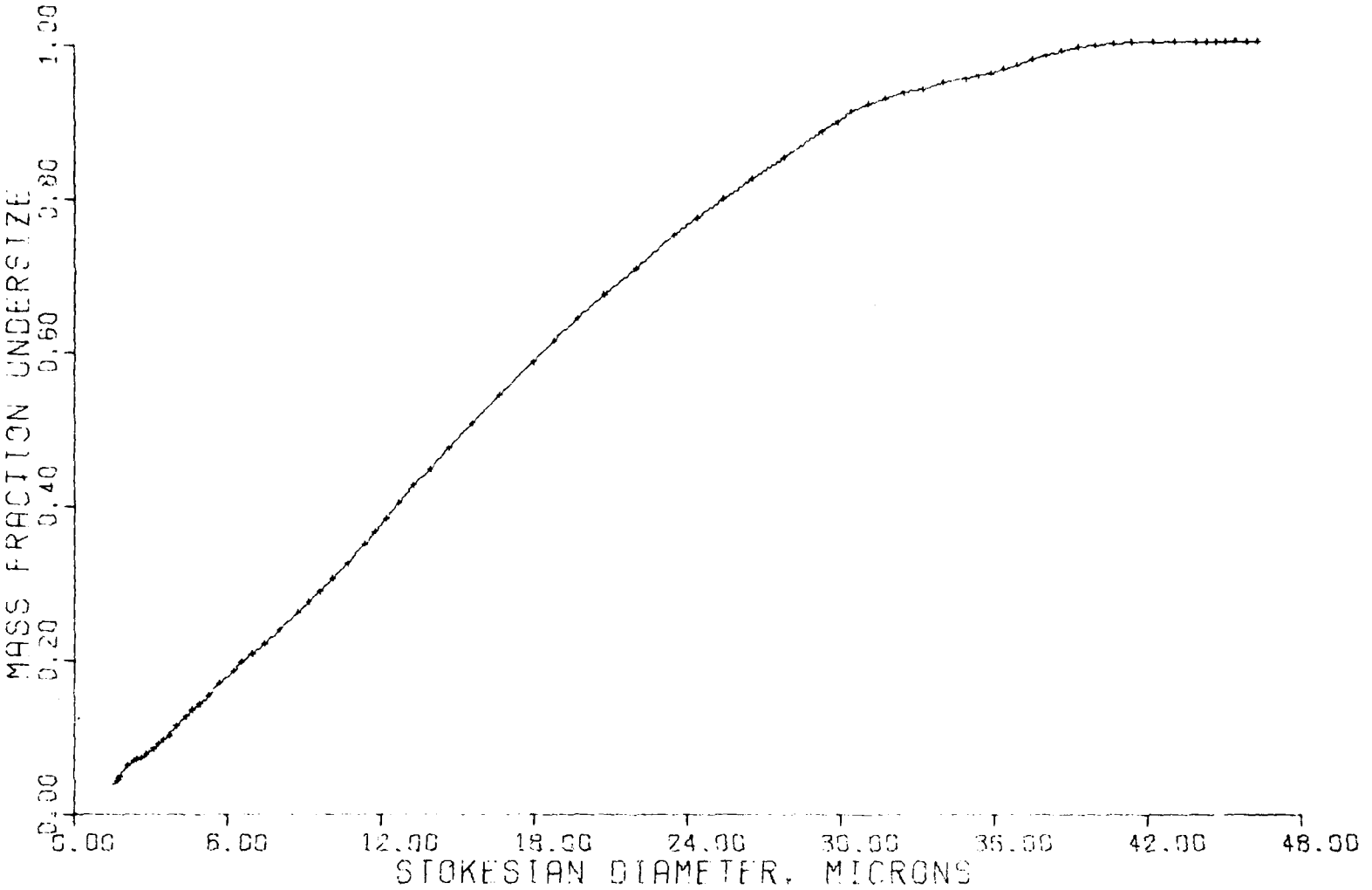

Figure 13. Experiment No. 7 Cumulative Particle Size Distribution of Johnson Baby Powder, Sample dtd 15 Jul 70. Mass Concentration 1.63 mg/cc.

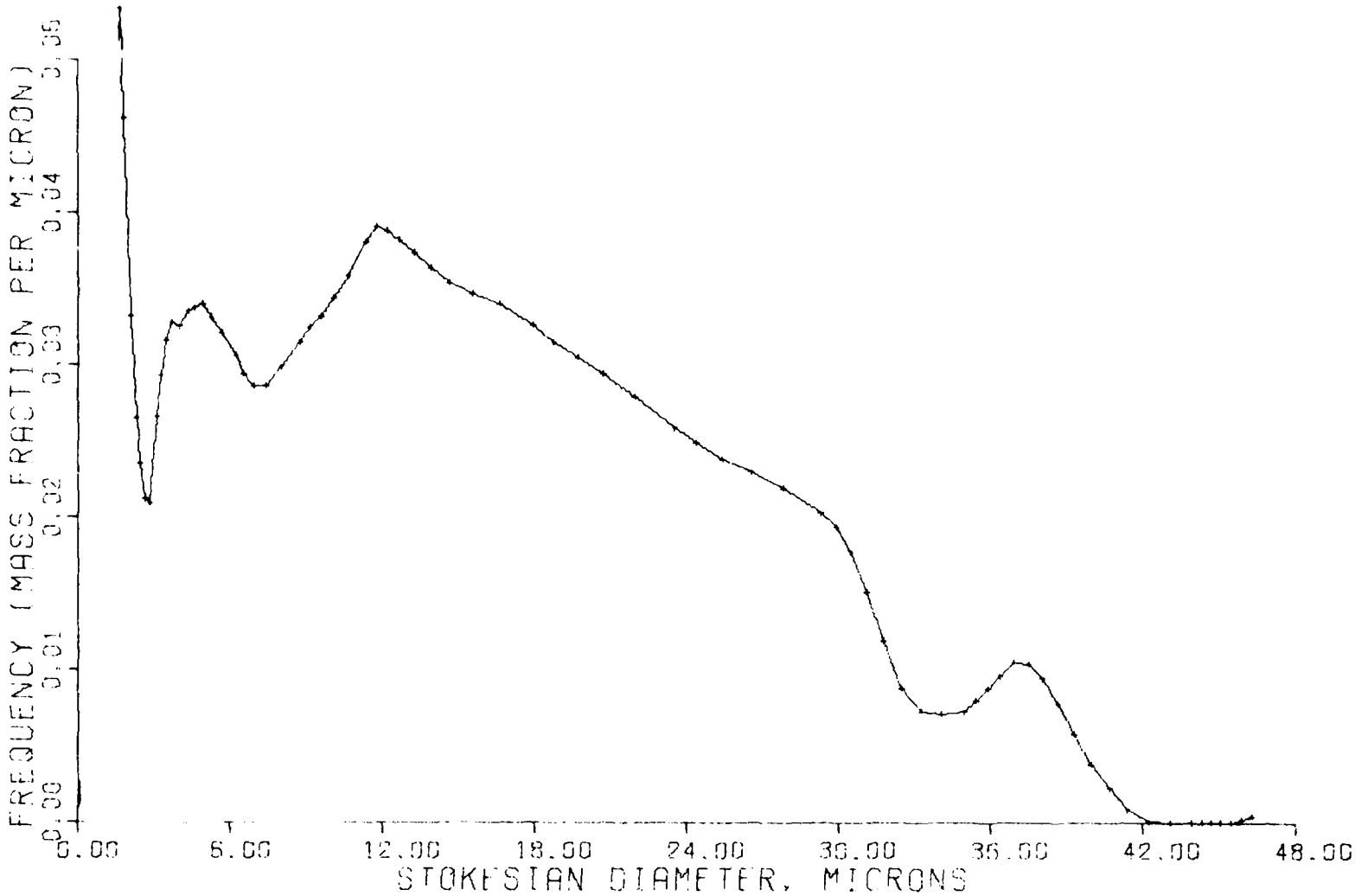

Figure 14. Experiment No. 7 Particle Size Frequency Distribution of Johnson Baby Powder, Sample dtd 15 Jul 70. Mass concentration 1.63 mg/cc.

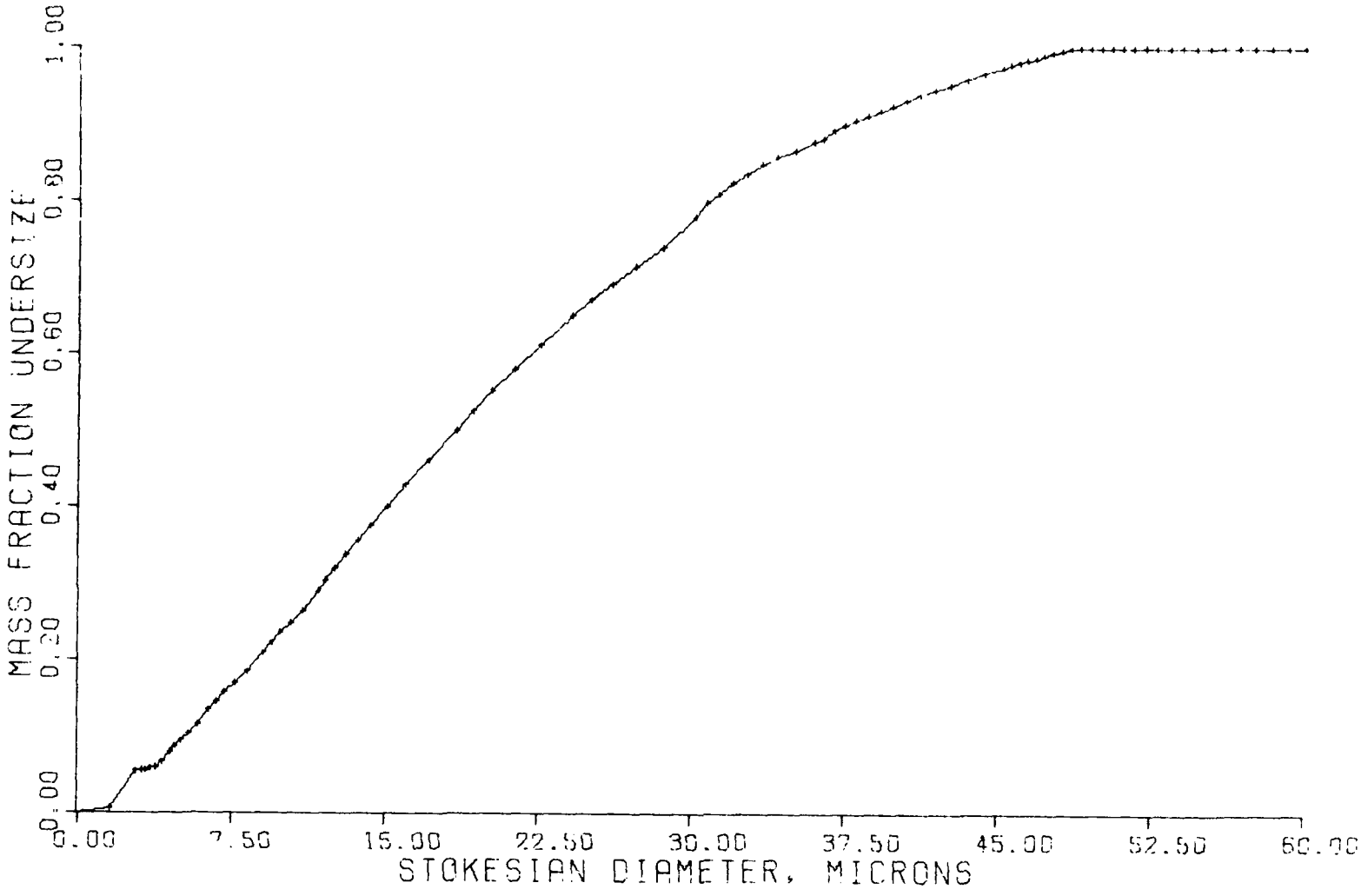

Figure 15. Experiment No. 8 Cumulative Particle Size Distribution of Johnson Baby Powder, Sample 9-1. Mass Concentration 1.55 mg/cc.

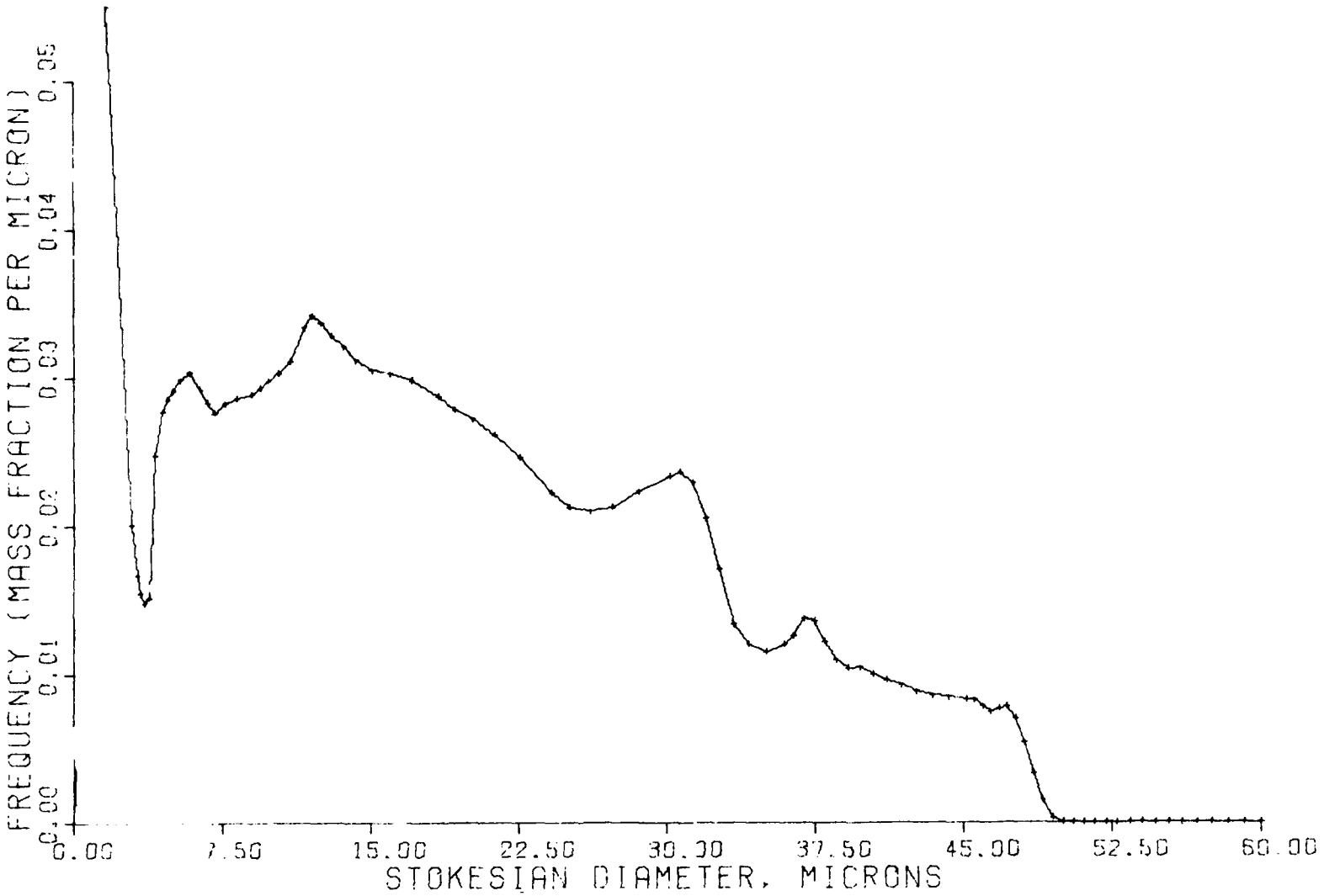

Figure 16. Experiment No. 8 Particle Size Frequency Distribution of Johnson Baby Powder, Sample 9-1. Mass Concentration 1.55 mg/cc.

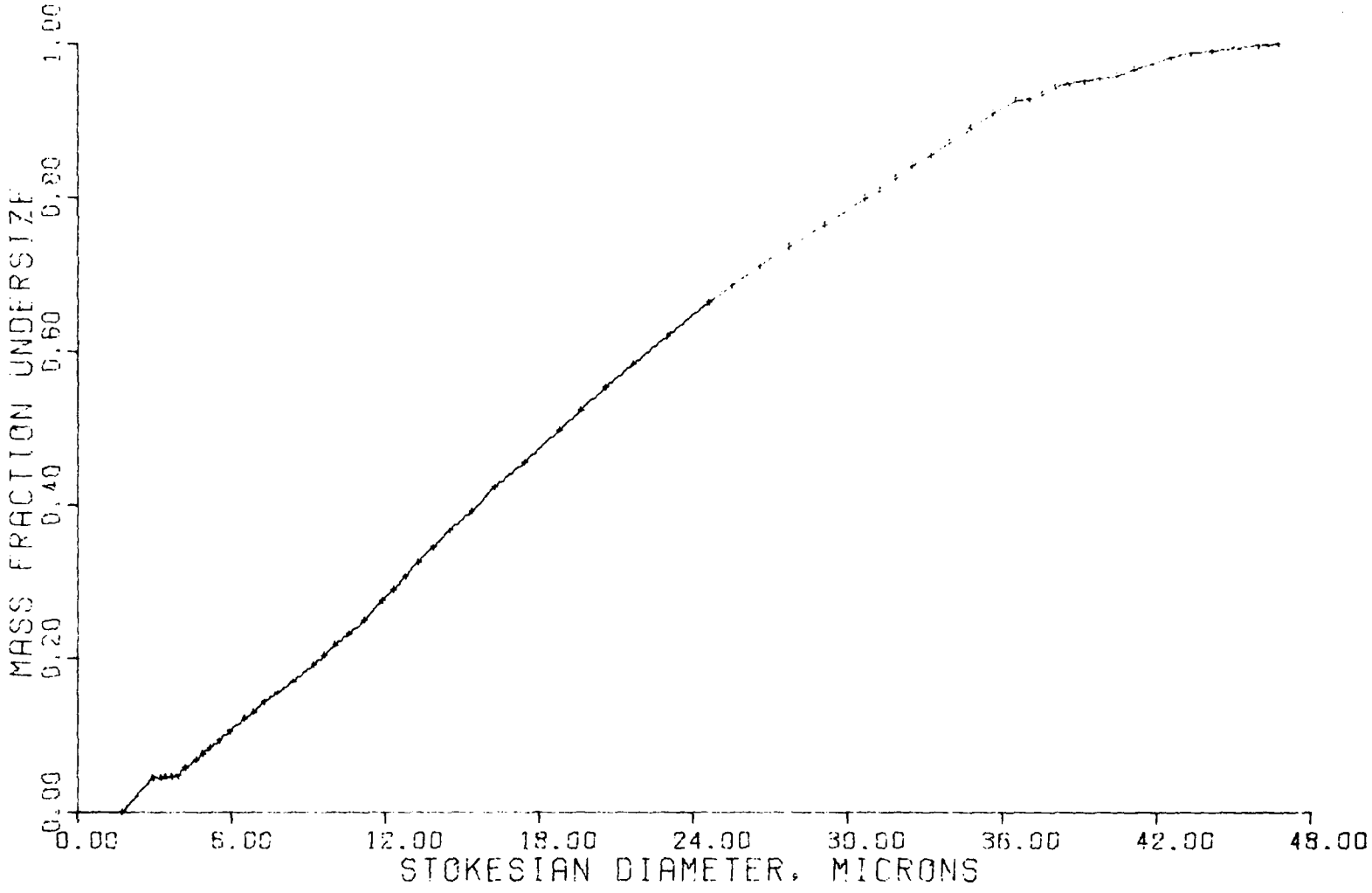

Figure 17. Experiment No. 9 Cumulative Particle Size Distribution of Johnson Baby Powder, Sample 9-2. Mass Concentration 1.50 mg/cc.

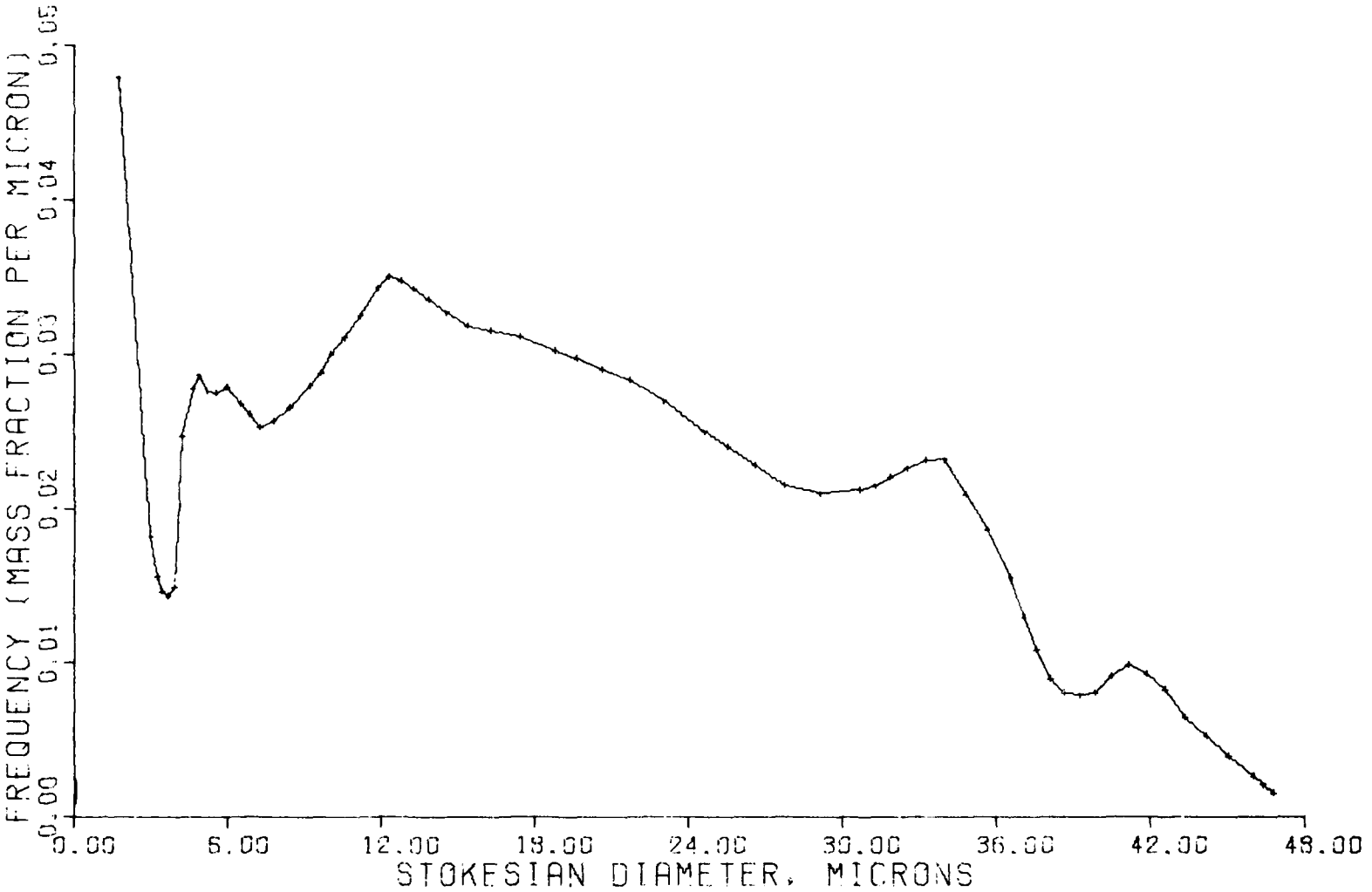

Figure 18. Experiment No. 9 Particle Size Frequency Distribution of Johnson Baby Powder, Sample 9-2. Mass Concentration 1.50 mg/cc.

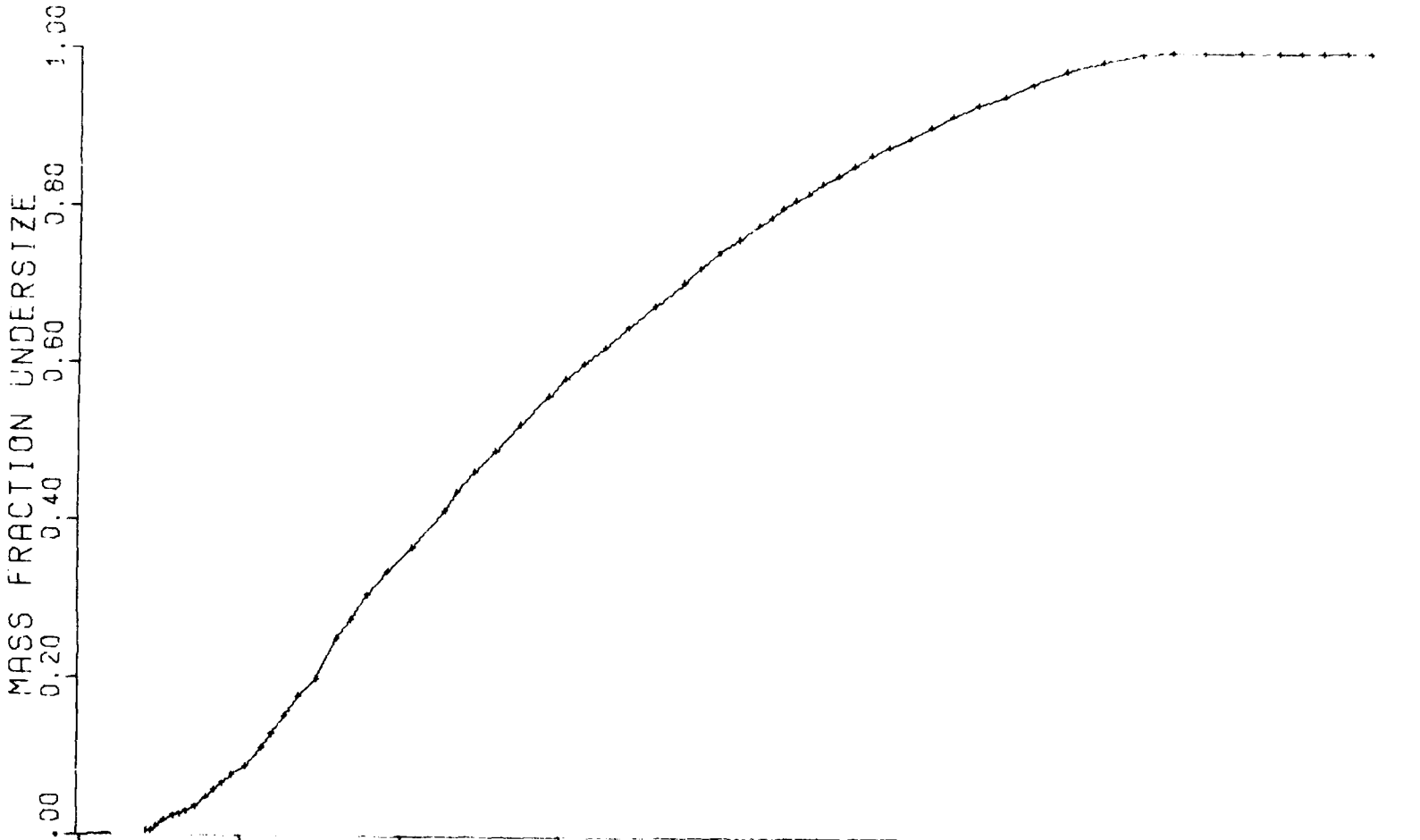

Figure 19. Experiment No. 10 Cumulative Particle Size Distribution of Johnson Baby Powder, Sample Perr. 3 Mar 71, Mass Concentration 1.41 mg/cc.

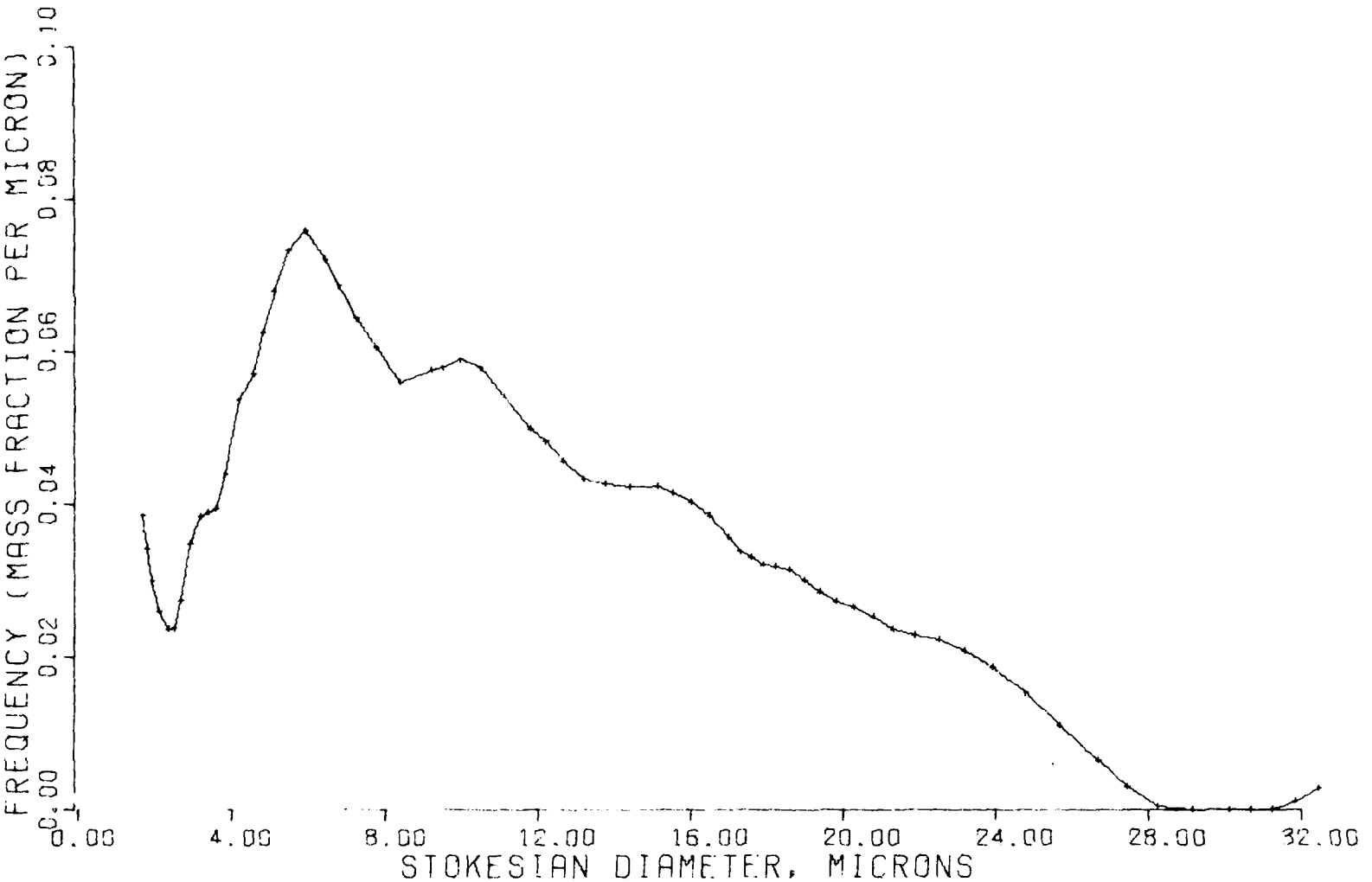

Figure 20. Experiment No. 10 Particle Size Frequency Distribution of Johnson Baby Powder, Sample Perr. 3 Mar 71. Mass Concentration 1.41 mg/cc.

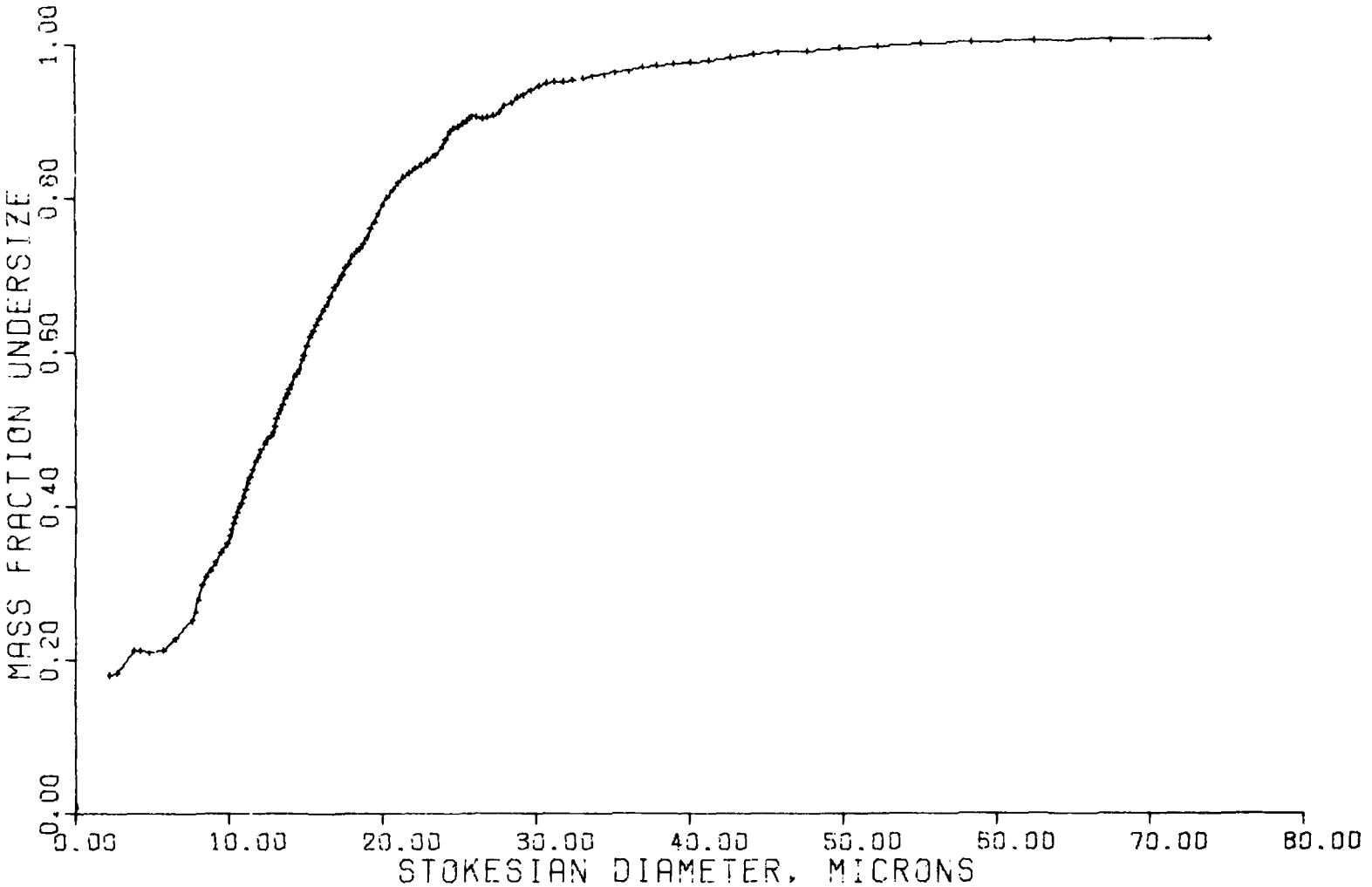

Figure 21. Experiment No. 11 Cumulative Particle Size Distribution of Tungsten Metal Powder -325 Mesh. Mass Concentration 0.55 mg/cc.

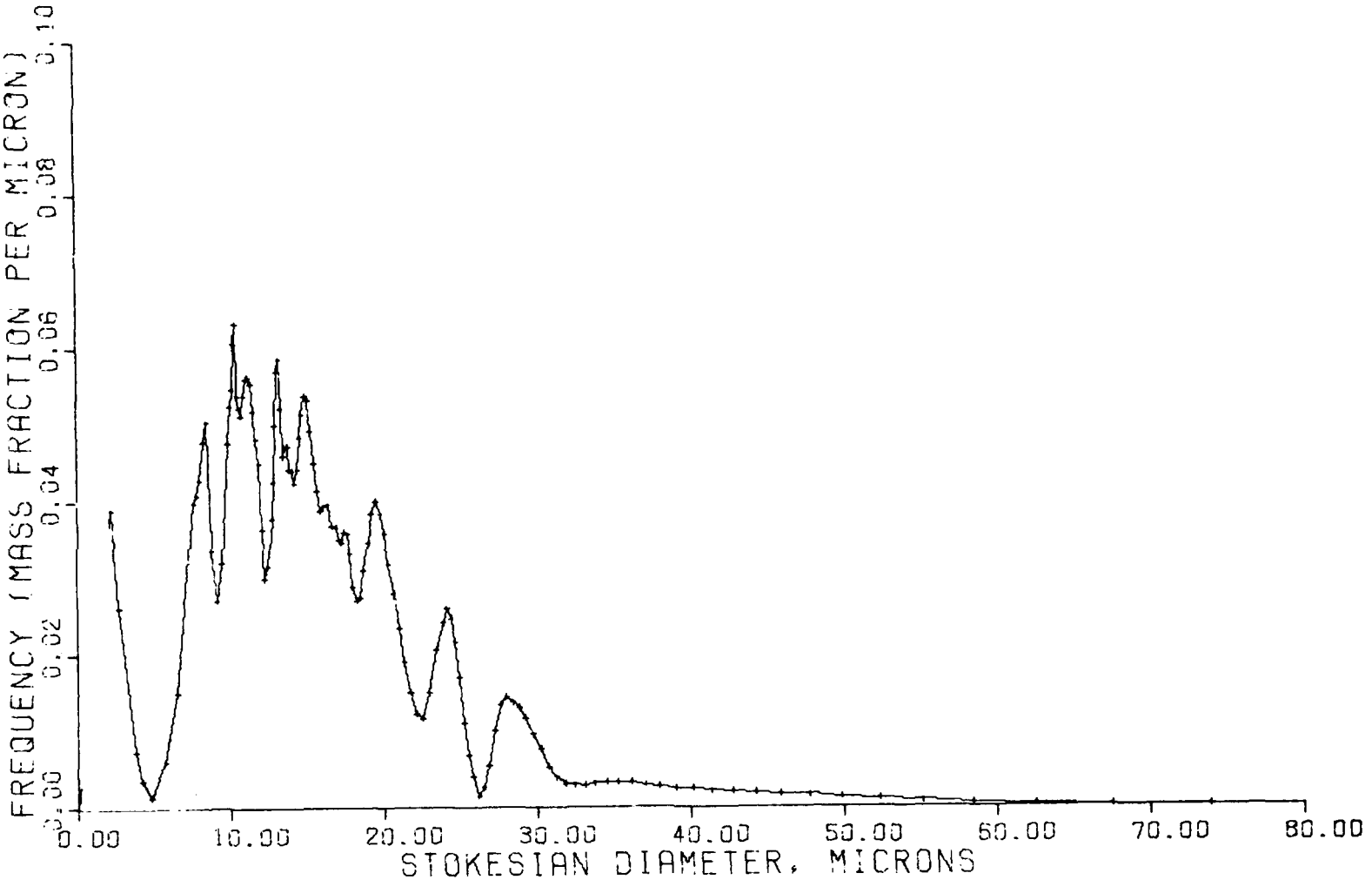

Figure 22. Experiment No. 11 Particle Size Frequency Distribution of Tungsten Metal Powder -325 Mesh. Mass Concentration 0.55 mg/cc.

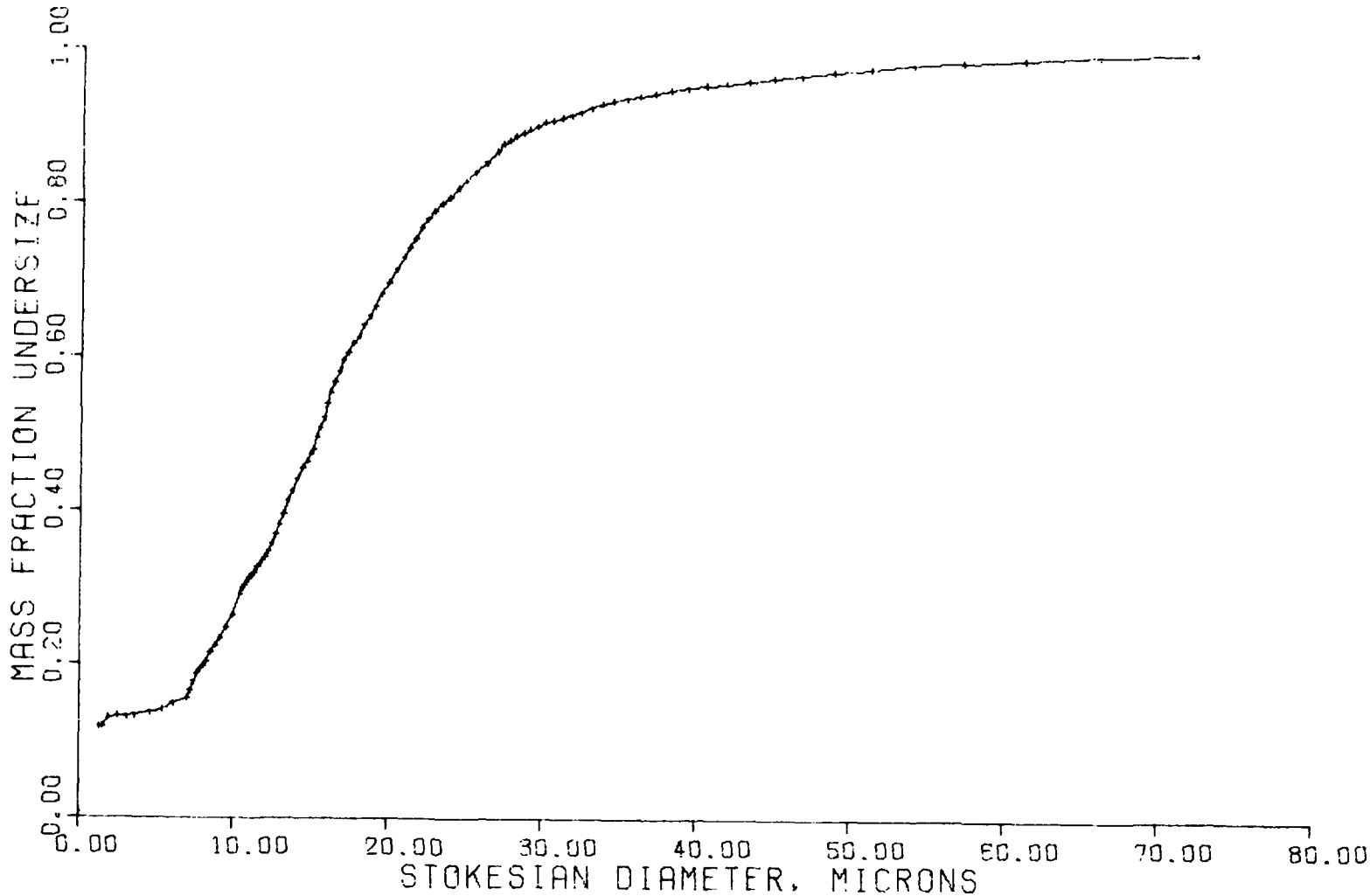

Figure 23. Experiment No. 12 Cumulative Particle Size Distribution of Tungsten Metal Powder -325 Mesh. Mass Concentration 1.19 mg/cc.

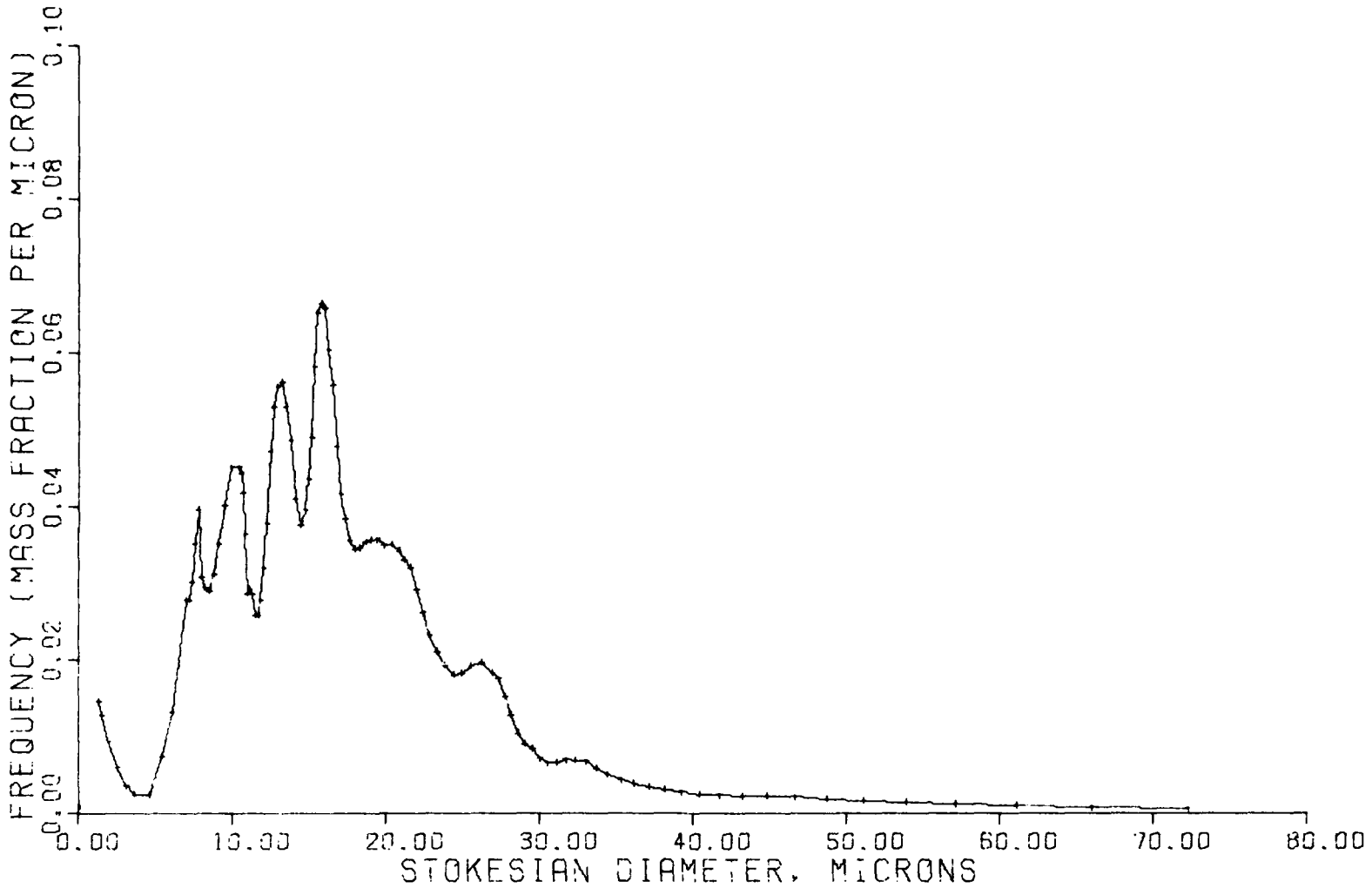

Figure 24. Experiment No. 12 Particle Size Frequency Distribution of Tungsten Metal Powder -325 Mesh. Mass Concentration 1.19 mg/cc.

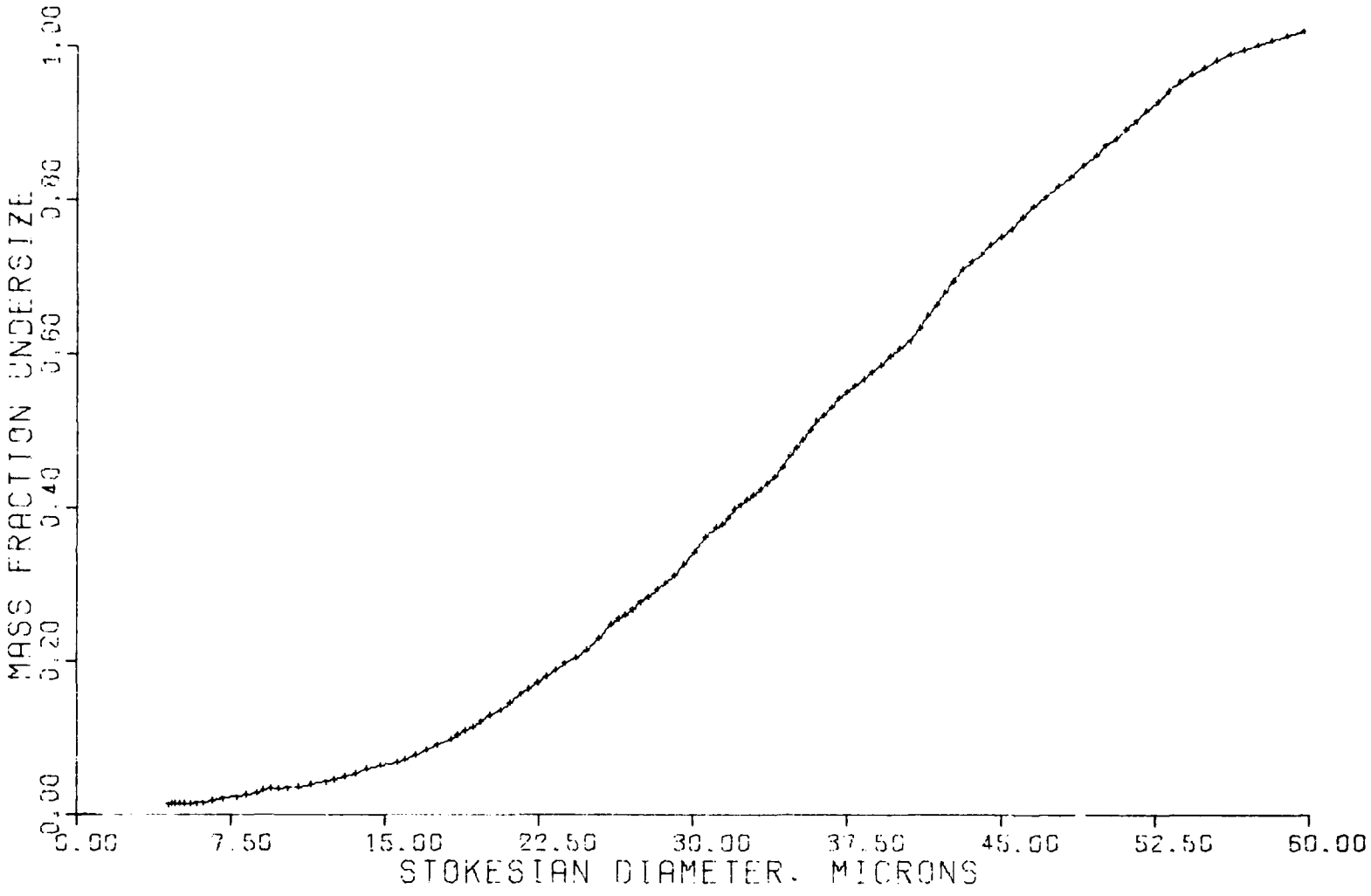

Figure 25. Experiment No. 13 Cumulative Particle Size Distribution of Titanium Metal Powder 1-10 Micron. Mass Concentration 1.15 mg/cc.

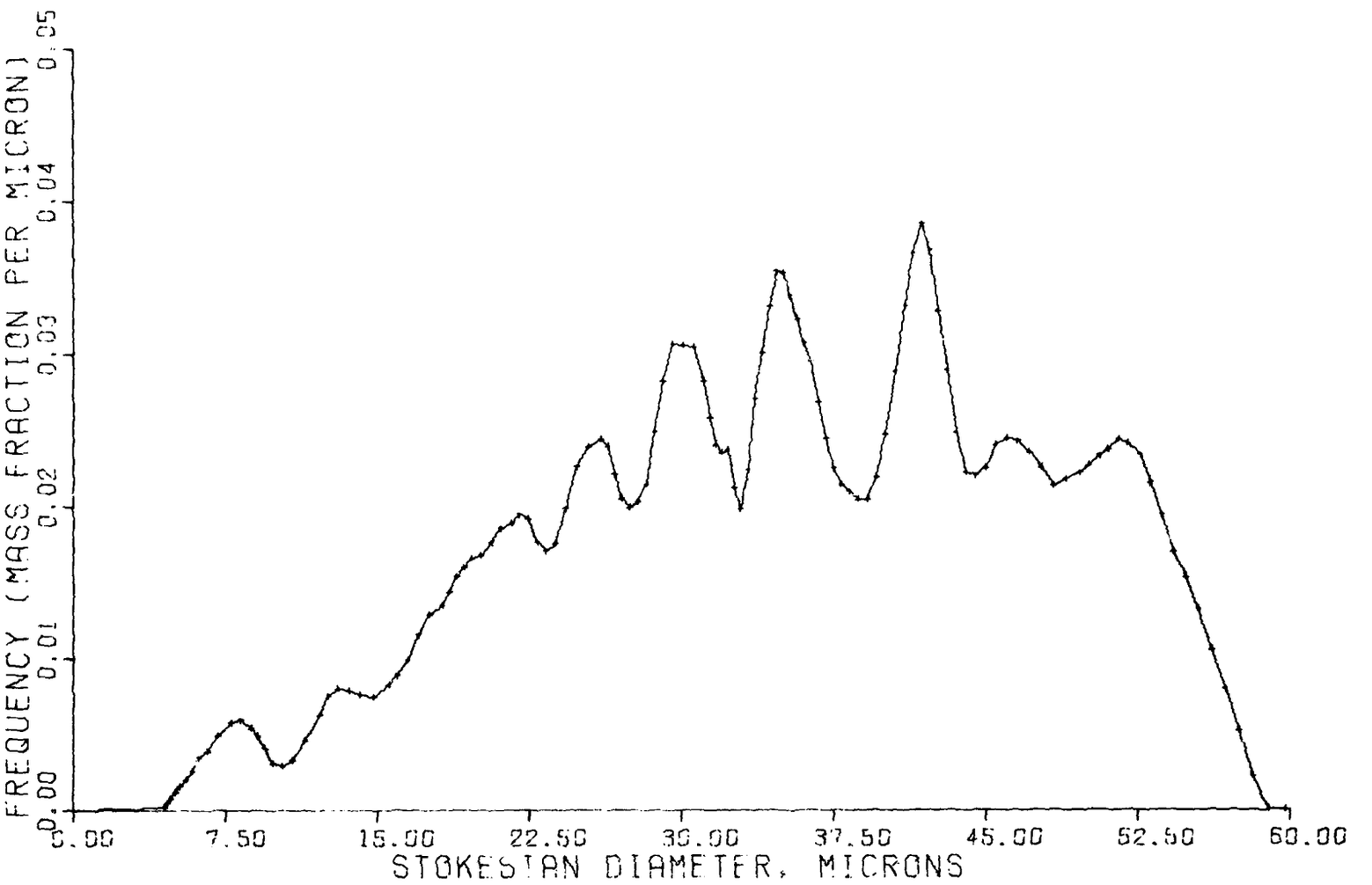

Figure 26. Experiment No. 13 Particle Size Frequency Distribution of Titanium Metal Powder 1-10 Micron. Mass Concentration 1.15 mg/cc.

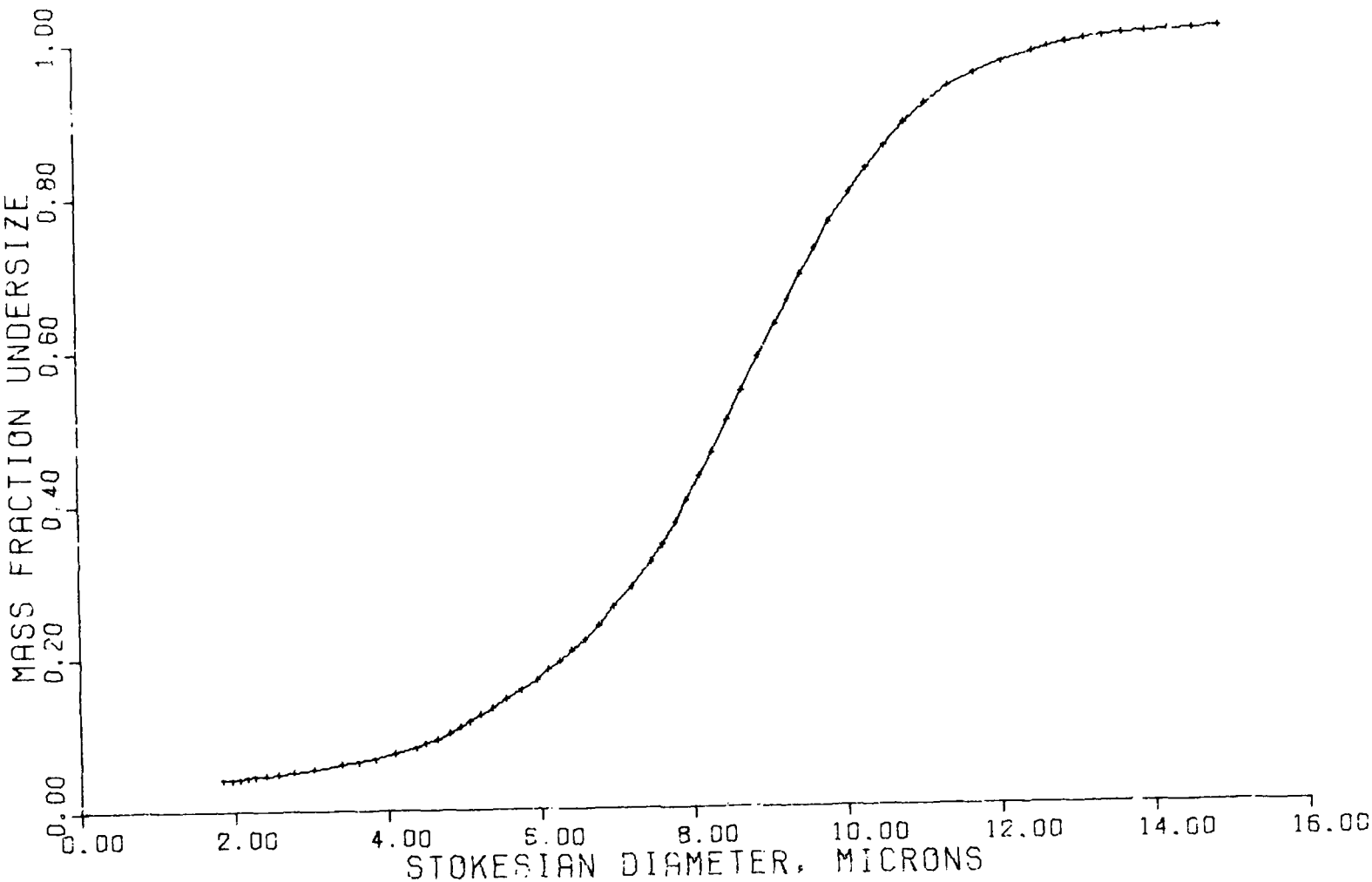

Figure 27. Experiment No. 14 Cumulative Particle Size Distribution of Aluminum Metal Powder 1-10 Micron. Mass Concentration 1.41 mg/cc.

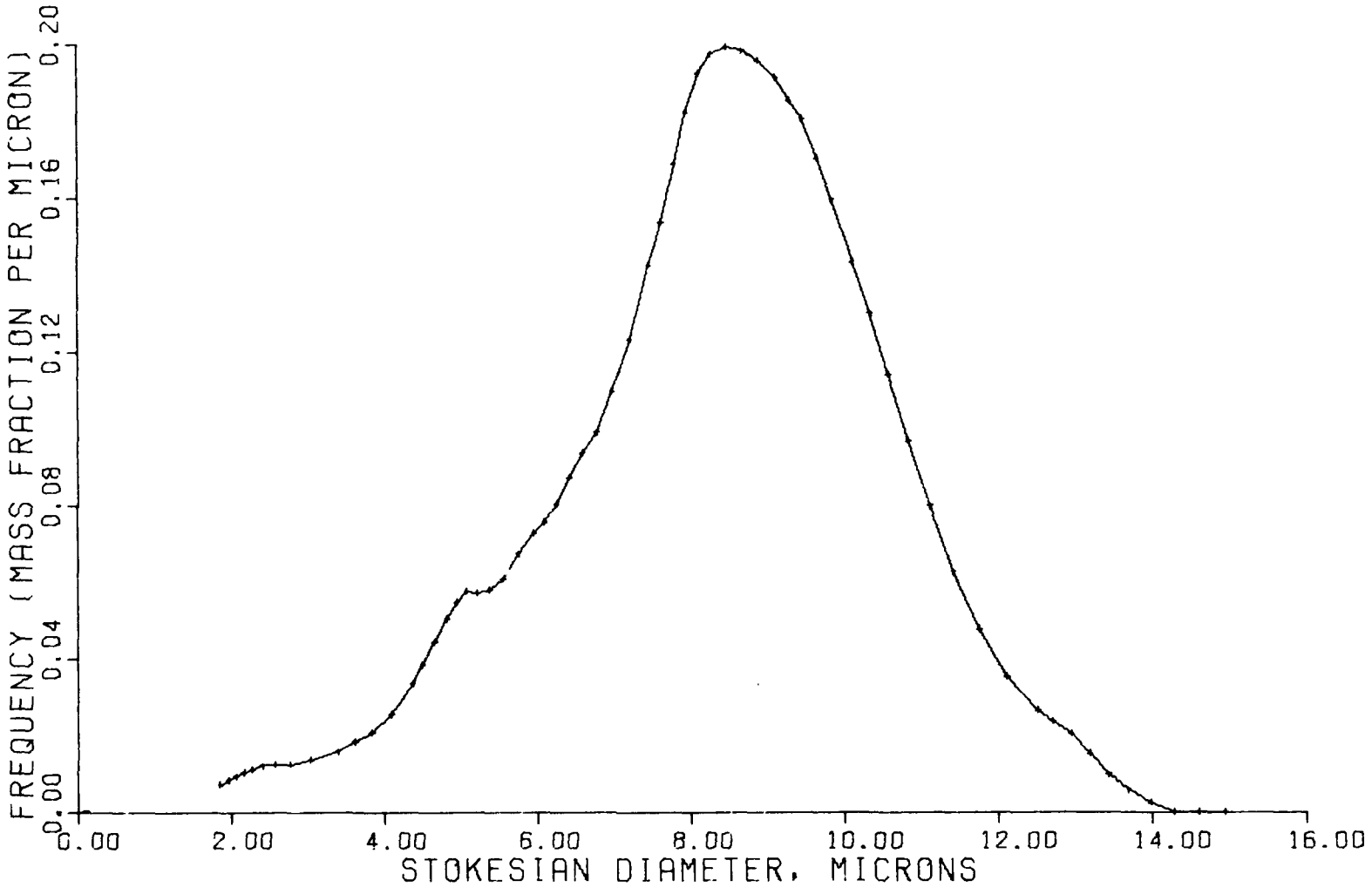

Figure 28. Experiment No. 14 Particle Size Frequency Distribution of Aluminum Metal Powder 1-10 Micron. Mass Concentration 1.41 mg/cc.

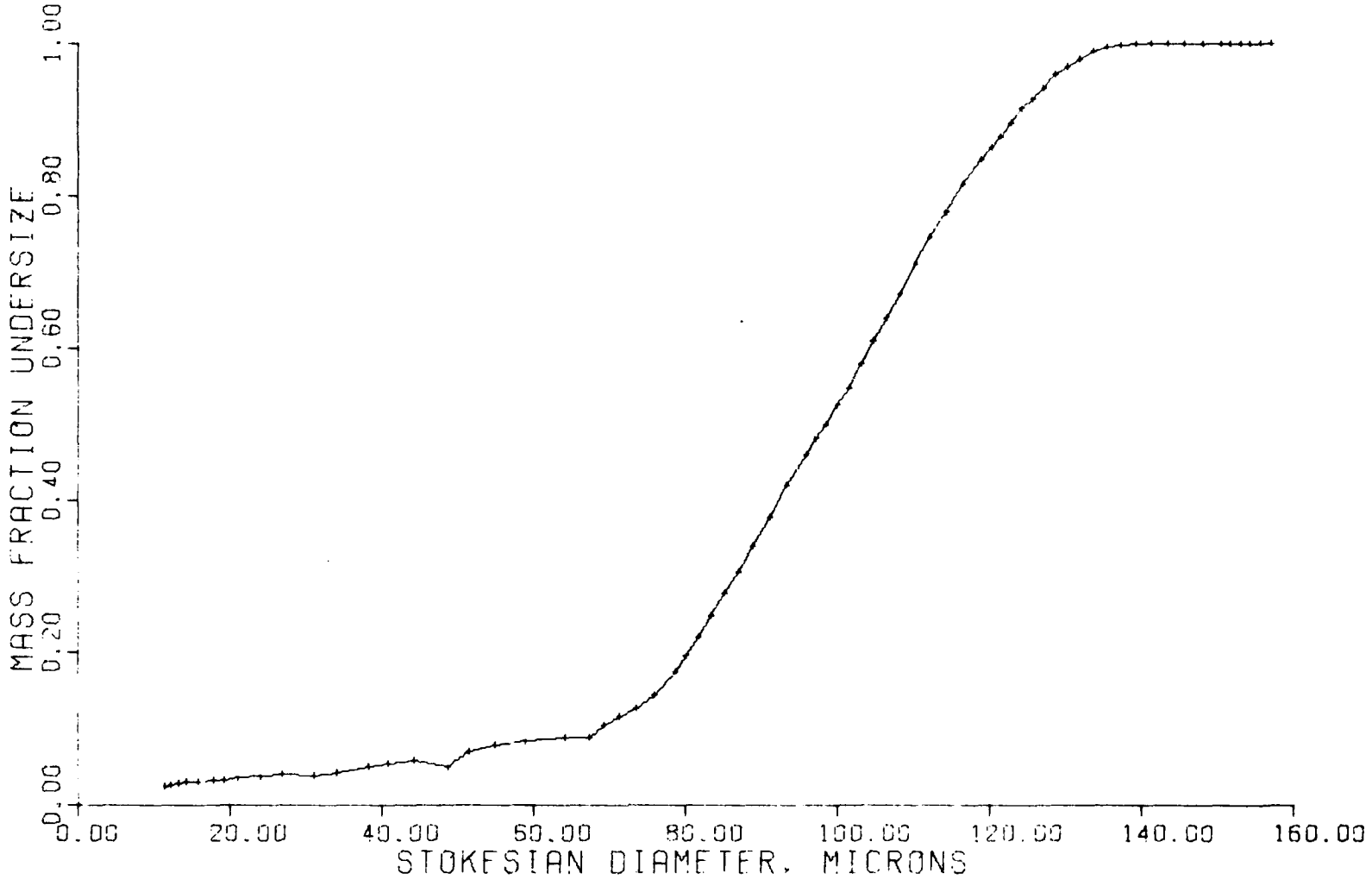

Figure 29. Experiment No. 15 Cumulative Particle Size Distribution of Aluminum Metal Powder -220+325 Mesh. Mass Concentration 1.14 mg/cc.

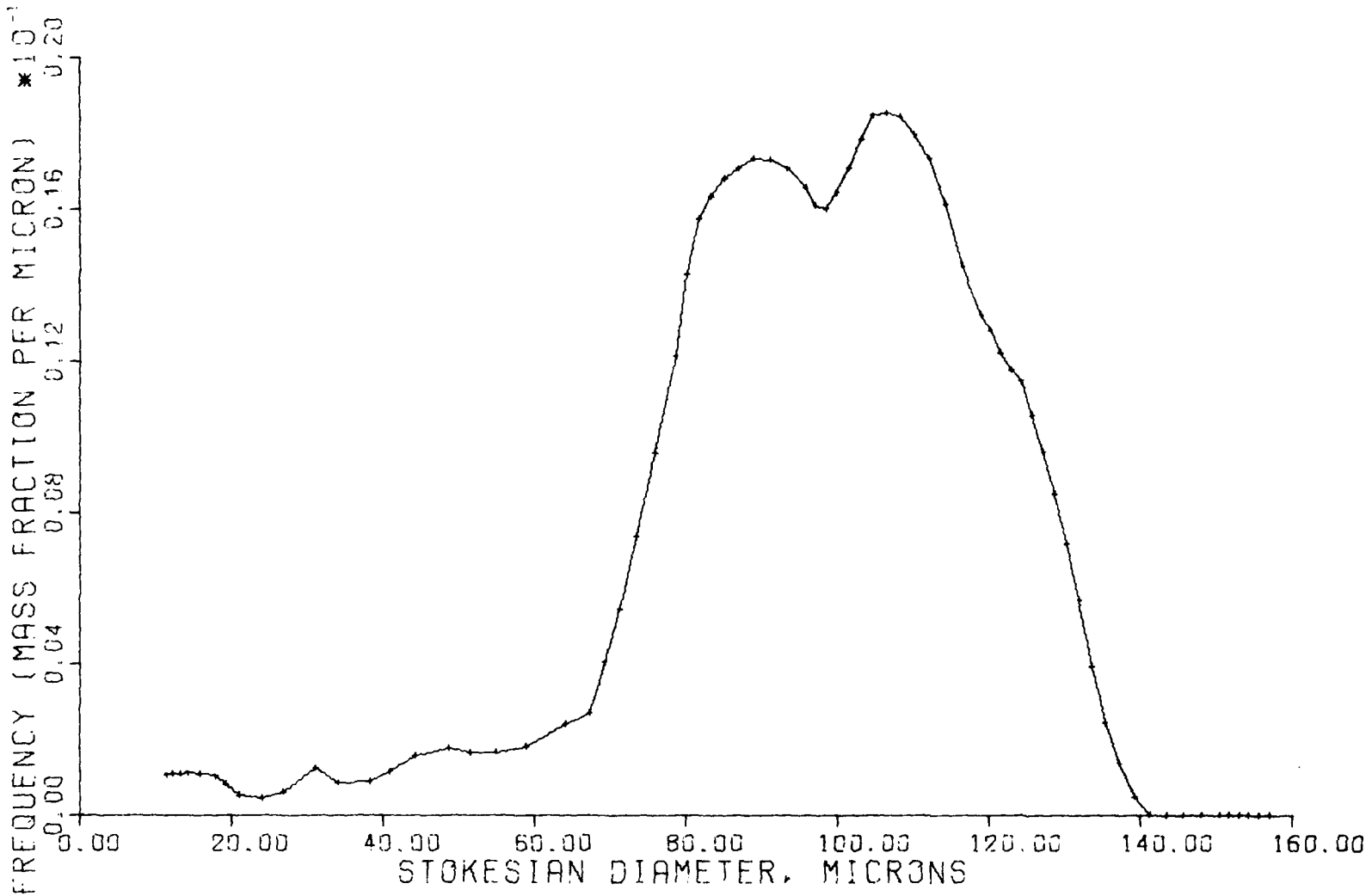

Figure 30. Experiment No. 15 Particle Size Frequency Distribution of Aluminum Metal Powder -200+325 Mesh. Mass Concentration 1.14 mg/cc.

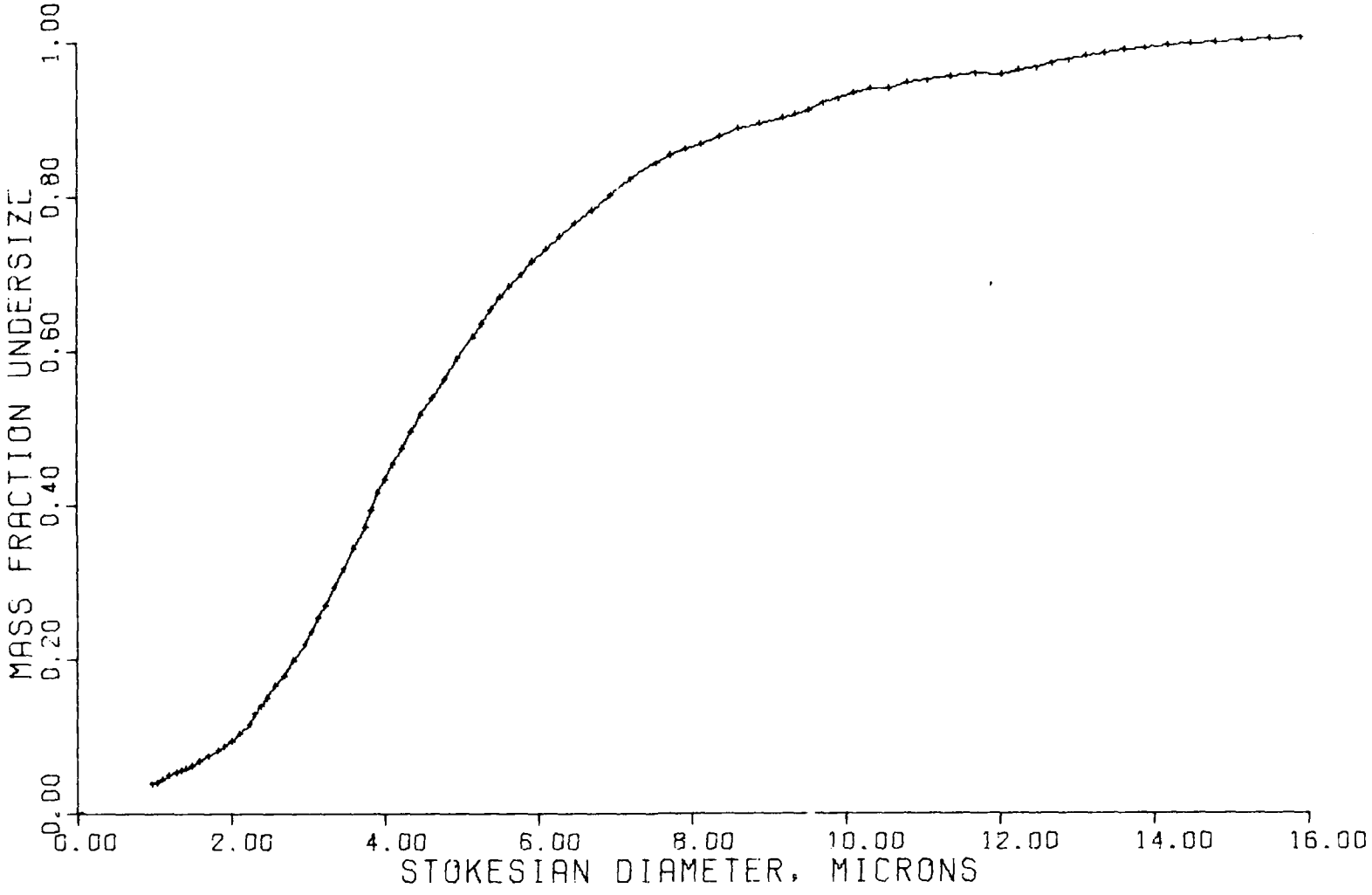

Figure 31. Experiment No. 16 Cumulative Particle Size Distribution of Zinc Metal Powder 0.5-5.0 Micron. Mass Concentration 1.03 mg/cc.

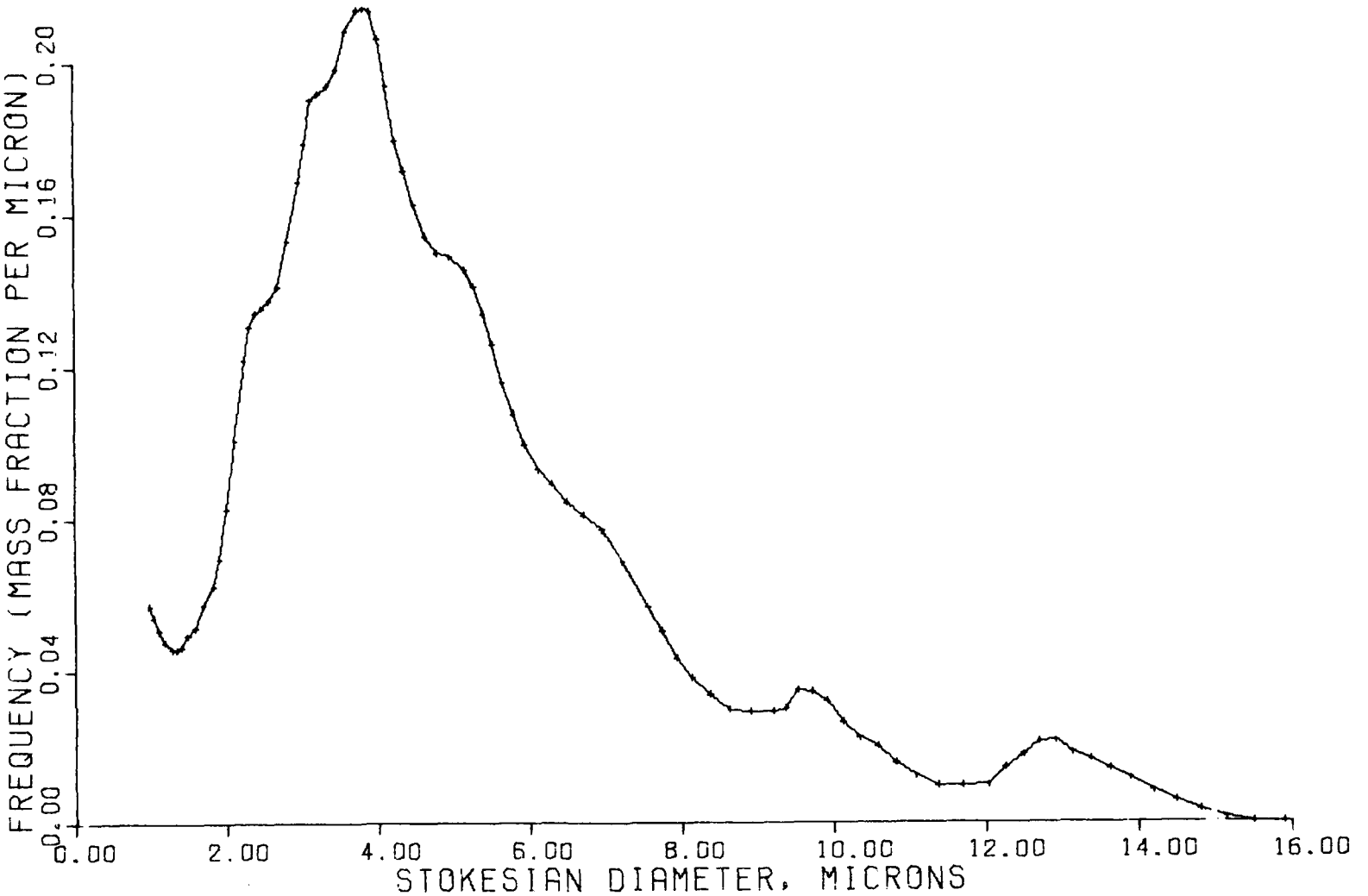

Figure 32. Experiment No. 16 Particle Size Frequency Distribution of Zinc Metal Powder 0.5-5.0 Micron. Mass Concentration 1.03 mg/cc.

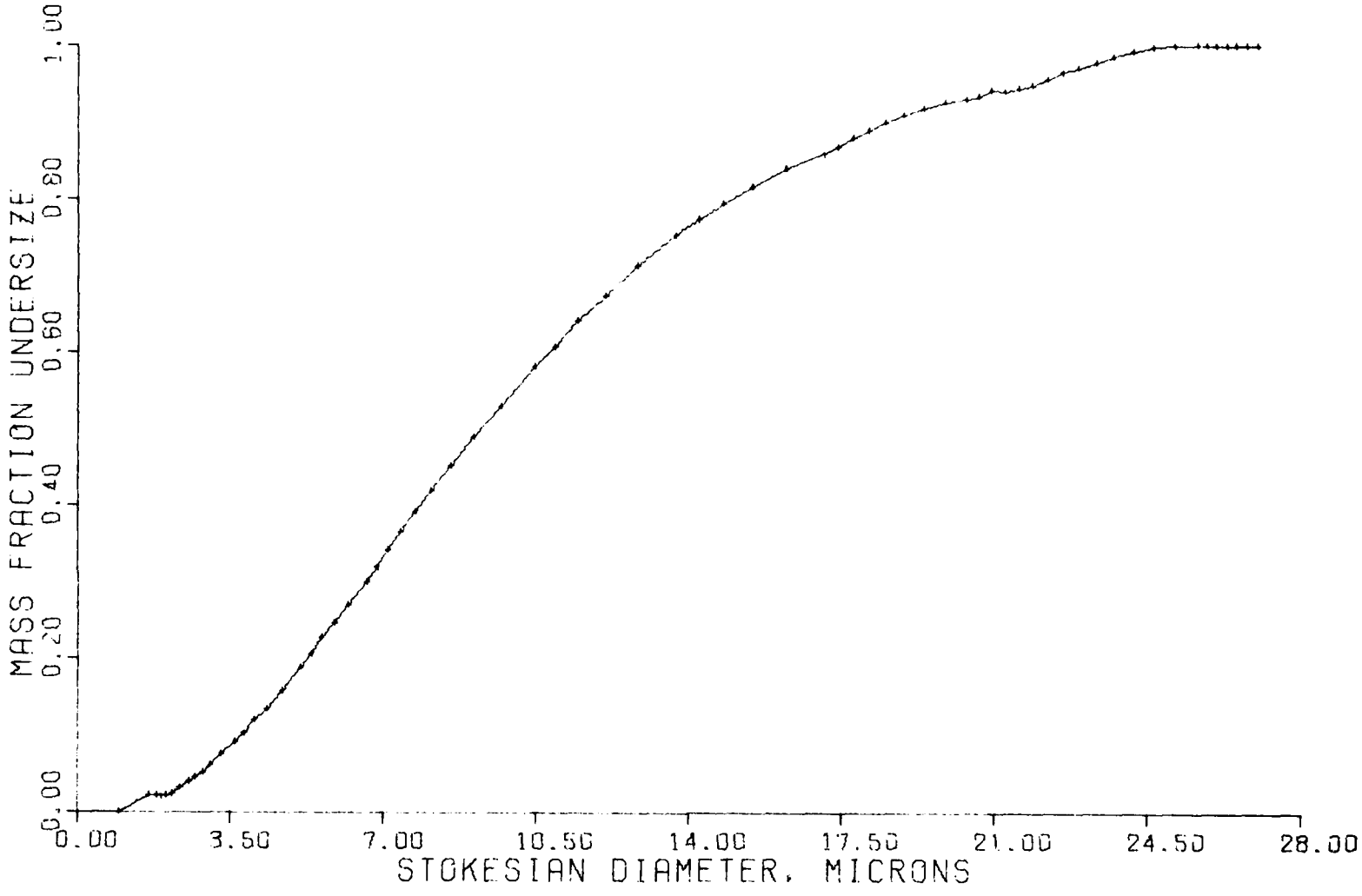

Figure 33. Experiment No. 17 Cumulative Particle Size Distribution of Zinc Metal Powder 1-10 Micron. Mass Concentration 1.03 mg/cc.

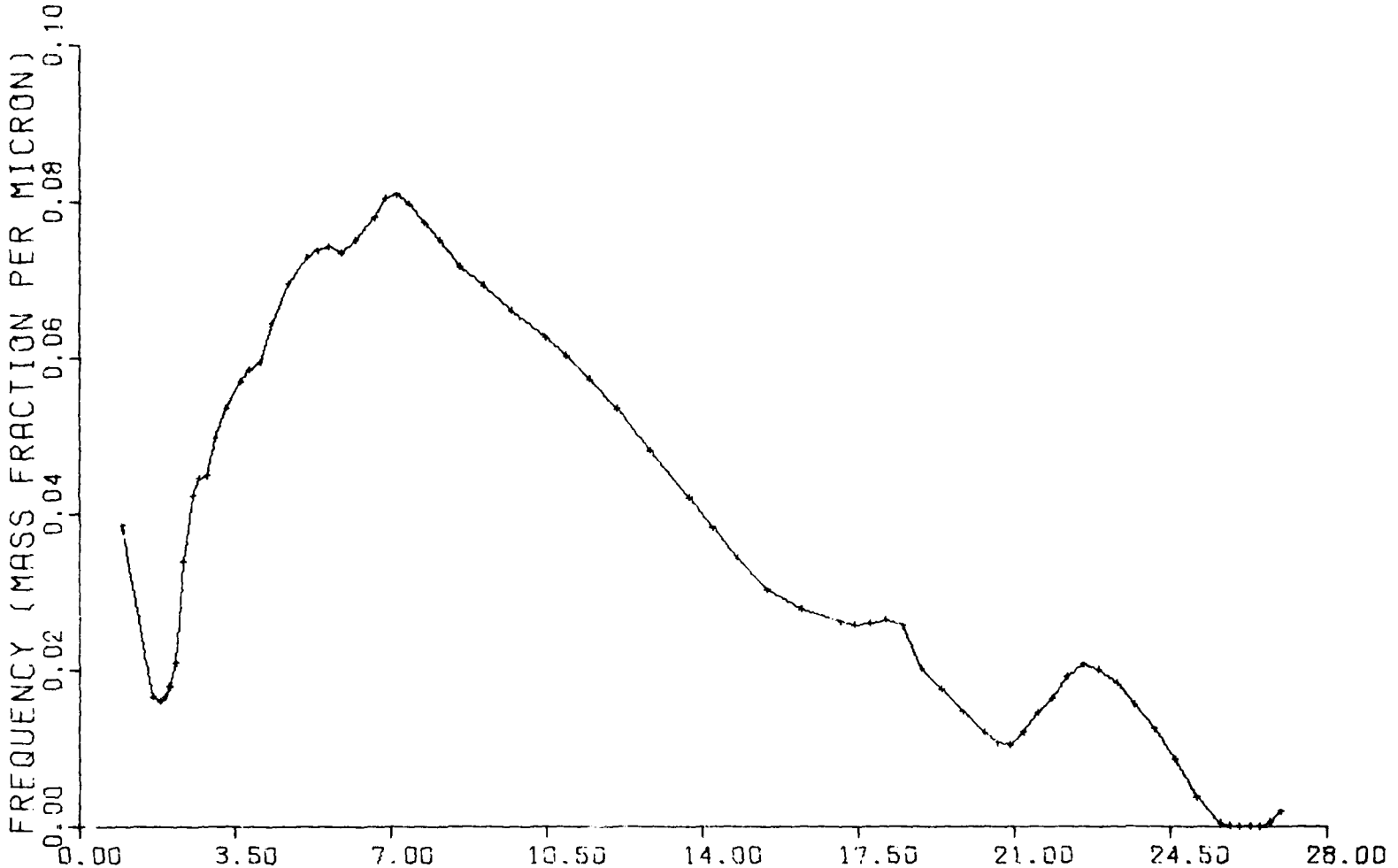

Figure 34. Experiment No. 17 Particle Size Frequency Distribution of Zinc Metal Powder 1-10 Micron. Mass Concentration 1.03 mg/cc.

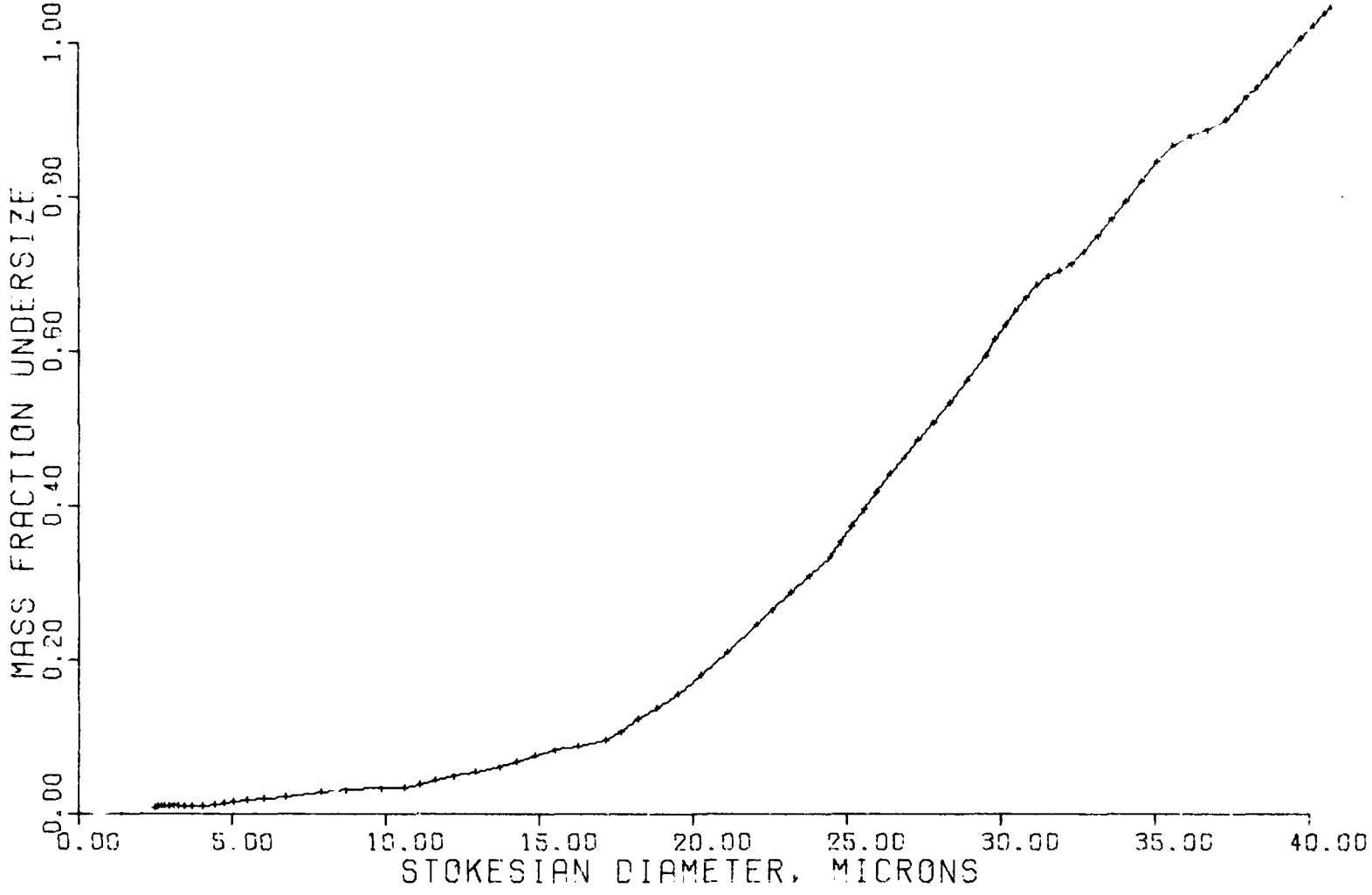

Figure 35. Experiment No. 18 Cumulative Size Distribution of Aluminum Oxide Powder -325 Mesh. Mass Concentration 0.66 mg/cc.

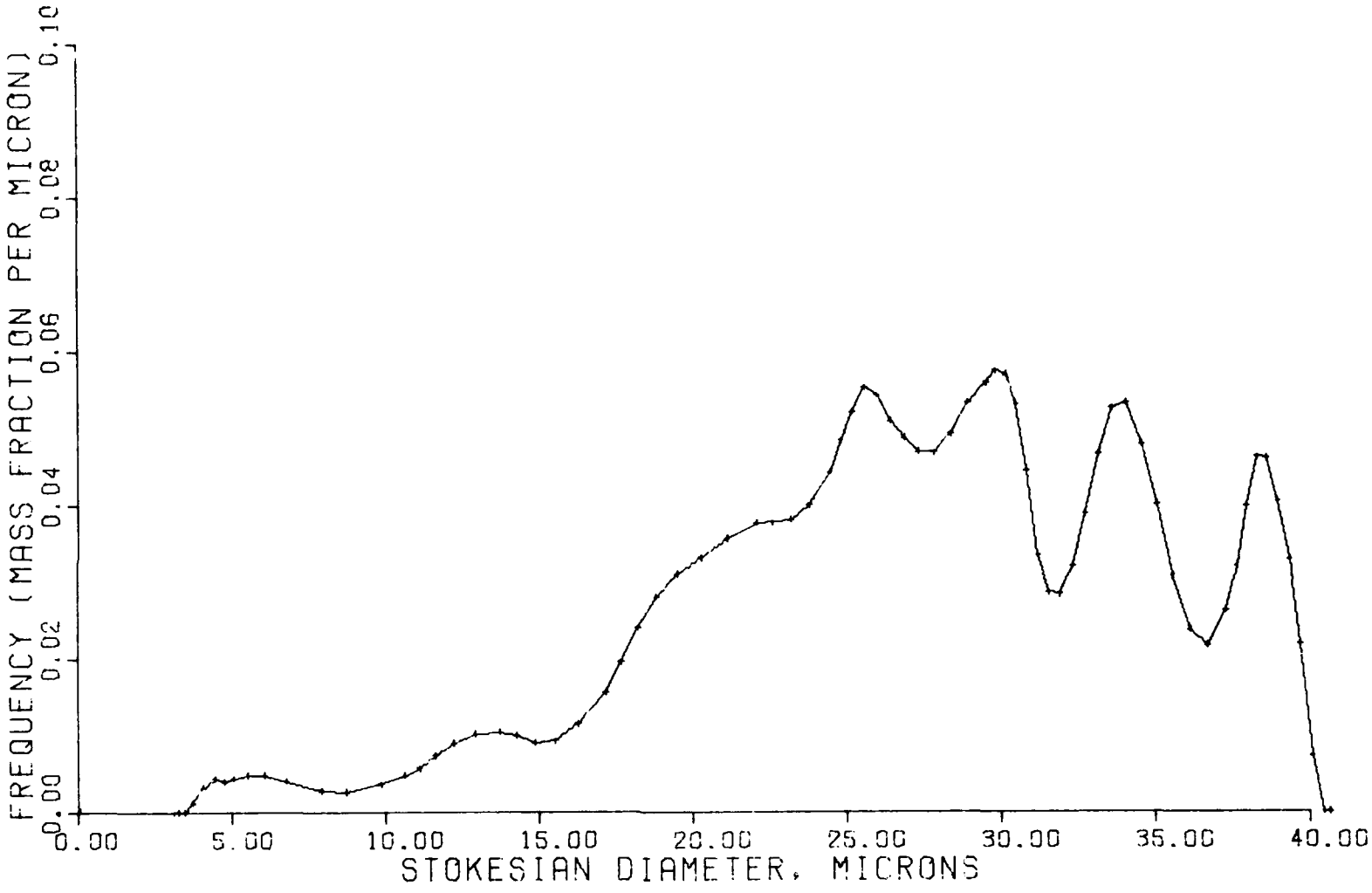

Figure 36. Experiment No. 18 Particle Size Frequency Distribution of Aluminum Oxide Powder -325 Mesh. Mass Concentration 0.66 mg/cc.

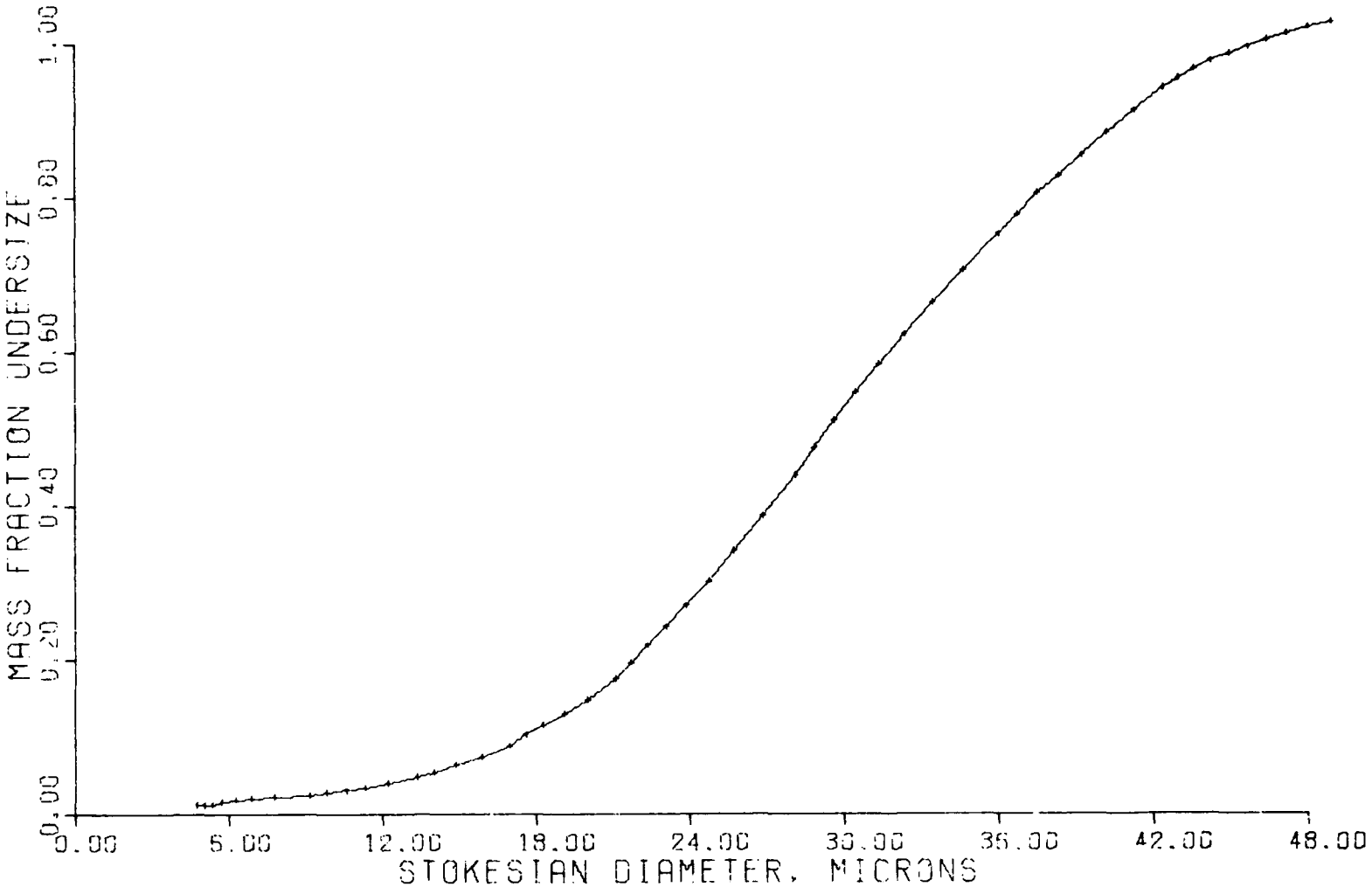

Figure 37. Experiment No. 19 Cumulative Particle Size Distribution of Aluminum Oxide Powder -325 Mesh. Mass Concentration 1.23 mg/cc.

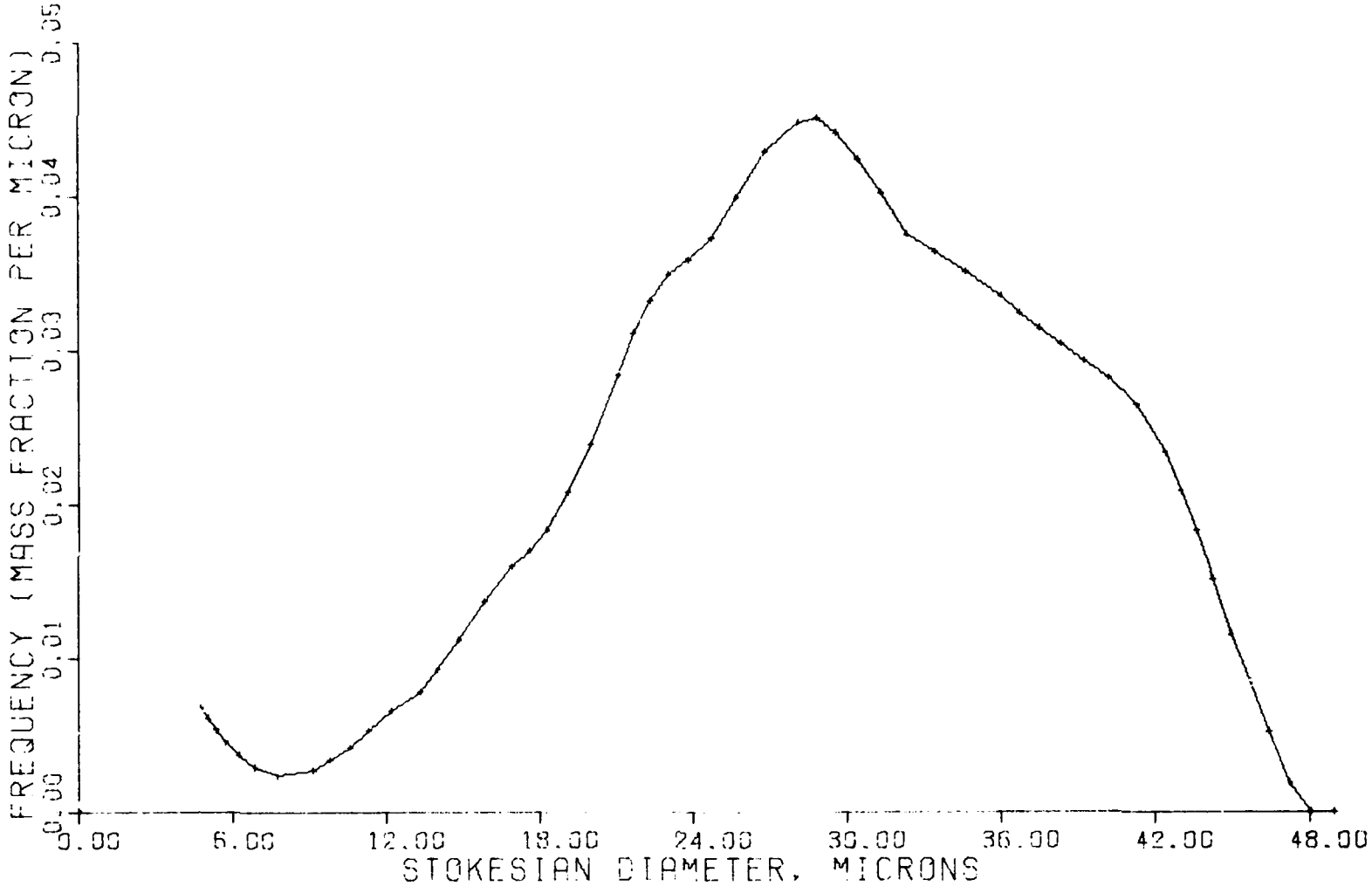

Figure 38. Experiment No. 19 Particle Size Frequency Distribution of Aluminum Oxide Powder -325 Mesh. Mass Concentration 1.23 mg/cc.

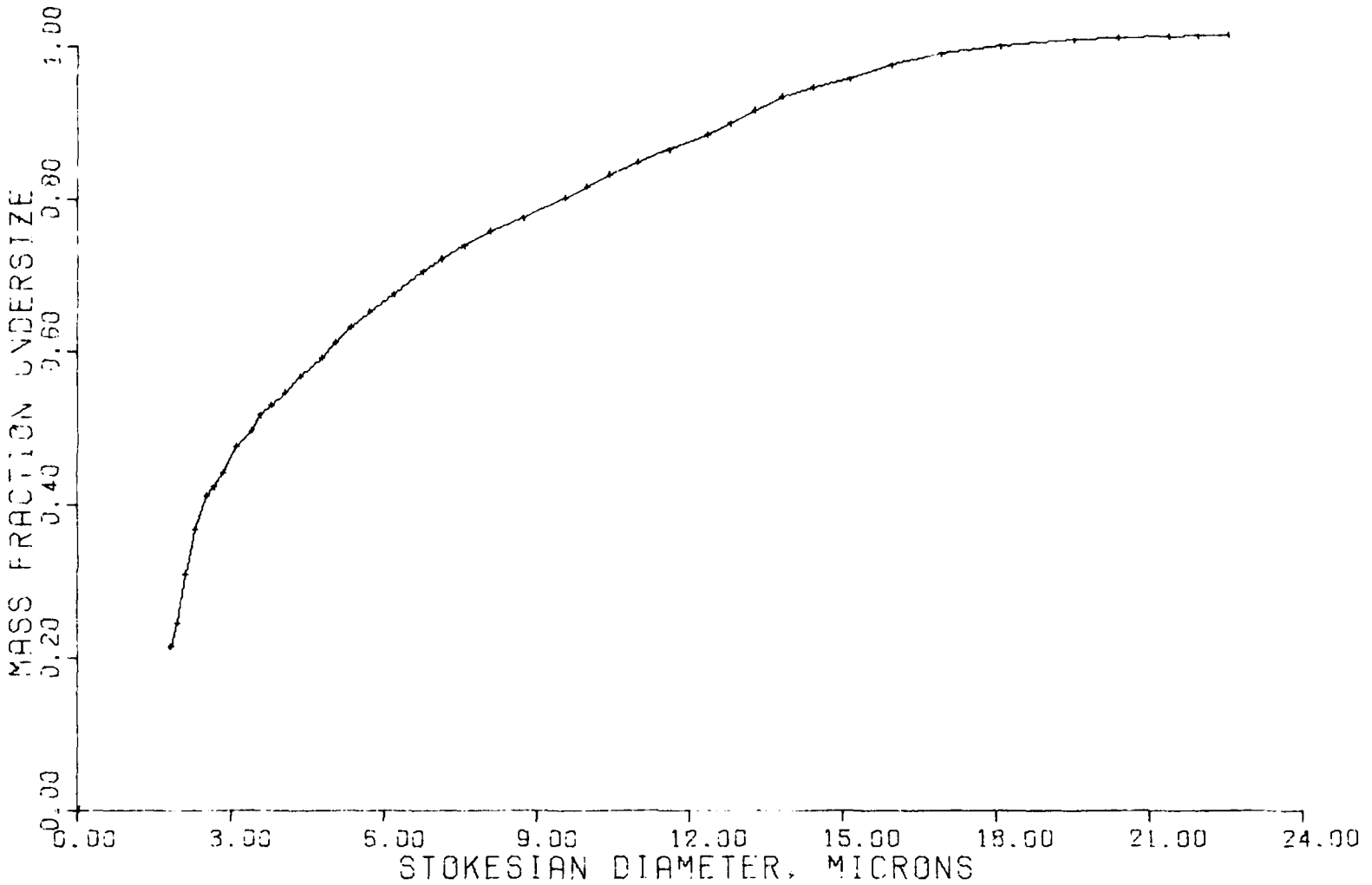

Figure 39. Experiment No. 20 Cumulative Particle Size Distribution of Fine Arizona Road Dust 75% 0-5 Micron. Mass Concentration 0.18 mg/cc.

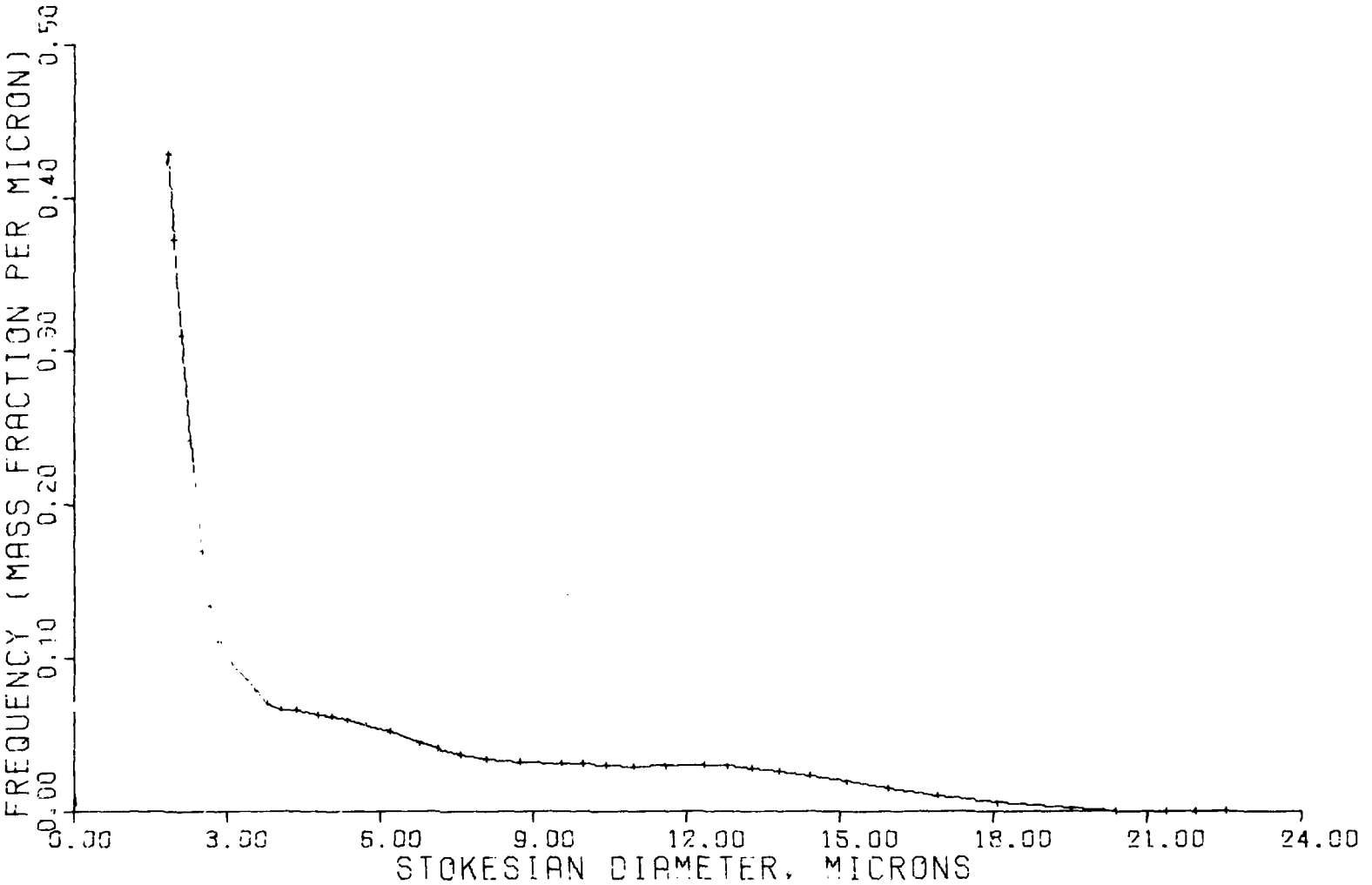

Figure 40. Experiment No. 20 Particle Size Frequency Distribution of Fine Arizona Road Dust 75% 0-5 Micron. Mass Concentrations 0.18 mg/cc.

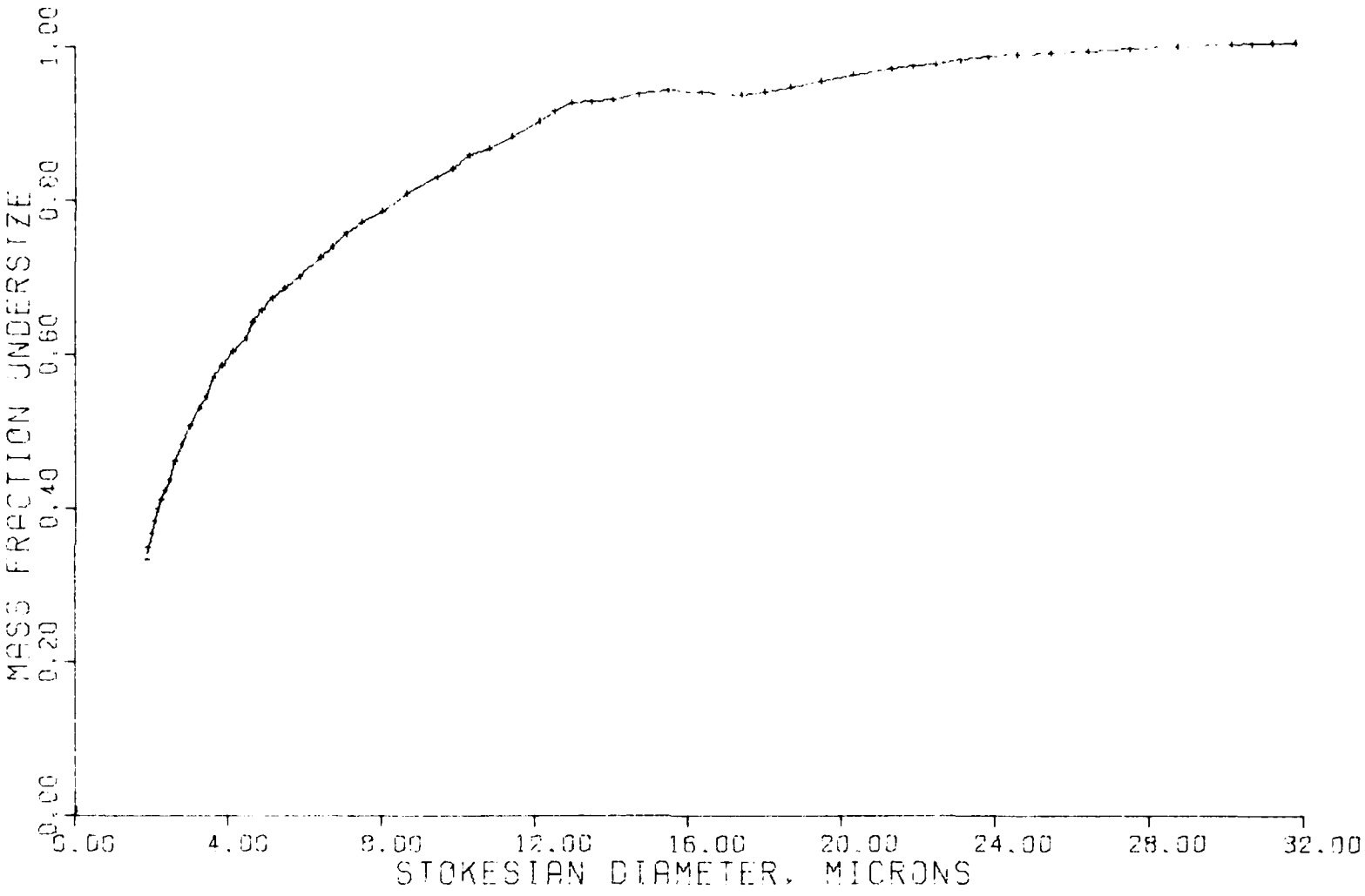

Figure 41. Experiment No. 21 Cumulative Particle Size Distribution of Fine Arizona Road Dust 75% 0-5 Micron. Mass Concentration 1.45 mg/cc.

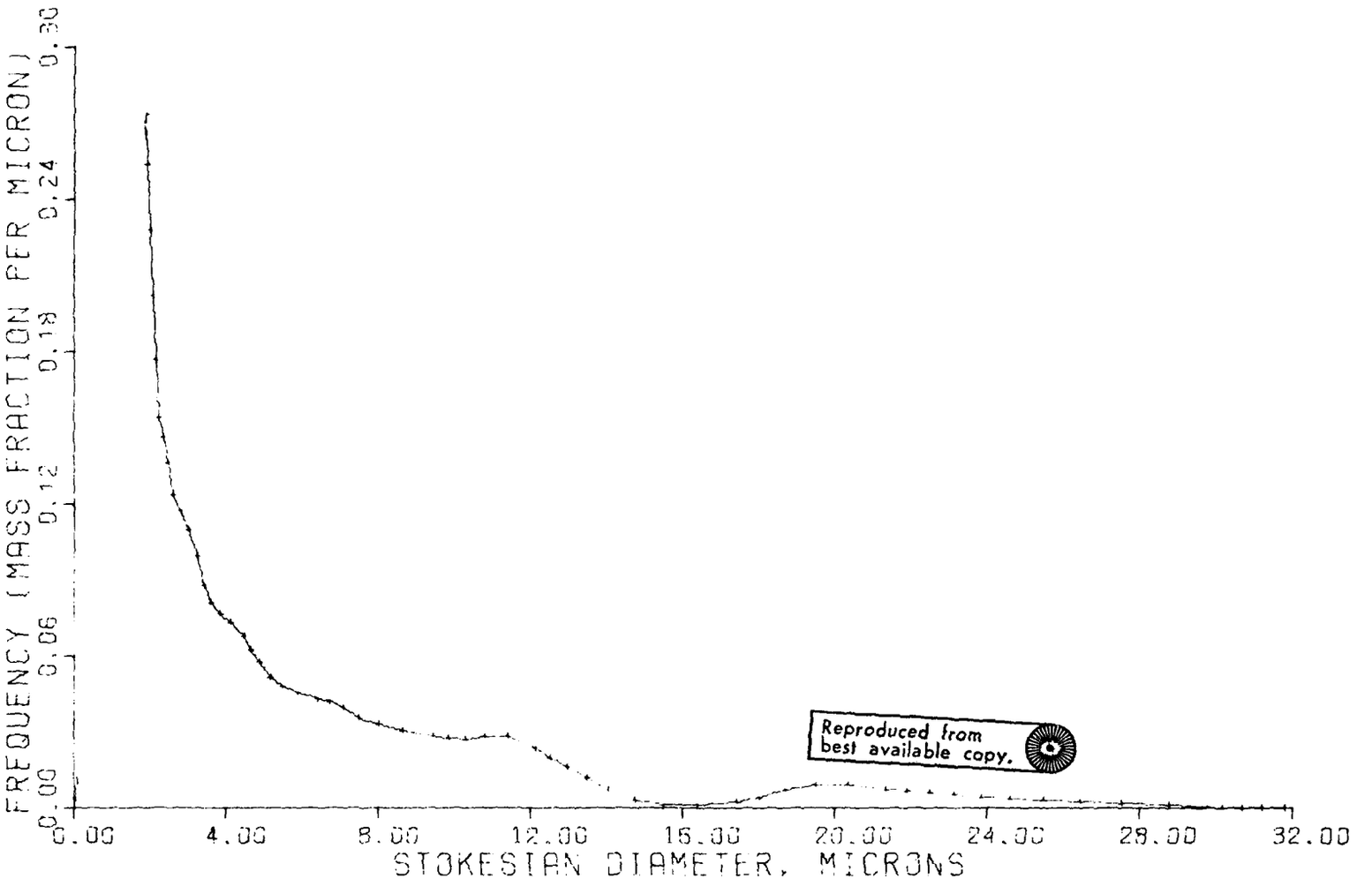

Figure 42. Experiment No. 21 Particle Size Frequency Distribution of Fine Arizona Road Dust 75% 0-5 Micron. Mass Concentration 1.45 mg/cc.

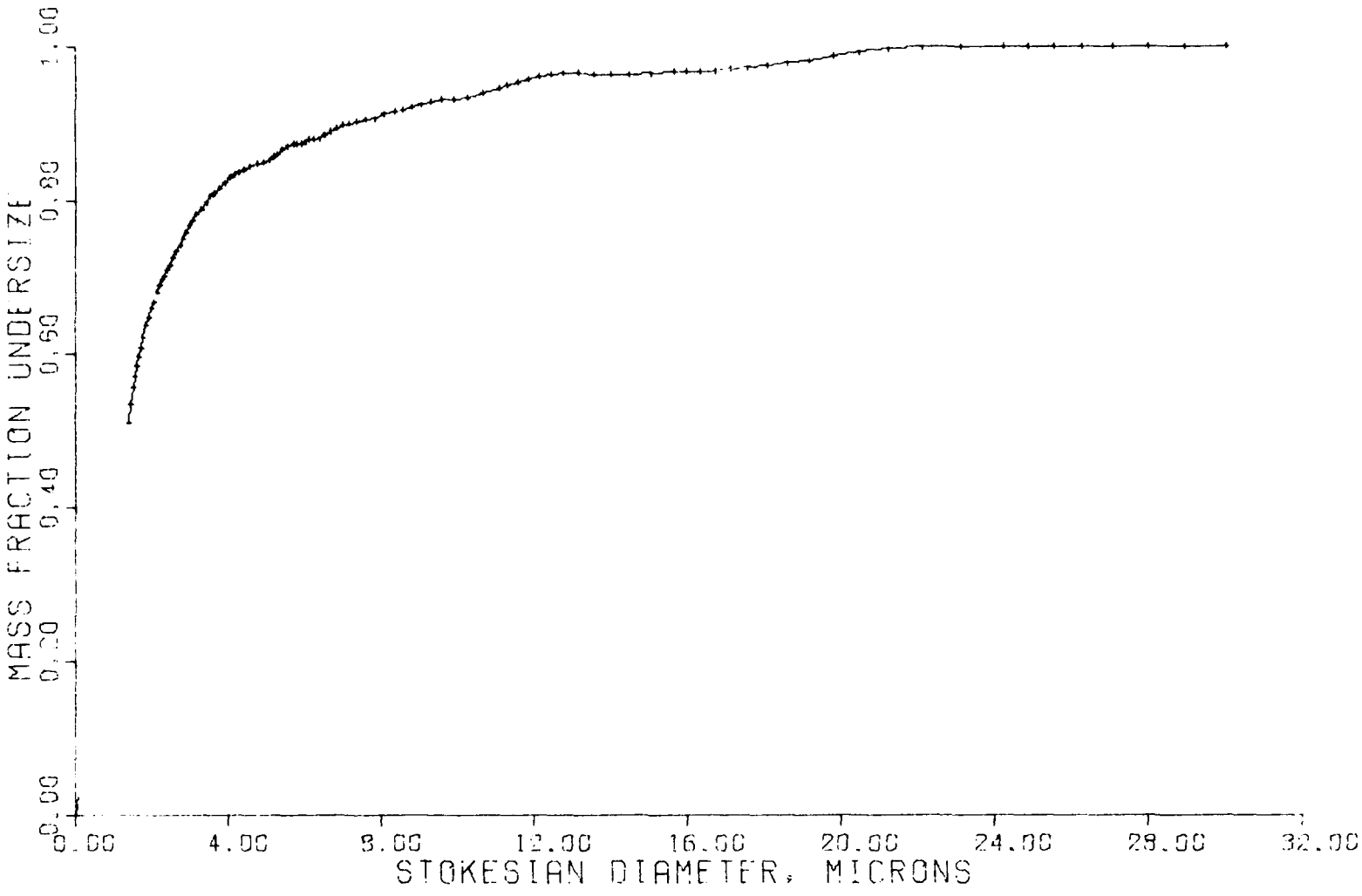

Figure 43. Experiment No. 22 Cumulative Particle Size Distribution of Amorphous Boron (Repowdered). Mass Concentration 1.53 mg/cc.

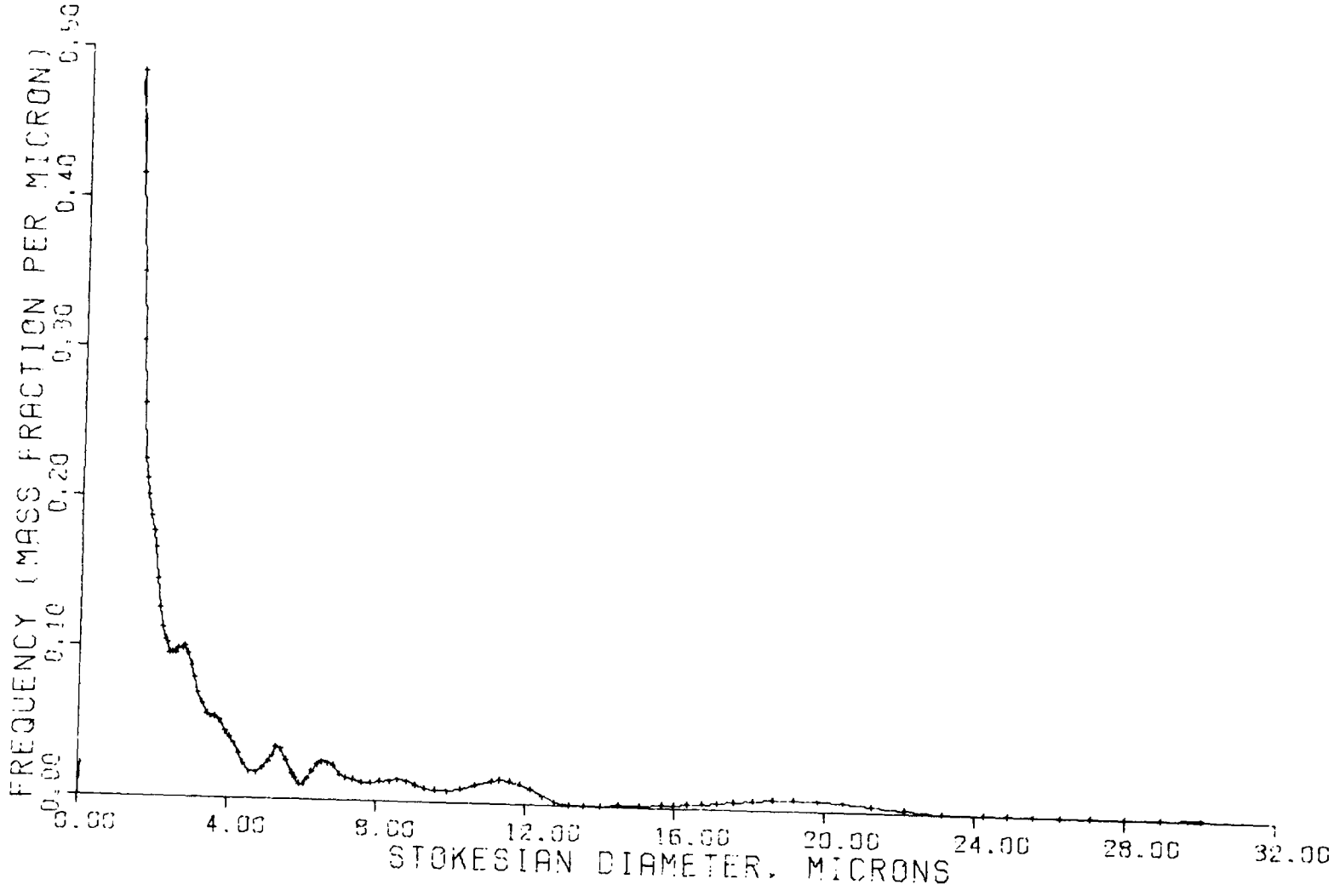

Figure 44. Experiment No. 22 Particle Size Frequency Distribution of Amorphous Boron (Repowdered). Mass Concentration 1.53 mg/cc.

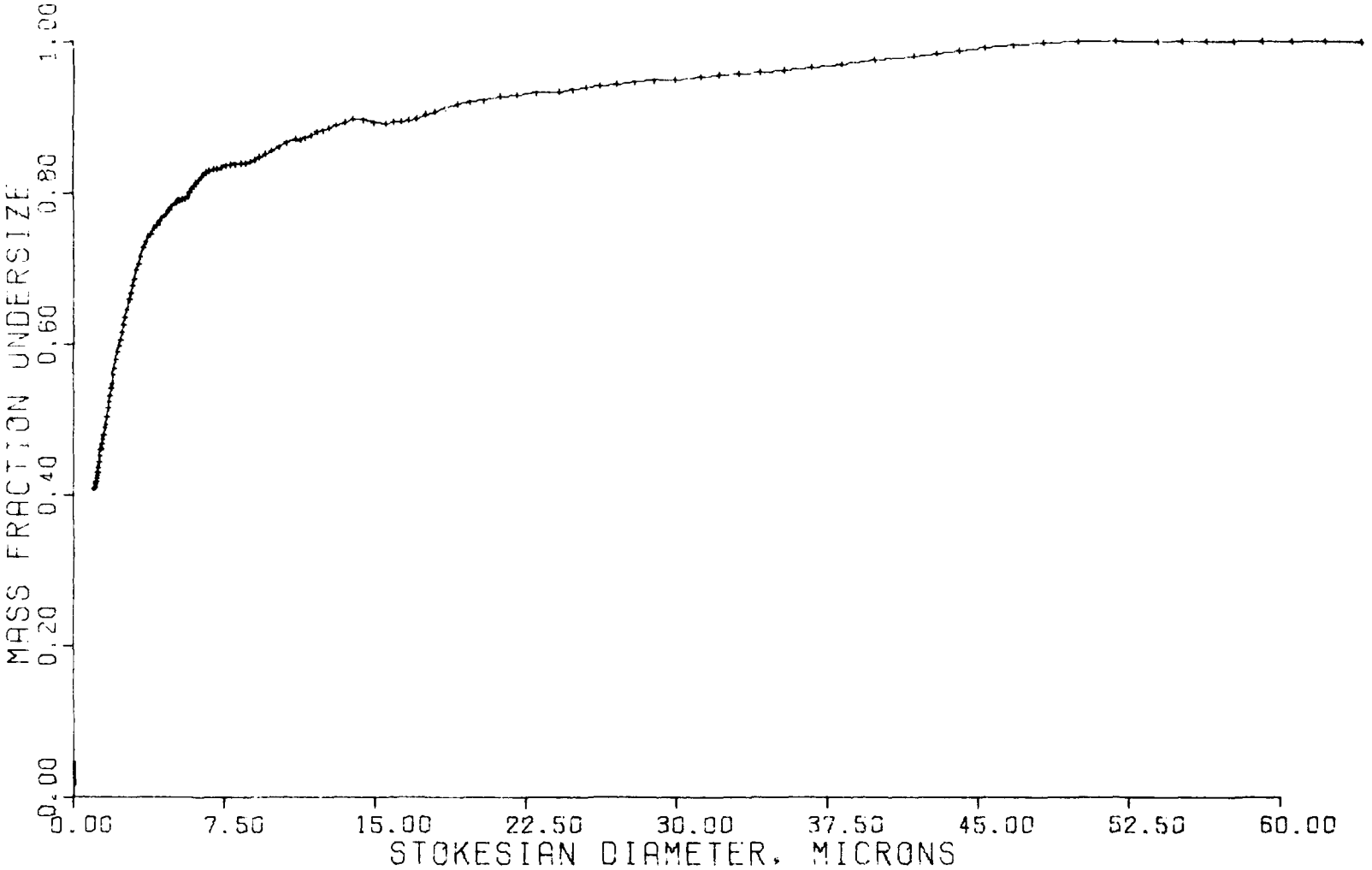

Figure 45. Experiment No. 23 Cumulative Particle Size Distribution of Amorphous Boron Powder 1 Micron. Mass Concentration 1.55 mg/cc.

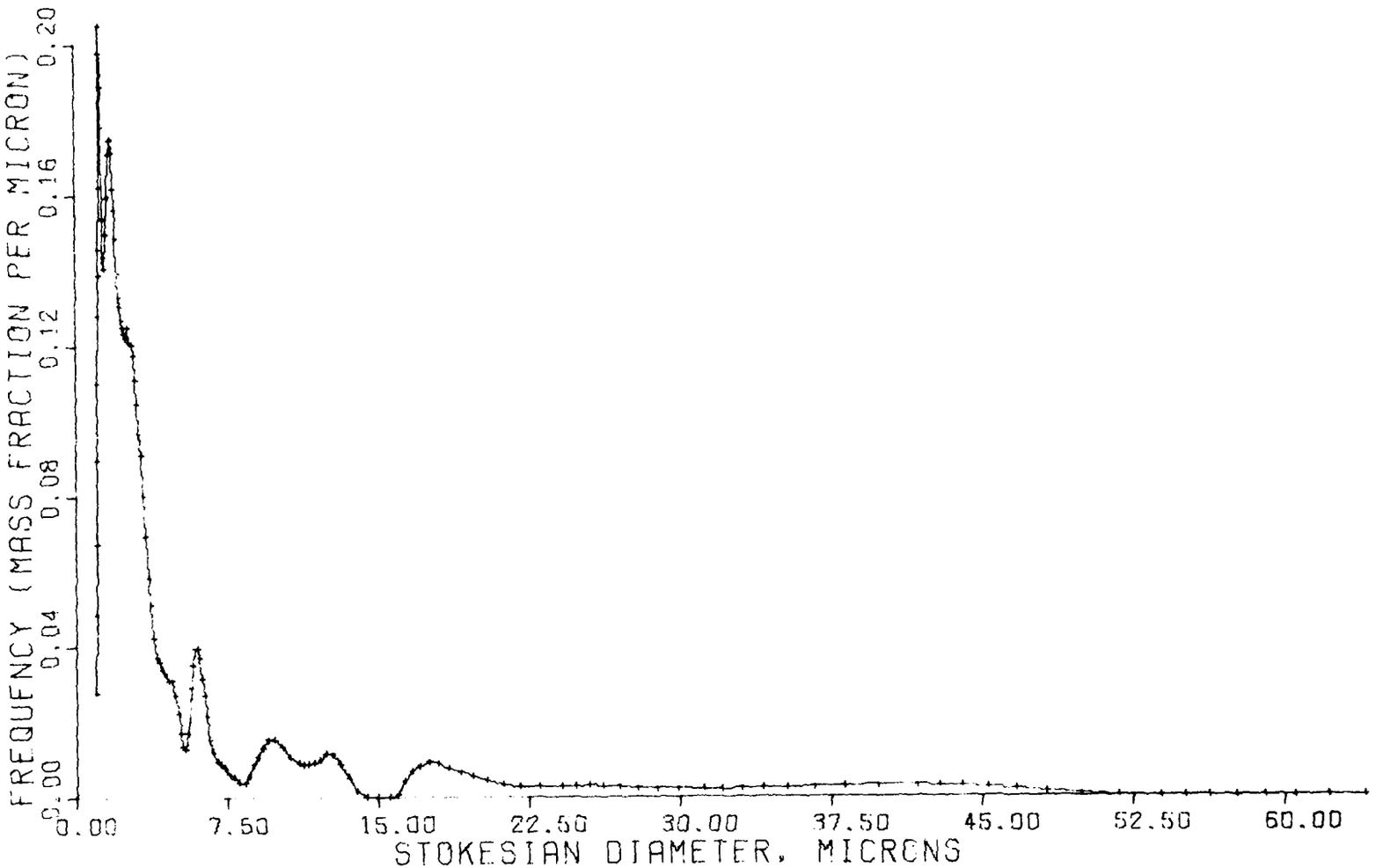

Figure 46. Experiment No. 23 Particle Size Frequency Distribution of Amorphous Boron Powder 1 Micron. Mass Concentration 1.55 mg/cc.

SECTION IV (CONTINUED)

B. RESULTS OF EXPERIMENTS CONDUCTED ON THE PHOTOSEDIMENTOMETER

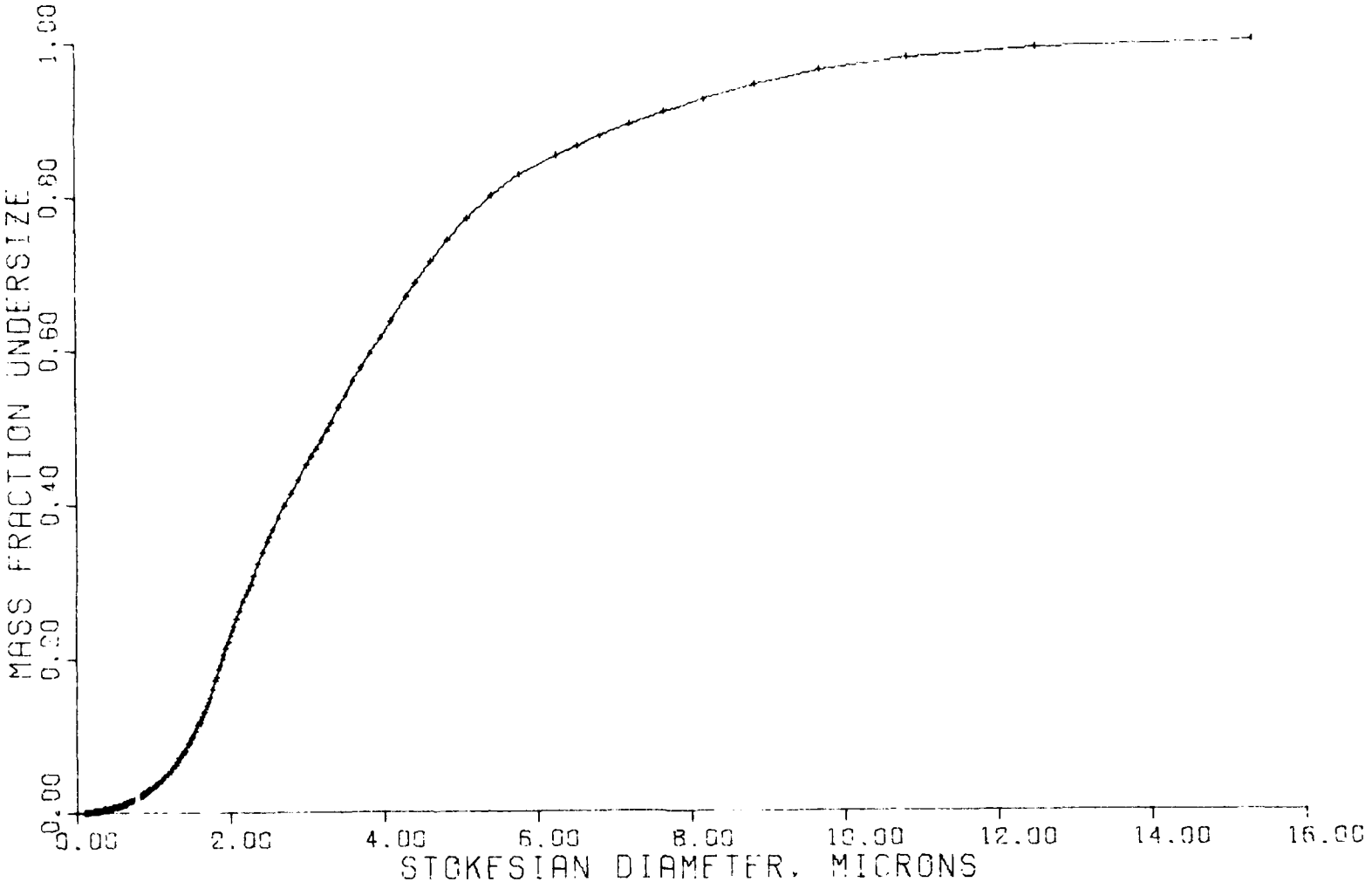

Figure 47. Experiment No. 24 Cumulative Particle Size Distribution of Fine Arizona Road Dust 75% 0-5 Micron. Concentration 10cc at 2×10^{-3} gm/cc.

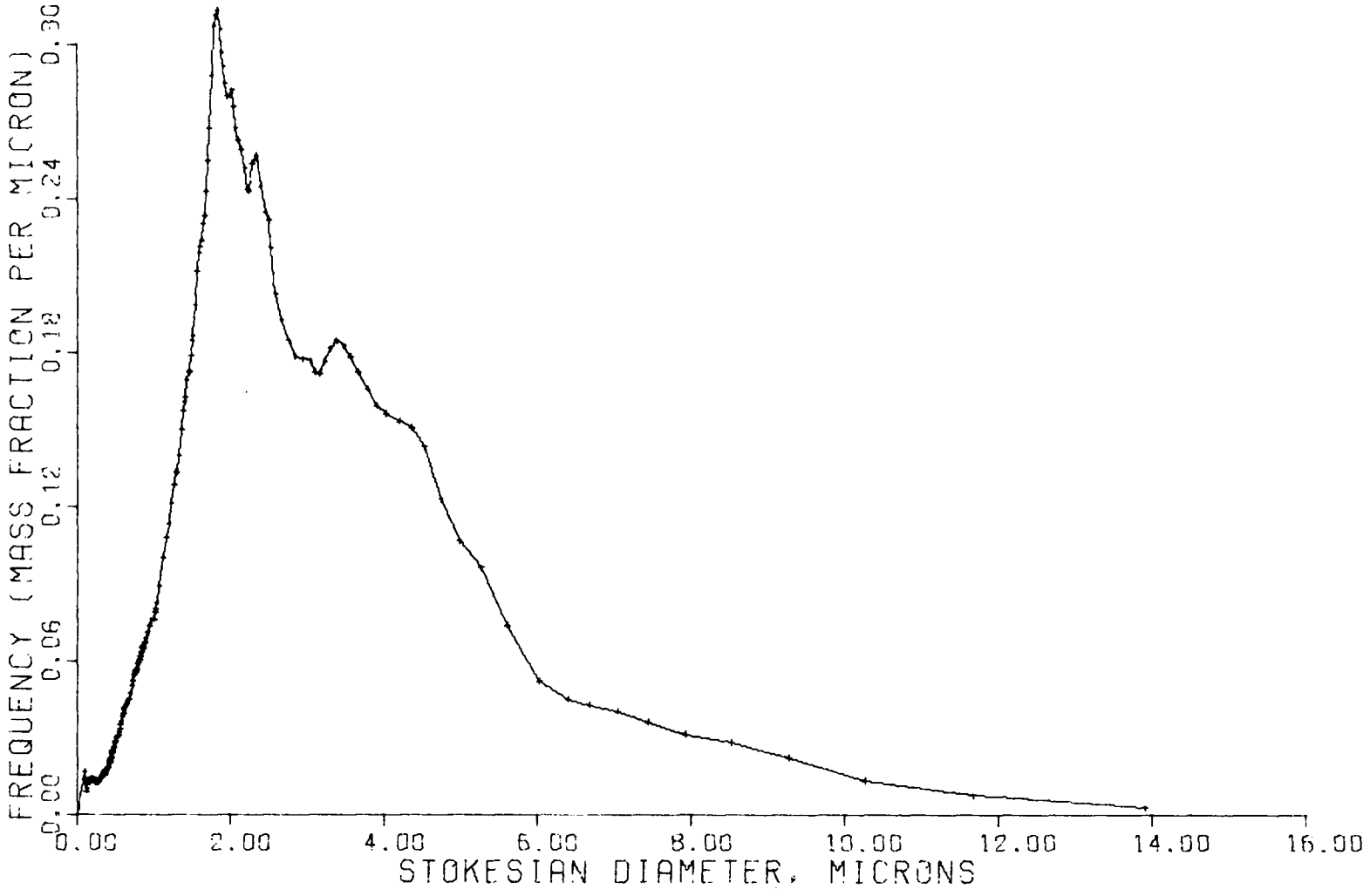

Figure 48. Experiment No. 24 Particle Size Frequency Distribution of Fine Arizona Road Dust 75% 0-5 Micron. Concentration 10cc at 2×10^{-3} gm/cc.

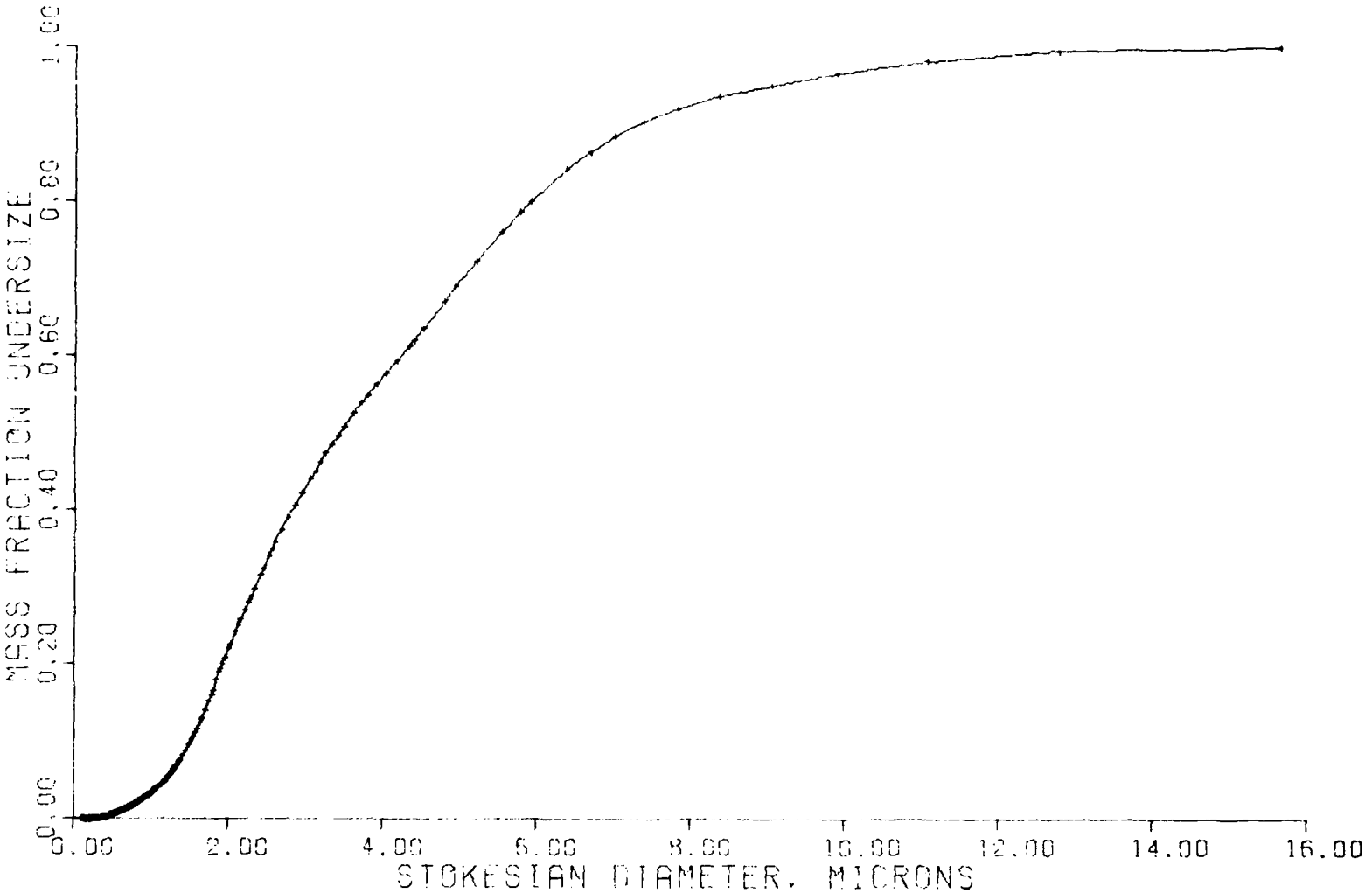

Figure 49. Experiment No. 25 Cumulative Particle Size Distribution of Fine Arizona Road Dust 75% 0-5 Micron. Concentration 10cc at 4×10^{-3} gm/cc.

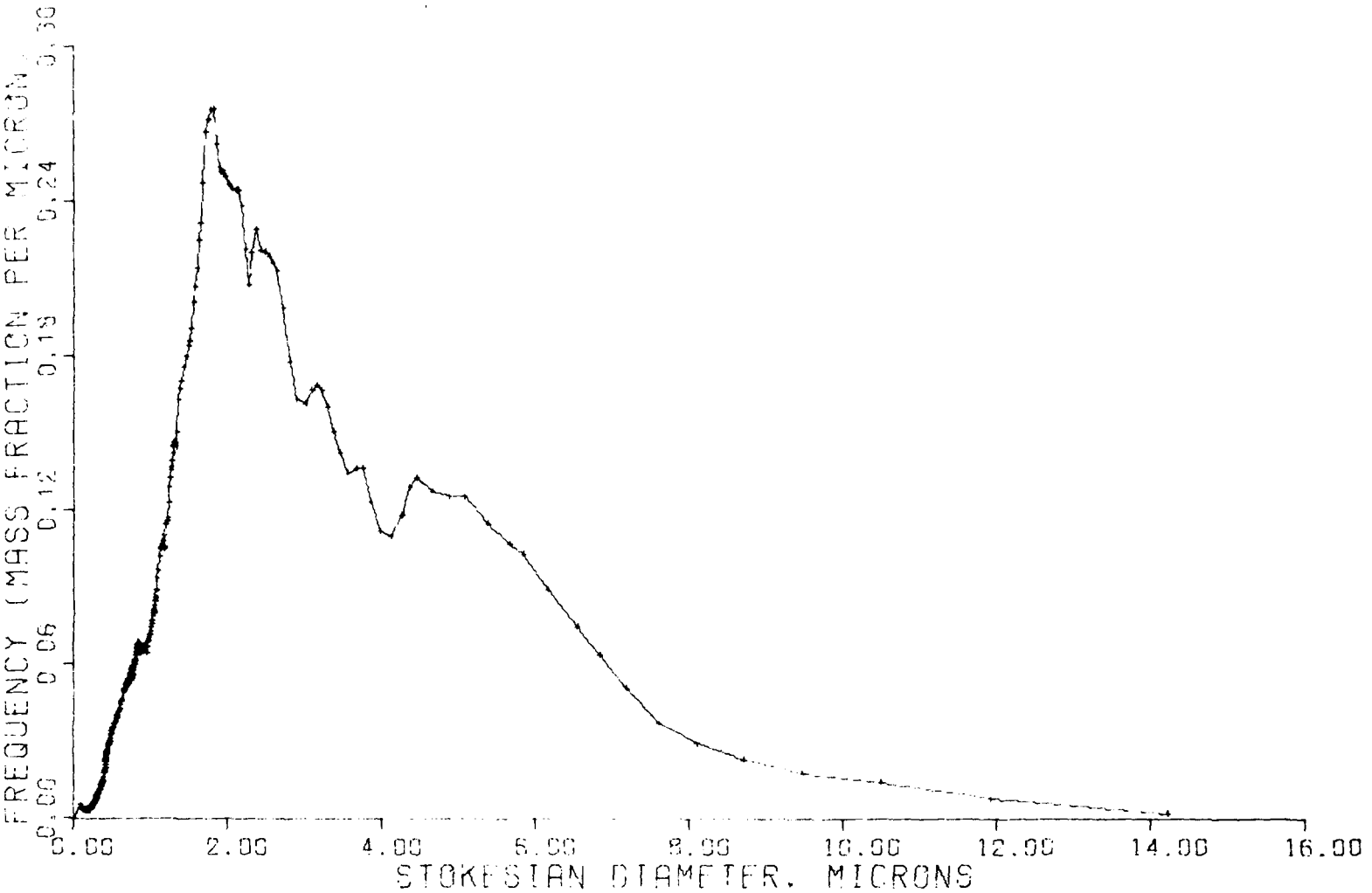

Figure 50. Experiment No. 25 Particle Size Frequency Distribution of Fine Arizona Road Dust 75% 0-5 Micron. Concentration 10cc at 4×10^{-3} gm/cc.

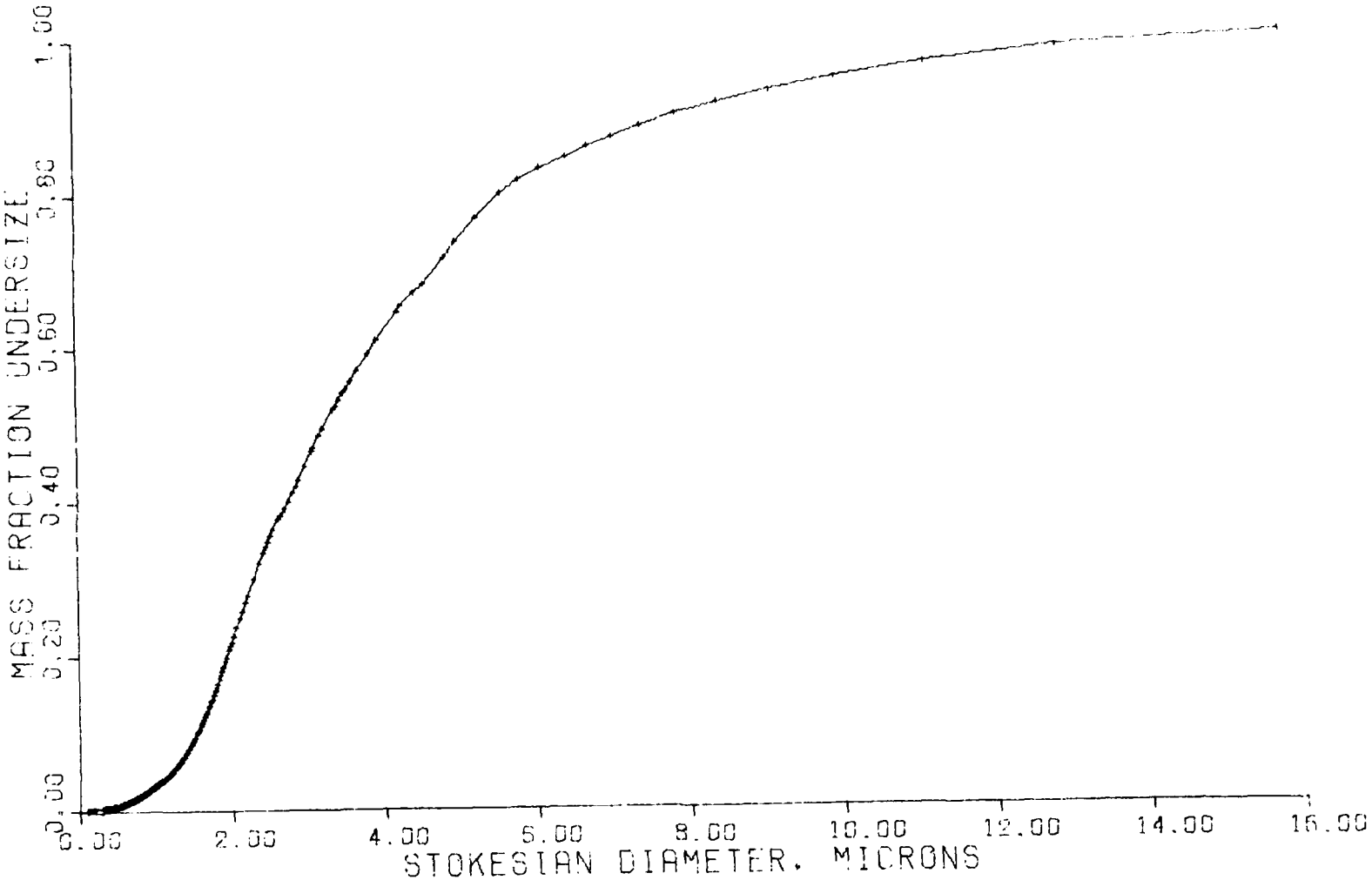

Figure 51. Experiment No. 26 Cumulative Particle Size Distribution of Fine Arizona Road Dust 75% 0-5 Micron. Concentration 10cc at 8×10^{-3} gm/cc.

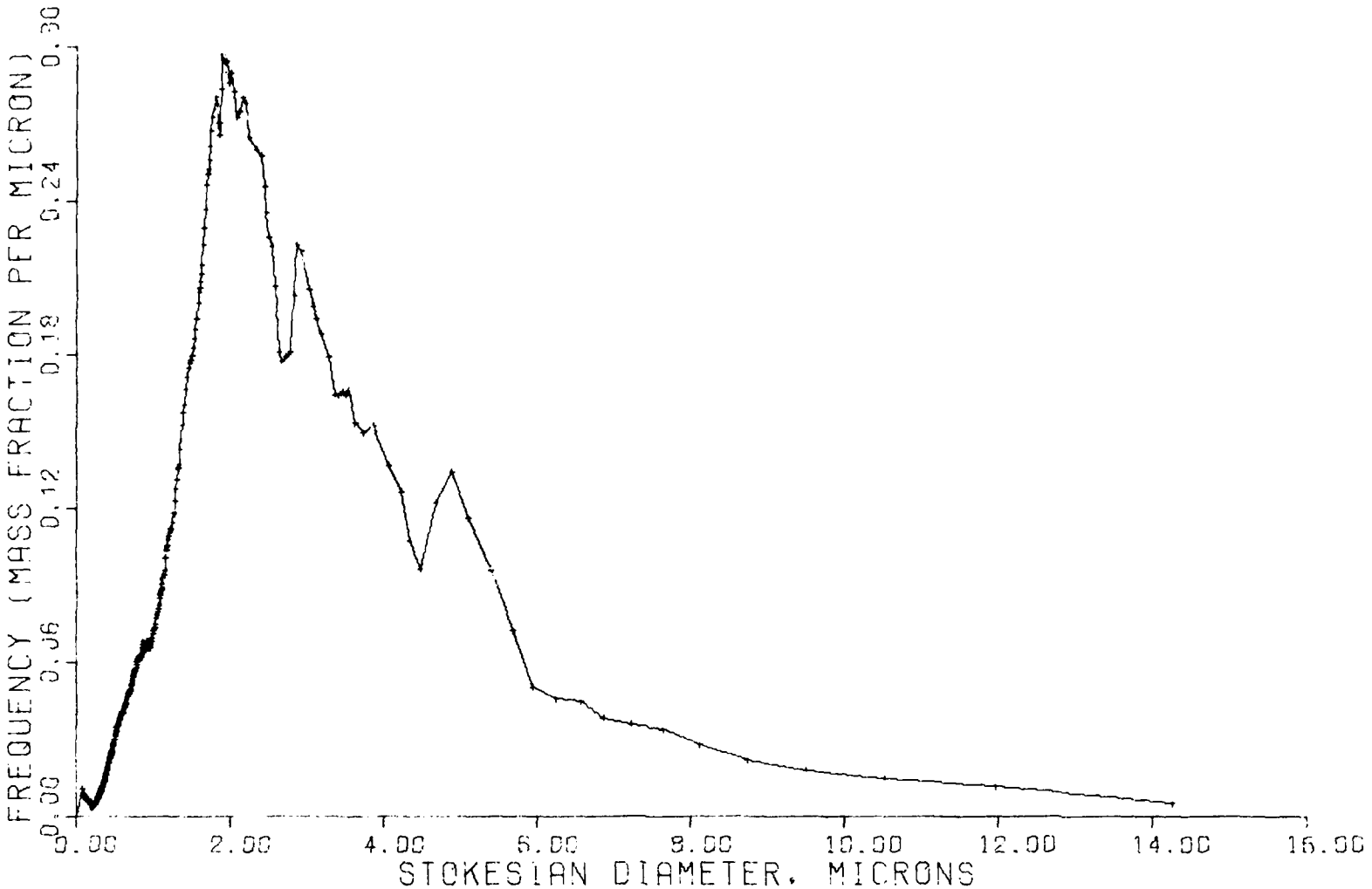

Figure 52. Experiment No. 26 Particle Size Frequency Distribution of Fine Arizona Road Dust 75% 0-5 Micron. Concentration 10cc at 8×10^{-3} gm/cc.

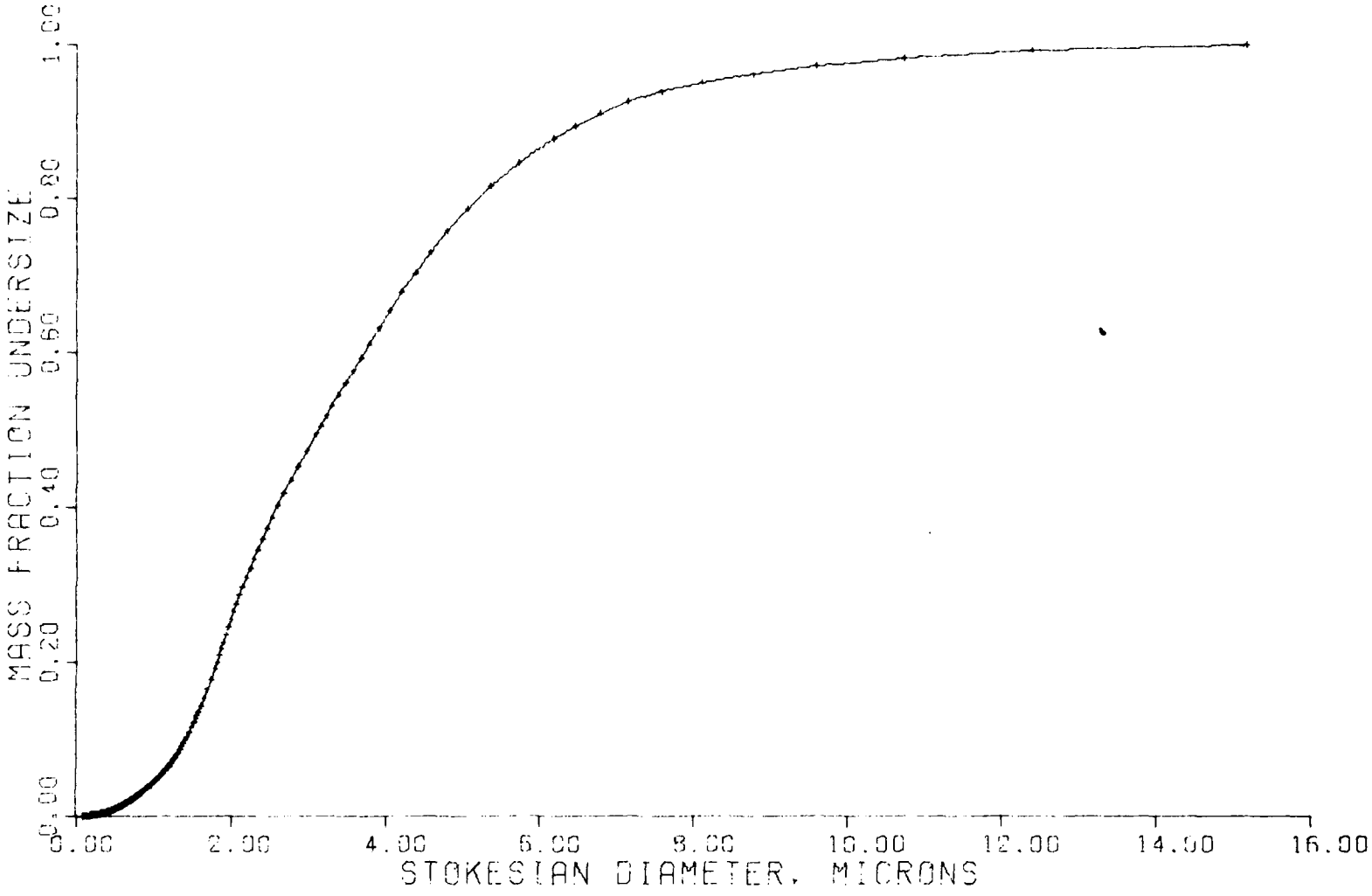

Figure 53. Experiment No. 27 Cumulative Particle Size Distribution of Fine Arizona Road Dust 75% 0-5 Micron, Buffer Layer. Concentration 10cc at 2×10^{-3}gm/cc.

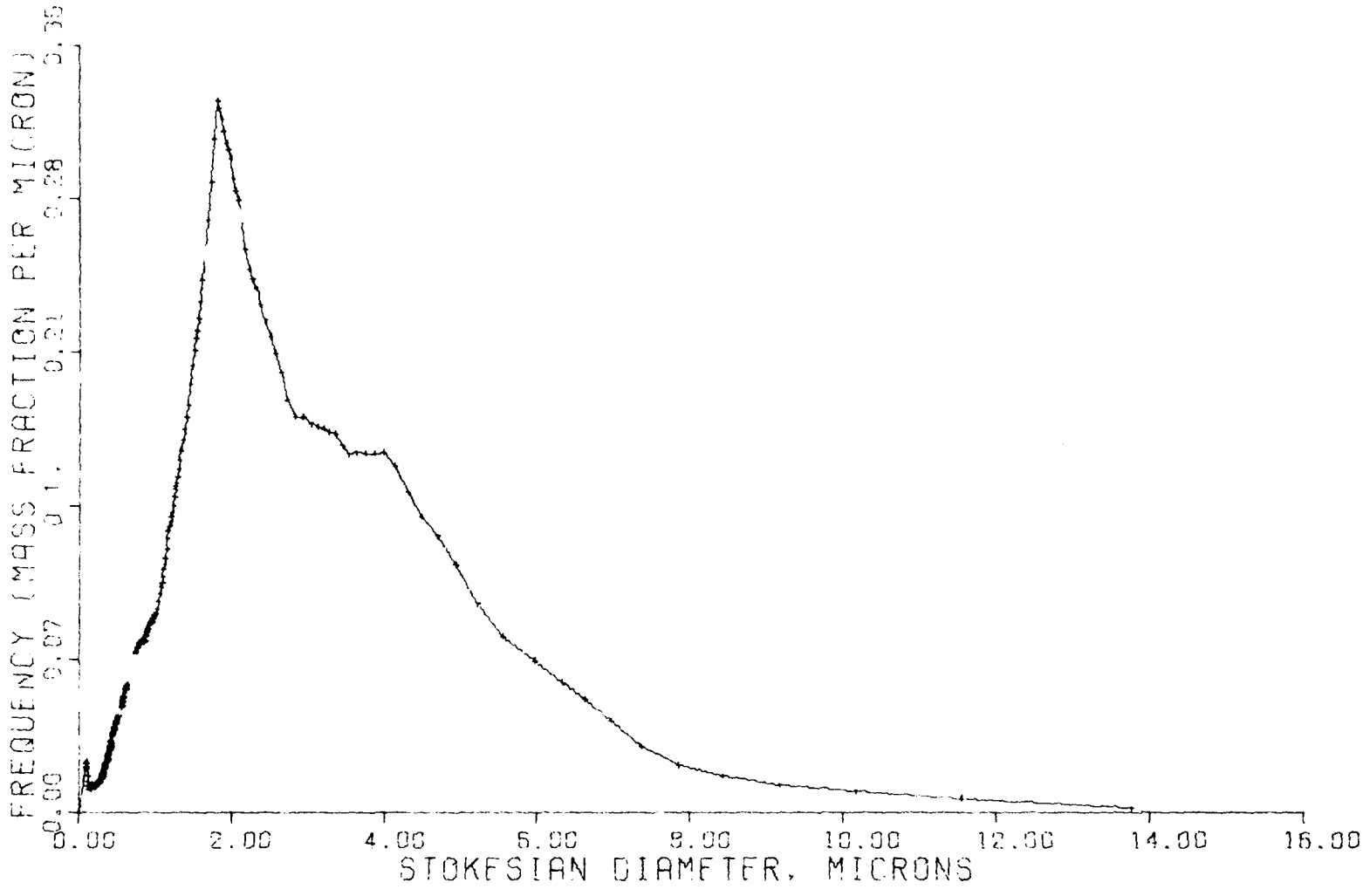

Figure 54. Experiment No. 27 Particle Size Frequency Distribution of Fine Arizona Road Dust 75% 0-5 Micron, Buffer Layer. Concentration 10cc at 2×10^{-3} gm/cc.

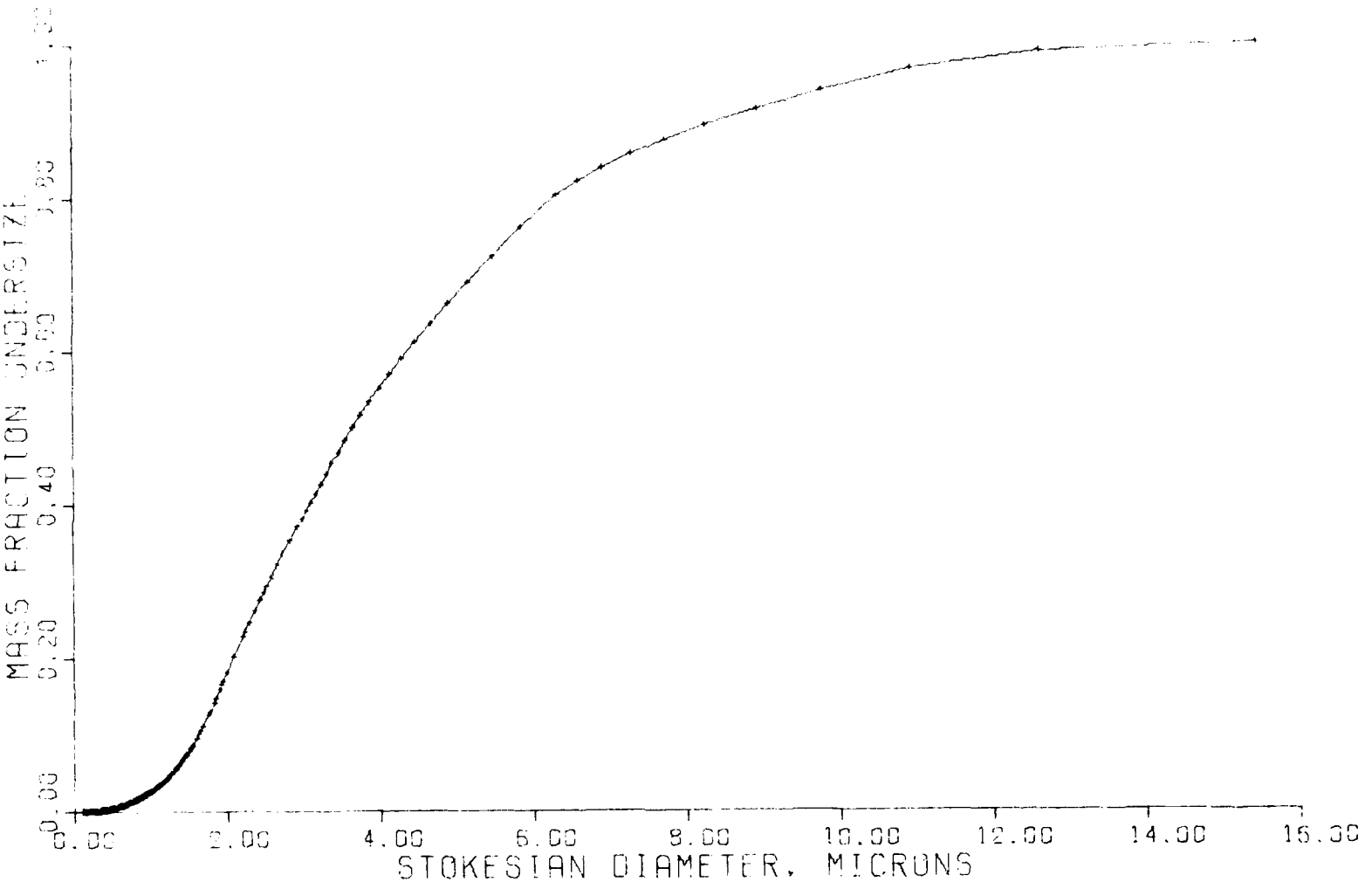

Figure 55. Experiment No. 28 Cumulative Particle Size Distribution of Fine Arizona Road Dust 75% 0-5 Micron, Buffer Layer. Concentration 10cc at 4 x 10^{-3}gm/cc.

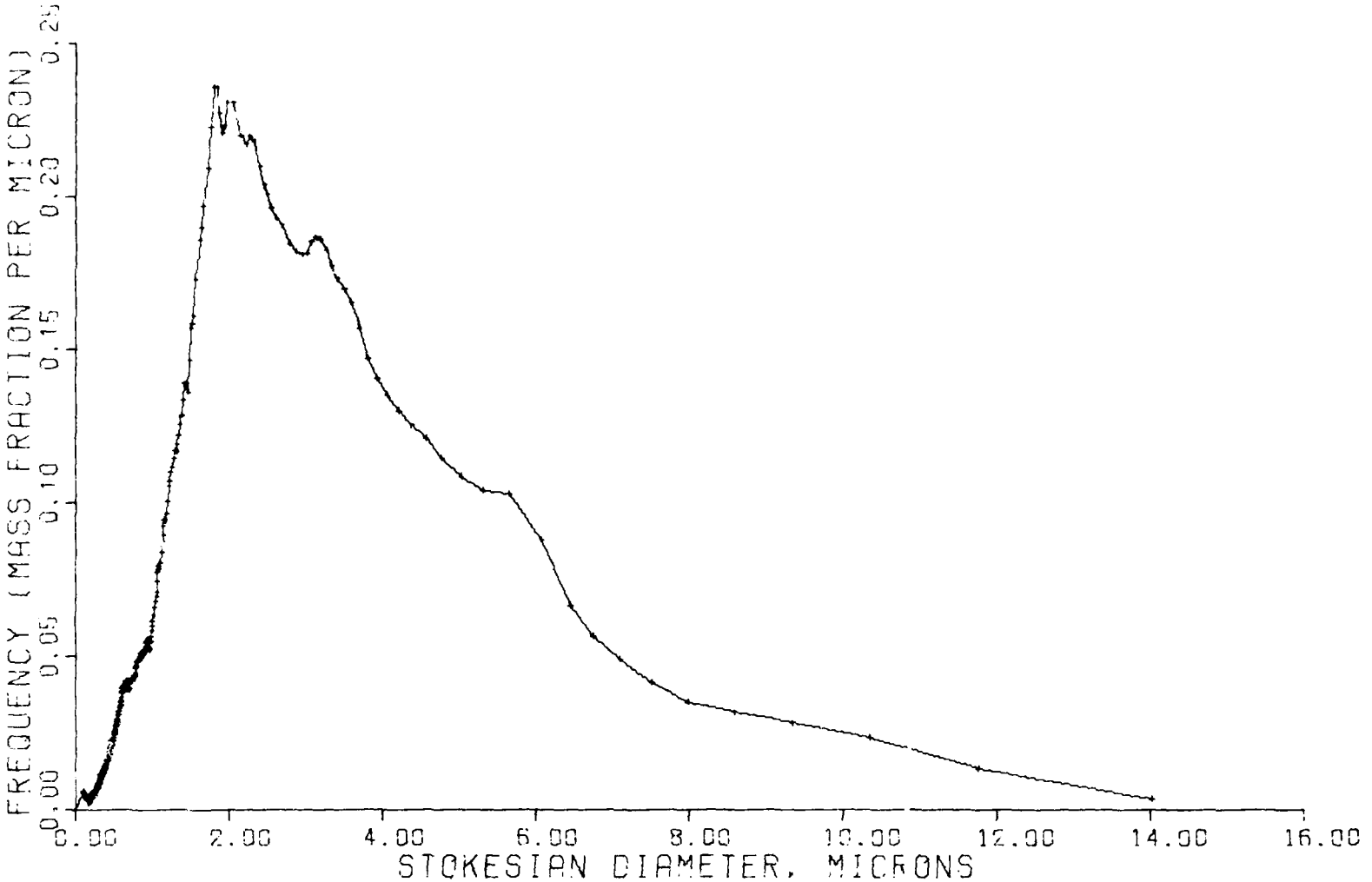

Figure 56. Experiment No. 28 Particle Size Frequency Distribution of Fine Arizona Road Dust 75% 0-5 Micron, Buffer Layer. Concentration 10cc at 4×10^{-3} gm/cc.

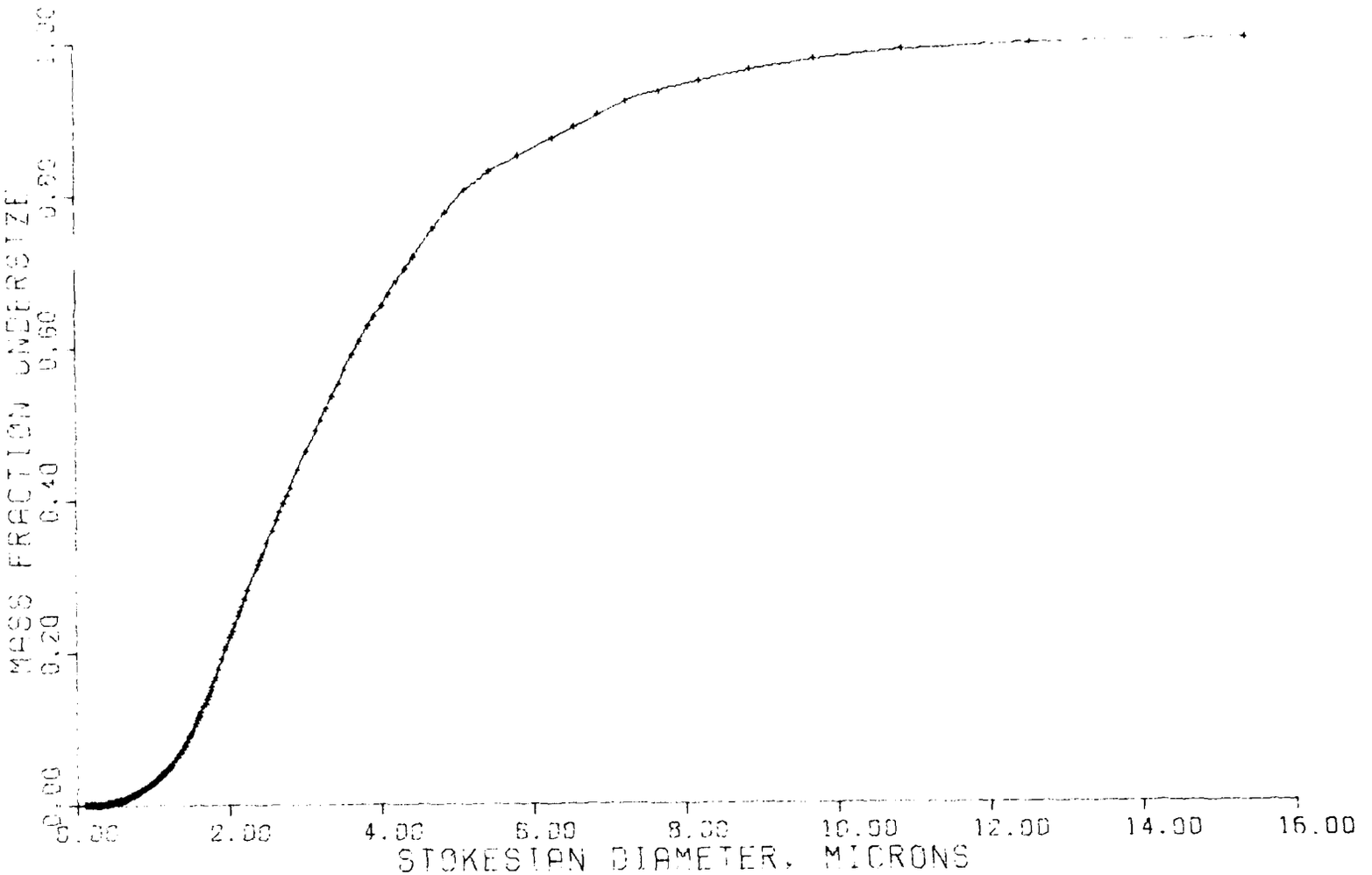

Figure 57. Experiment No. 29 Cumulative Particle Size Distribution of Fine Arizona Road Dust 75% 0-5 Micron, Buffer Layer. Concentration 10cc at 8 x 10^{-3}gm/cc.

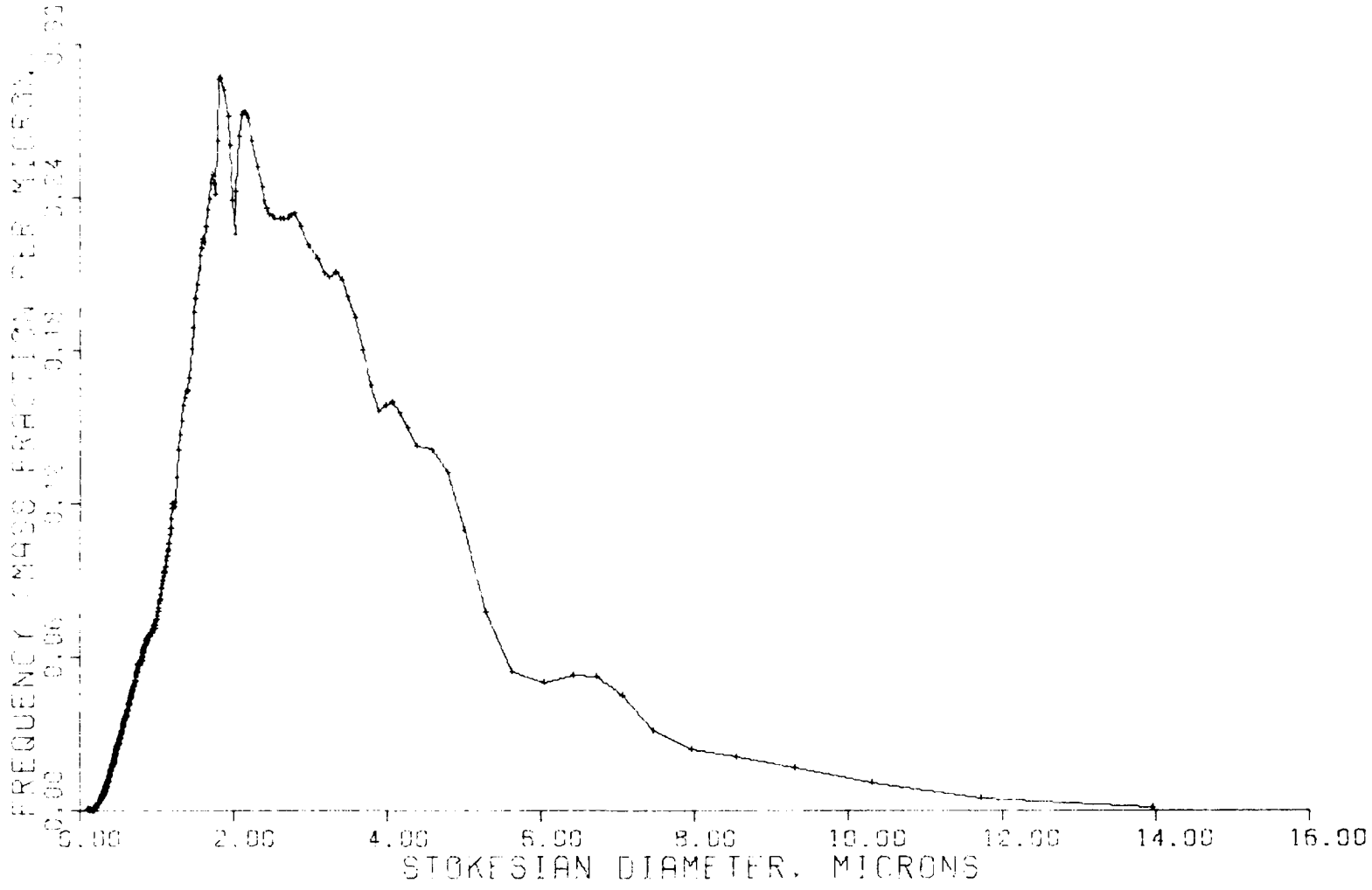

Figure 58. Experiment No. 29 Particle Size Frequency Distribution of Fine Arizona Road Dust 75% 0-5 Micron, Buffer Layer. Concentration 10cc at 8 x 10^{-3} gm/cc.

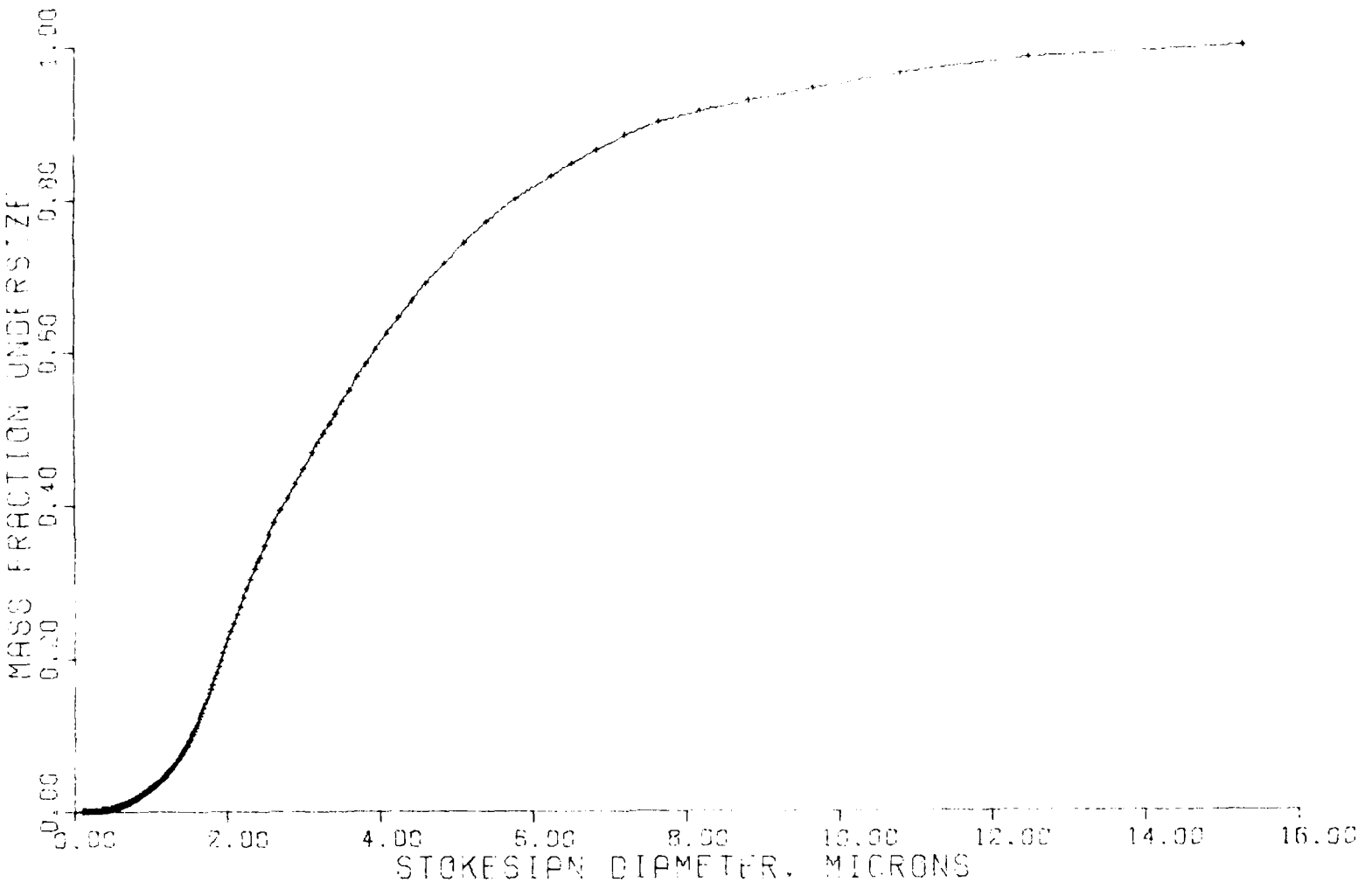

Figure 59. Experiment No. 30 Cumulative Particle Size Distribution of Arizona Road Dust X-Fine, Buffer Layer. Concentration 10cc at 2×10^{-3} gm/cc.

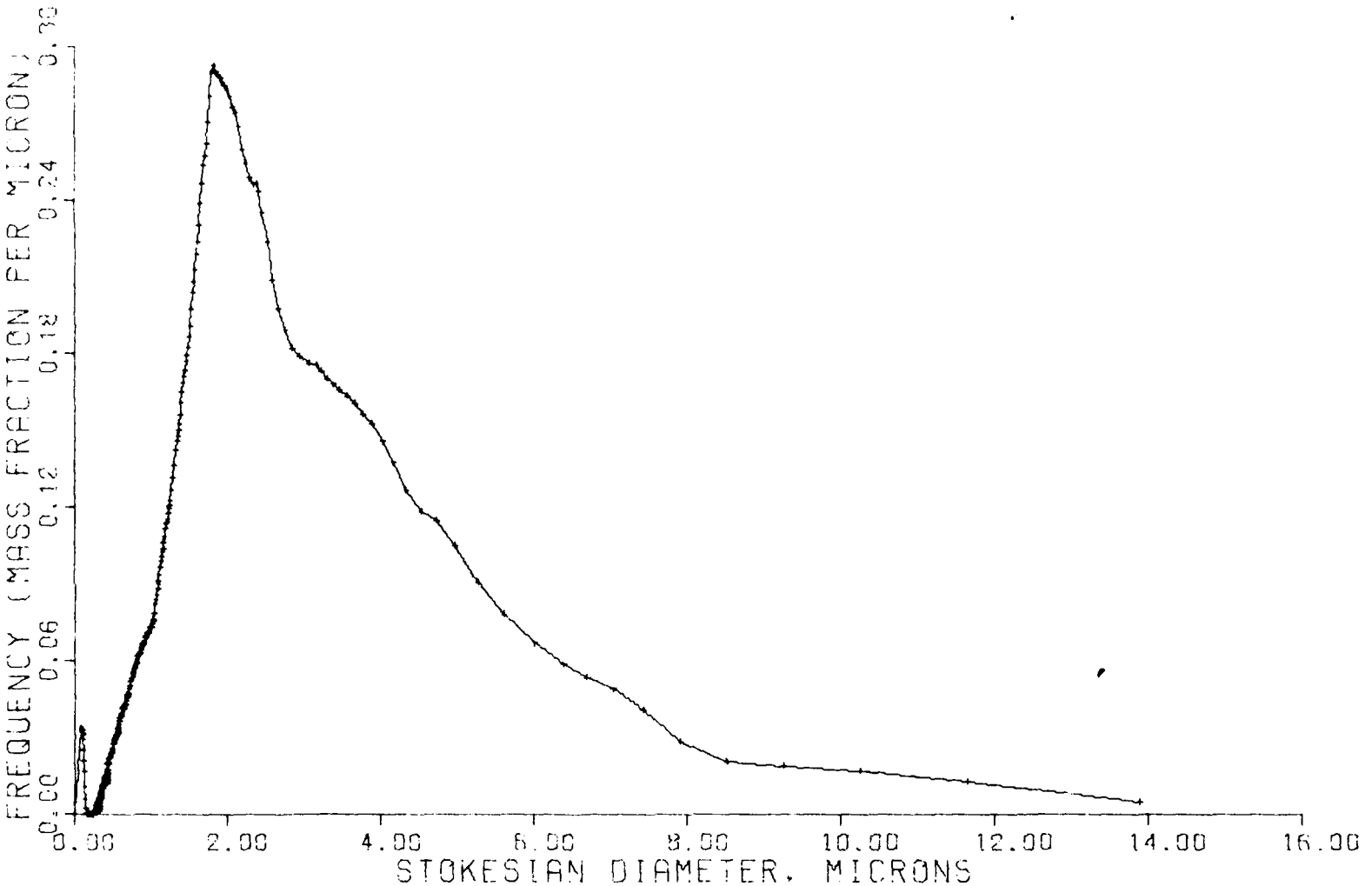

Figure 60. Experiment No. 30 Particle Size Frequency Distribution of Arizona Road Dust X-Fine, Buffer Layer. Concentration 10cc 2 x 10^{-3} gm/cc.

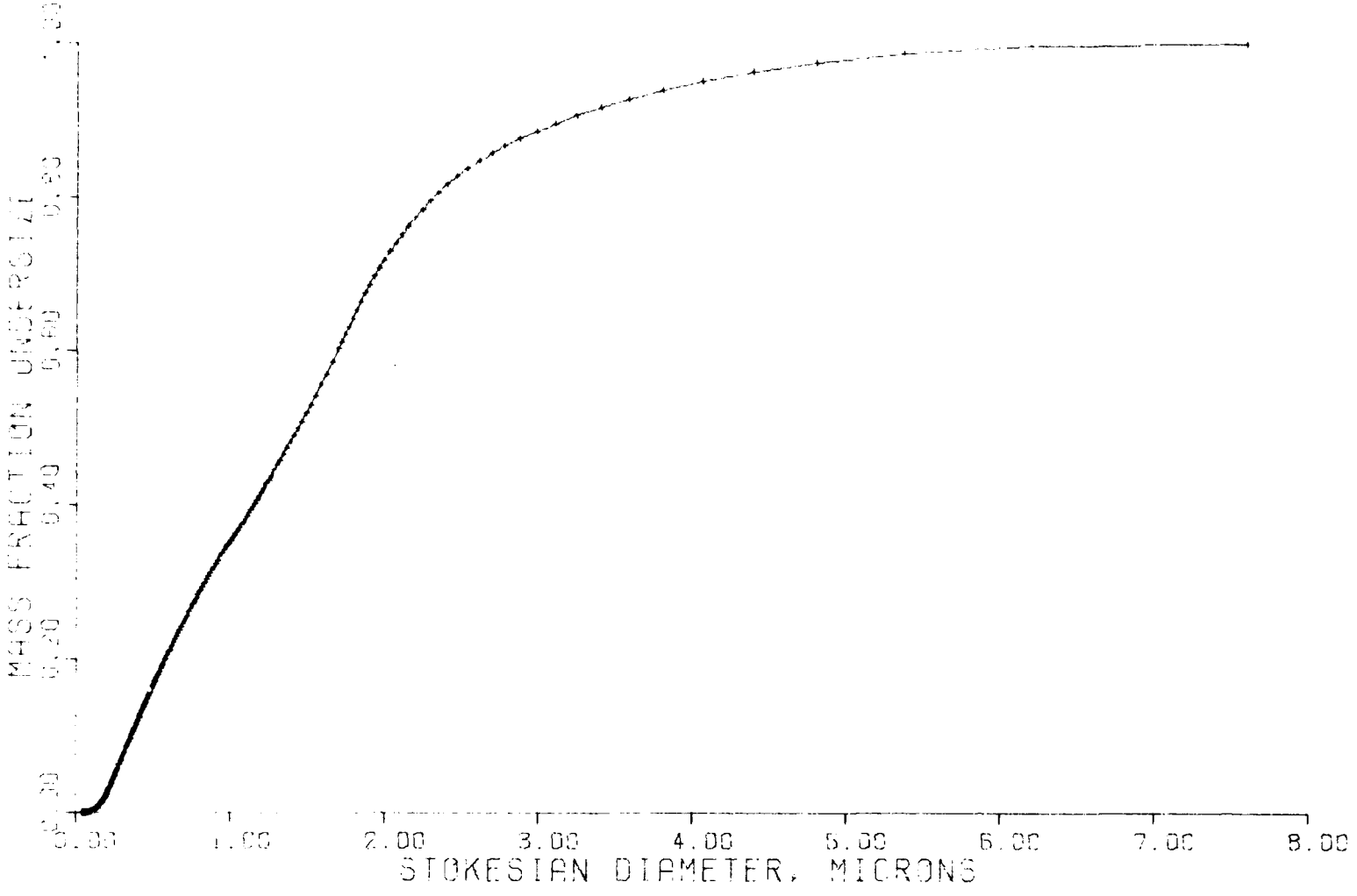

Figure 61. Experiment No. 31 Cumulative Particle Size Distribution of Amorphous Boron Powder, Buffer Layer. Concentration 10cc at 7.5×10^{-3} gm/cc.

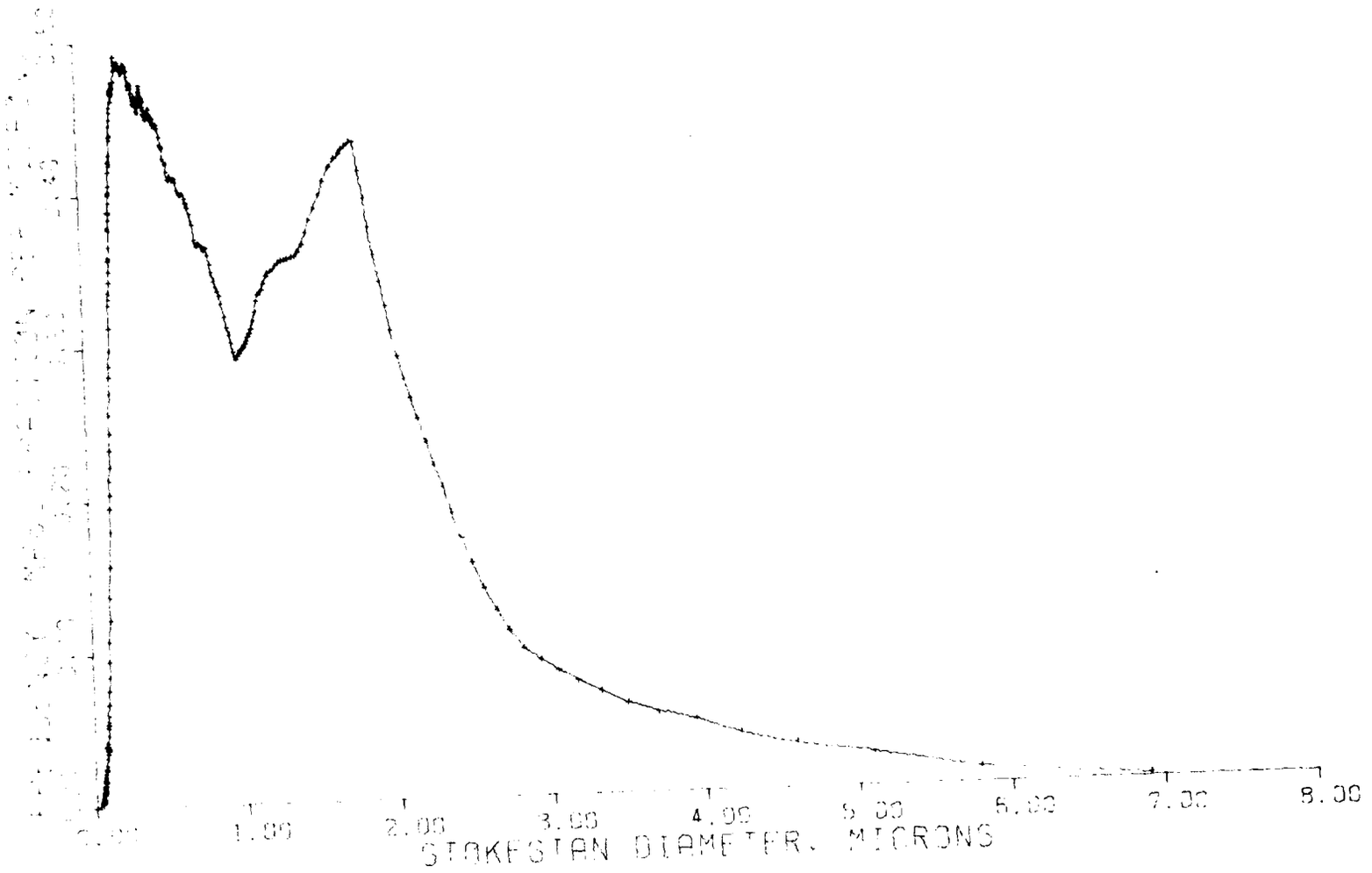

Figure 62. Experiment No. 31 Particle Size Frequency Distribution of Amorphous Boron Powder, Buffer Layer. Concentration 10cc at 7.5×10^{-3} gm/cc.

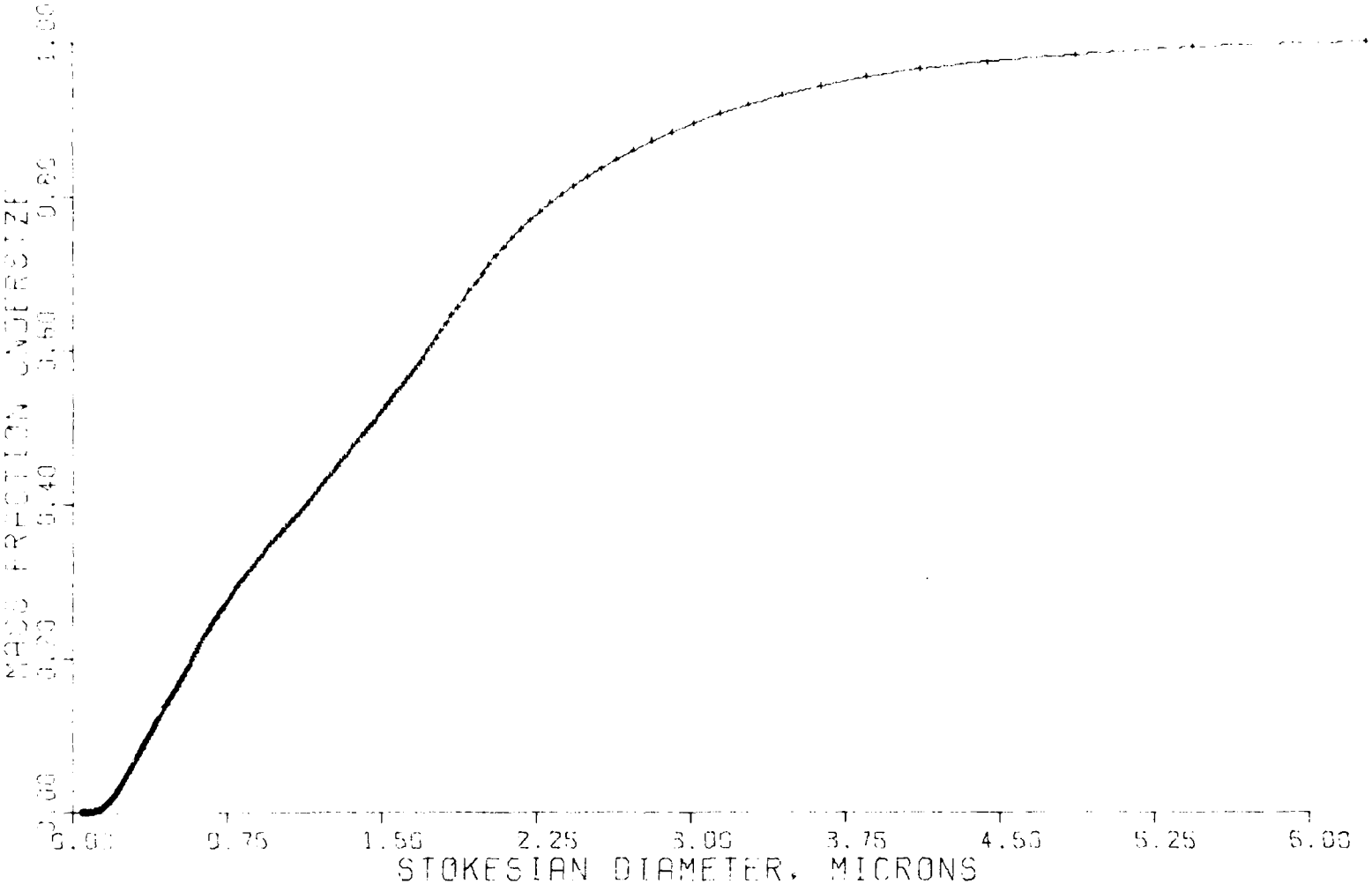

Figure 63. Experiment No. 32 Cumulative Particle Size Distribution of Amorphous Boron (Repowdered), Buffer Layer. Concentration 10cc at 5 x 10^{-3} gm/cc.

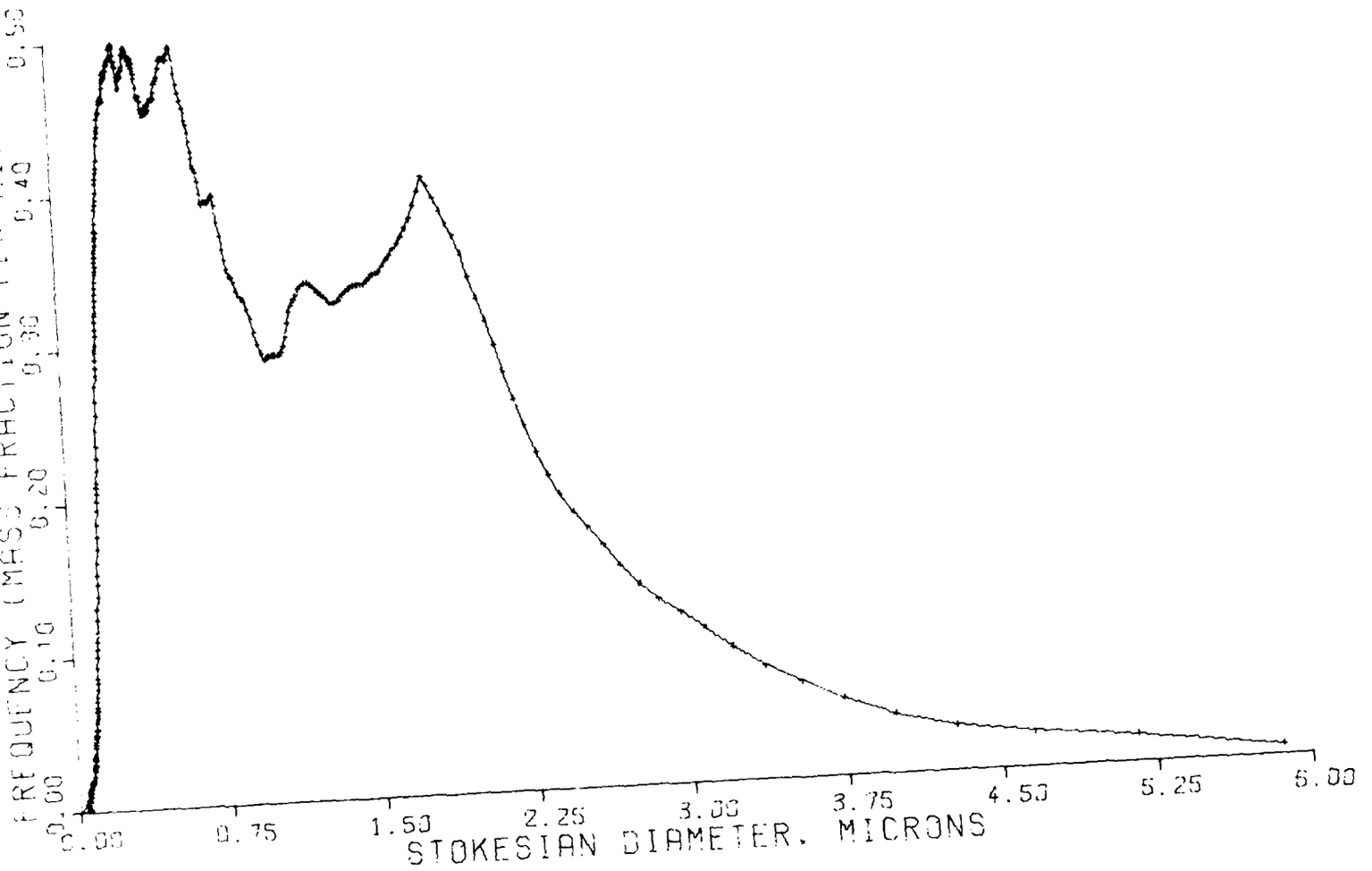

Figure 64. Experiment No. 32 Particle Size Frequency Distribution of Amorphous Boron (Repowdered), Buffer Layer. Concentration 10cc 5 x 10^{-3} gm/cc.

V. REFERENCES

1. Jackomis, W. N., and Von Ohain, H. J. P., Aeromechanical Characteristics of Nuclear Reactor Cavities Using Colloidal Fuels, AIAA Paper No. 70-1222, AIAA 7th Annual Meeting and Technical Display, Houston, Texas, October 1970.

2. Shelnutt, J. William, Capt, USAF, Particle Size Analysis by Sedimentation, Aerospace Research Laboratories Report 71-0134, August 1971.

3. Turman, B. N., and Hasinger, S. H., Experimental Flow Studies of the Colloid Core Reactor Concept, pp. 269-275, Proceedings, AIAA/NASA 2nd Symposium on Uranium Plasmas, Atlanta, Georgia, November 1971.

4. Anderson, L. A., Hasinger, S. H., and Turman, B. N., Two Component Vortex Flow Studies with Implications for the Colloid Core Nuclear Rocket Concept, AIAA Paper No. 71-637, AIAA/SAE 7th Propulsion Joint Specialist Conference, Salt Lake City, Utah, June 1971.

Appendix A
Data Used in Analysis of Experiments
Conducted on Sedimentation Balance

Experiment No.	Sedimentation Fluid		Density of Particles (gm/cc)	Settling Height (cm)
	Absolute Viscosity (poise)	Density of Fluid (gm/cc)		
1	0.01017	0.9986	2.78	24.03
2	0.01017	0.9990	2.78	24.45
3	0.01017	0.9990	2.78	24.15
4	0.01017	0.9990	2.78	22.70
5	0.01017	0.9990	2.78	24.13
6	0.01017	0.9990	2.78	23.57
7	0.01017	0.9983	2.78	22.10
8	0.01017	0.9986	2.78	23.36
9	0.01017	0.9986	2.78	24.22
10	0.01017	0.9986	2.78	25.12
11	0.0605	1.1263	19.1	22.10
12	0.0605	1.1263	19.1	21.11
13	0.03855	1.1021	4.43	25.50
14	0.01017	0.9986	2.69	25.45
15	0.08850	1.1444	2.66	25.30
16	0.01017	0.9986	7.04	25.20
17	0.01035	0.9988	6.99	24.80

Appendix A (Continued)
Data Used in Analysis of Experiments
Conducted on Sedimentation Balance

Experiment No.	Sedimentation Fluid		Density of Particles (gm/cc)	Settling Height (cm)
	Absolute Viscosity (poise)	Density of Fluid (gm/cc)		
18	0.01017	0.9986	3.85	25.50
19	0.03855	1.1021	3.85	25.12
20	0.01017	0.9986	2.67	24.50
21	0.01017	0.9986	2.67	24.40
22	0.01017	0.9986	2.34	25.30
23	0.01017	0.9986	2.34	25.00

Appendix B
Data Used in Analysis of Experiments
Conducted on Photosedimentometer

Experiment No.	Sedimentation Fluid		Density of Particles (gm/cc)	Initial Radius (cm)
	Absolute Viscosity (poise)	Density of Fluid (gm/cc)		
24	0.00871	0.996	2.67	6.24
25	0.00888	0.996	2.67	6.1[illegible]
26	0.00882	0.996	2.67	6.0[illegible]
27	0.00827	0.996	2.67	6.11
28	0.00837	0.996	2.67	6.01
29	0.00821	0.996	2.67	5.96
[illegible]	0.00831	0.996	2.67	6.06
31	0.00680	0.9930	2.34	4.39
32	0.00688	0.99321	2.34	4.33

Appendix C
Results of Sediment Recovery

Experiment No.	Powder Material	Sedimentation Fluid	Initial Weight in Suspension (mg)	Weight Recovered from Collecting Pan (mg)	Weight Recovered from Bottom of Sedimentation Vessel (mg)
*1	Johnson Baby Powder Regular Grade	Distilled Water with 0.5% Liqui-Nox	443	441	2.2
2	Johnson Baby Powder Regular Grade	Distilled Water with 1.0% Liqui-Nox	998	830	161
3	Johnson Baby Powder Regular Grade	Distilled Water with 1.0% Liqui-Nox	990	945	27
4	Johnson Baby Powder Modified	Distilled Water with 1.0% Liqui-Nox	493	413	83
5	Johnson Baby Powder Modified	Distilled Water with 1.0% Liqui-Nox	785	547	203
6	Johnson Baby Powder Modified	Distilled Water with 1.0% Liqui-Nox	970	766	171
7	Johnson Baby Powder Sample dated 15 Jul 1970	Distilled Water with 0.1% Liqui-Nox	742	645	90
*8	Johnson Baby Powder Sample 9-1	Distilled Water with 0.5% Liqui-Nox	656	644	11.2
*9	Johnson Baby Powder Sample 9-2	Distilled Water with 0.5% Liqui-Nox	673	651	11.4

Appendix C (Continued)

Experiment No.	Powder Material	Sedimentation Fluid	Initial Weight in Suspension (mg)	Weight Recovered from Collecting Pan (mg)	Weight Recovered from Bottom of Sedimentation Vessel (mg)
*10	Johnson Baby Powder Sample Perr. 3 Mar 1971	Distilled Water with 0.5% Liqui-Nox	642	NR	NR
11	Tungsten Metal Powder -325 Mesh	Aqueous Glycerin Solution with 0.1% Liqui-Nox	222	175	NR
12	Tungsten Metal Powder -325 Mesh	Aqueous Glycerin Solution with 0.1% Liqui-Nox	453	358	NR
*13	Titanium Metal Powder 1-10 Micron	Aqueous Glycerin Solution with 0.5% Liqui-Nox	532	714	NR
*14	Aluminum Metal Powder 1-10 Micron	Distilled Water with 0.5% Liqui-Nox	650	648	NR
*15	Aluminum Metal Powder -200+325 Mesh	Aqueous Glycerin Solution with 0.5% Liqui-Nox	524	527	NR
*16	Zinc Metal Powder 0.5-5 Micron	Distilled Water with 0.5% Liqui-Nox	453	473	NR
*17	Zinc Metal Powder 1-10 Micron	Distilled Water with 0.5% Liqui-Nox	484	468	17

Appendix C (Continued)

Experiment No.	Powder Material	Sedimentation Fluid	Initial Weight in Suspension (mg)	Weight Recovered from Collecting Pan (mg)	Weight Recovered from Bottom of Sedimentation Vessel (mg)
*18	Aluminum Oxide Powder -325 Mesh	Distilled Water with 0.5% Liqui-Nox	305	307	NR
*19	Aluminum Oxide Powder -325 Mesh	Aqueous Glycerin Solution with 0.5% Liqui-Nox	558	568	NR
*20	Fine Arizona Road Dust 75% 0-5 Micron	Distilled Water with 0.5% Liqui-Nox	80	NR	NR
*21	Fine Arizona Road Dust 75% 0-5 Micron	Distilled Water with 0.5% Liqui-Nox	638	557	15
*22	Boron Repowdered	Distilled Water with 0.5% Liqui-Nox	700	NR	NR
*23	Boron as Received 1 Micron	Distilled Water with 0.5% Liqui-Nox	700	565	111

*Asterisk indicates experiments where sedimentation cylinder bottom seal was used.

NR indicates no recovery made.

Appendix D
List of Materials Analyzed

No.	Type of Dust & Powder Analyzed	Particle Shape	Source of Supply
1	Johnson Baby Powder Regular Commercial Grade	Powder mixture composed of globular fines, granular, angular and flaky irregular size particles	Johnson & Johnson New Brunswick, N.J.
2	Johnson Baby Powder Modified Regular Commercial Grade	Fairly uniform coarse rounded off particles associated with a small fraction of fines	10.7 Kg regular grade powder was modified by a non-conventional type of separator which yielded 1.3 Kg of coarse powder
3	Fine Air Cleaner Test Dust (Arizona Road Dust)	Uniform mixture of angular and irregular size particles	General Motors Corp. AC Spark Plug Div. Flint, Michigan
4	Tungsten Metal Powder, Grade AA: 99.9%-325 Mesh	Uniform mixture of angular and sub-angular particles	Consolidated Astronautics Div., United Int'l. Rsch. Inc., 230 Marcus Blvd., Hauppauge, N.Y. 11787
5	Titanium Metal Powder, 1-10 Micron Stock No. 20-10-08	Mixture composed of globular, angular, sub-angular and elongated irregular particles	Materials for Industry, Inc. P.O. Box 204 Ambler, PA 19002
6	Aluminum Metal Powder, 1-10 Micron Stock No. 1-2-04	Fairly uniform mixture of granular, nodular and irregular particles	Materials for Industry, Inc. P.O. Box 204 Ambler, PA 19002

Appendix D (Continued)
List of Materials Analyzed

No.	Type of Dust & Powder Analyzed	Particle Shape	Source of Supply
7	Aluminum Metal Powder, -200+325 Mesh Stock No. 1-2-03	Uniform mixture of nodular, globular and elongated globular particles	Materials for Industry, Inc. P.O. Box 204 Ambler, PA 19002
8	Zinc Metal Powder 0.5-5.0 Micron Stock No. 26-1-02	Spherical particles	Materials for Industry, Inc. P.O. Box 204 Ambler, PA 19002
9	Zinc Metal Powder 1-10 Micron Stock No. 26-1-01	Spherical particles	Materials for Industry, Inc. P.O. Box 204 Ambler, PA 19002
10	Aluminum Oxide Powder, -325 Mesh Stock No. 1-2-42	Mixture of angular and chip-like irregular fragments	Materials for Industry, Inc. P.O. Box 204 Ambler, PA 19002
11	Boron, Amorphous Trona 1 Micron	Mixture of globular, nodular and irregular particles	American Potash and Chemical Corp. 3000 West 6th St. Los Angeles, CA 90005

Appendix E
Density of Various Solids
Measurements Made With Helium-Air Pycnometer

*Aluminum Metal Powder	2.66 - 2.69 gm/cc
*Aluminum Oxide Powder	3.85 gm/cc
*Argo Corn Starch	1.50 gm/cc
*AC Fine Air Cleaner Test Dust	2.67 gm/cc
*AC Coarse Air Cleaner Test Dust	2.67 gm/cc
*Boron Powder (Amorphous)	2.34 gm/cc
Butter-Fly Incense (Japan)	1.52 gm/cc
*Butter-Fly Incense Ash	3.45 gm/cc
*Dry Kem-S Powder (Casco Fire Extinguisher Powder)	2.21 gm/cc
*Foundry Dust	2.51 gm/cc
*Glass Beads Superbrite (Type 380-5005)	2.40 gm/cc
*Johnson Baby Powder	2.78 gm/cc
*Modified Johnson Baby Powder	2.78 gm/cc
*Magnesium Oxide	3.62 gm/cc
*Room Dust	1.67 gm/cc
Silicon Dioxide	2.16 gm/cc
*Tobacco Ash	2.36 - 2.42 gm/cc
*Titanium Metal Powder	4.43 gm/cc
*Tungsten Disulfide Powder (Sylvania Special Grade)	6.94 gm/cc
*Tungsten Metal Powder	19.09 gm/cc
*Zinc Metal Powder	6.99 - 7.04 gm/cc

*Dispersions of materials indicated by asterisk were tested and compared on a merit basis. All dispersed well in distilled water with either 0.5% Liqui-Nox or 0.5% Basic-H.

Appendix F
Instruments and Equipment Used in Conducting Measurements and Investigations

1	Cahn R G Automatic Electro Balance #2000 and Particle Sedimentation Accessory #2800	Cahn Instrument Co. 7500 Jefferson Street Paramount, CA
2	Strip-Chart Recorder Servo/ Riter II Model FS02W6D	Texas Instruments Inc. Houston, TX 77006
3	Precision Constant Temperature Circulating System	Precision Scientific Co. 3737 W. Cortland Street Chicago, IL 60647
4	Photosedimentometer Model 3000	Martin Sweets Co. Inc. 3131 Market Street Louisville, KY 40212
5	Metallurgical Microscope Metalstar Model 2200 Photomicrography Equipment Series 682 with Graflok Camera Back and Polariod Land 4 x 5 Film Holder #500	American Optical Co. Instrument Div. Buffalo, N.Y. 14215
6	Haake Falling Ball Viscometer	Haake Instruments, Inc. 244 Saddle River Road Rochelle Park, N.Y. 07662
7	Fisher Brand Hydrometers	E. H. Sargent & Co. 10400 Taconic Terrace Cincinnati, OH 45215
8	Helium-Air Pycnometer Model 1302	Micromeritics Instrument Corp. 800 Goshen Springs Road Norcross, GA 30071
9	Data Viewer Model 300 Data Scaler Model 400	Data Scaler P.O. Box 378 Westfield, MA
10	Electric Oven Blue M Electric Co. Model SW-17 TA	Matheson Scientific Div. of Will Ross Inc. 12101 Centron Place Cincinnati, OH 45246

Appendix F (Continued)
Instruments and Equipment Used in Conducting
Measurements and Investigations

11	Ultrasonic Cleaner Blackstone Model HT-11.2-HW	Matheson Scientific Div. of Will Ross Inc. 12101 Centron Place Cincinnati, OH 45246