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TITLE

CHARACTERISTICS OF SIMULANT AEROSOLS FOR STUDY OF THE BCD INLET NOZZLE

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CHARACTERISTICS OF SIMULANT AEROSOLS FOR STUDY OF THE BCD INLET NOZZLE

by

J. Ho

April 1991

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RÉSUMÉ

L'efficacité du système de détection biochimique dépend de la capacité de concentration de son dispositif de prélèvement. Ce dispositif a été conçu de façon à concenter, dans une suspension aqueuse de 100 μL, les substances présentes dans 100 L d'air, ce qui correspond à un facteur de concentration de 10^6. Toutefois, des études préliminaires ont indiqué qu'effectivement seules les particules possédant un diamètre de plus de 2,5 μm étaient concentrées. Ainsi, ce détecteur ne permet pas de déceler les aérosols dont les gouttelettes possèdent un diamètre inférieur à 2,5 μm. Cette limite constitue un problème d'importance, car une large part des aérosols d'agents biologiques serait constituée, estime-t-on, de gouttelettes de diamètre inférieur à 2,5 μm.

Dans le cadre du programme de mise au point d'un système de détection biochimique, le CRDS a entrepris d'étudier ce dispositif de prélèvement. Il a d'abord étudié les caractéristiques des aérosols simulants des agents biologiques, en vue de déterminer si le diamètre limite de 2,5 μm influait de façon significative sur la capacité de détection. Il a ensuite examiné un certain nombre de nébuliseurs conçus pour produire des aérosols constitués de fines gouttelettes, afin de déterminer si le dispositif de prélèvement pourrait piéger ces gouttelettes.

Les résultats de ces mesures ont révélé qu'environ 90% de toutes les gouttelettes produites par les nébuliseurs typiques, tant gros que moyens, ont un diamètre qui se situe dans la plage de prélèvement du concentrateur. Dans le cas des aérosols produits par de petits nébuliseurs de fines particules, ce chiffre est d'environ 50 – 80%. Des études portant sur divers nébuliseurs ont révélé que le diamètre des gouttelettes d'aérosol qu'ils produisent se situe dans la plage nominale de prélèvement du système de détection biochimique. Les résultats fournissent des renseignements de toute première importance sur les projections globales relatives à la performance du système de détection biochimique et sur l'analyse de la menace que sont les nuages d'agents chimiques/biologiques dispersés sous forme d'un aérosol.

ABSTRACT

The successful operation of the Biochemical Detector (BCD) system depends on the concentration capabilities of the inlet nozzle component. This device was designed to concentrate the contents in 100 L of air into 100 μL of aqueous suspension, providing a 10^6 concentration factor. However, preliminary studies have indicated that only particles with diameters greater than 2.5 μm diatemer were effectively concentrated. This observation implies that the BCD will not detect aerosols of diameter less than 2.5 μm. This limitation is a major concern as it is believed that biological warfare agent aerosols might have significant amounts of material in particles with size ranges below 2.5 μm.

Under the BCD development program, DRES took on the task of studying the inlet nozzle. First, the characteristics of biological simulant aerosols were studied to determine if the 2.5 μm BCD concentrator cut-off limit created a significant detection problem. Second, a number of aerosol generating devices designed to produce fine particles were studied in order to determine if aerosols from these could be collected by the BCD inlet nozzle.

The results of these measurements revealed that typical large to medium scale aerosol generators produced about 90% of total particulate material within the collection range of the BCD concentrator. The corresponding result for small scale fine particle generators is about 50 – 80%. Studies on a variety of aerosol generating devices revealed that their output aerosols fall in the range of the design specifications of the BCD inlet nozzle. The results provide critical information for overall BCD performance projections and threat analysis of CB aerosol clouds.

INTRODUCTION

The Biochemical Detector (BCD) consists of an aerosol collection module upstream of a detection module which functions by exploiting immunological properties of threat agents. Its successful operation depends on the concentration capabilities of the inlet nozzle (IN) component. A major part of the IN design was based on the virtual impactor which has been studied theoretically by Marple (Marple and Chien 1980), who is also the IN manufacturing contractor. This device was designed to concentrate the contents in 100 L of air to 100 µL of aqueous suspension, providing a 10^6 concentration factor. However, results of preliminary performance studies indicated that only particles with diameters greater than 2.5 µm were effectively concentrated (Marple, 1990). This implied that the BCD system will not be able to detect aerosols of diameter less than 2.5 µm. This limitation is of concern as it is believed that biological aerosols might be dispersed with significant amounts of material in size ranges below 2.5 µm.

The virtual impactor principle has been implemented in the dichotomous sampler (Loo et al. 1979), a commercially available aerosol collector. In the dichotomous sampler (DS), particle separation is achieved by a virtual impactor. In this device, a nozzle is used to accelerate the particle-laden air stream which flow into a separation chamber. Under the influence of differential flow rates, flow trajectories for large and small particles are aerodynamically diverted resulting in a separation of coarse and fine particle streams. Approximately 10% of the flow (the minor flow) is allowed to flow through the receiving tube and serve as a carrier gas stream for coarse particles (greater than 2.5 µm, mass median aerodynamic diameter or MMAD), while the remaining 90%, the major flow, contains the fine particles (less than 2.5 µm) not separated by the virtual impactor.

These two streams are separately filtered to provide the coarse and fine fractions. By comparison, in the BCD IN design, the major flow containing fine particles are dumped to achieve a partial concentration effect, thus resulting in a sampling bias toward particles greater than 2.5 μm. Since the DS is the functional equivalent of the BCD IN nozzle, using this device to study aerosols from different kinds of generators will provide information on the performance of the BCD IN system.

Under the BCD development program, DRES took on the task of studying the inlet nozzle problem. First, the characteristics of biological simulant aerosols were studied to determine if the 2.5 μm diameter BCD concentrator cut-off created a significant detection limitation. To illustrate the concept of mass median aerodynamic diameter which is the relevant measure for the BCD IN, mass concentration data are compared with number concentration plots. Second, a number of aerosol generating devices designed to produce fine particles were studied in order to determine if aerosols from these could contain significant fraction of the total dispersed mass with a particle size that could not be collected by the BCD IN. Information gathered from these studies will also be useful for threat analysis.

METHODS AND MATERIAL

BW Simulant

A spore suspension of *Bacillus subtilis Var. niger species globigii* (BG) was used as the simulant. Viability of the sample was 1 x 10^9 cells per ml (100% BG slurry). Lower concentrations used in the experiments were obtained by diluting BG slurry with distilled water. In most experiments a 50% BG slurry was used. When small and medium scale nebulizers were being characterized, a 2 mL volume of this

slurry was used to generate an aerosol to fill the test chamber. A 100 mL volume was required when a large scale disseminator was used.

AEROSOL GENERATOR

Large Scale Generator

A Micronair generator (Model AU7000, Micronair Limited, Bembridge Fort, Sandown, Isle of Wight, PO36 8QS, England) provided an example of a large scale device. This unit was equipped with a 110 VAC motor which drives a 18 cm dia. propeller at maximum speed (>10000 rpm) giving wet droplets of about 30 μm in diameter dispersed by a spinning cage. The sample suspension was delivered at 1 L/min from a pressurized separatory funnel. This container was pressurized (1.6-1.7 atm) from a nitrogen tank. Secondary dispersion of the aerosol was achieved by the propeller, assisted by two auxiliary fans.

Medium Scale Generators

This group is represented by commercial devices capable of delivering 10-100 mL/min liquid. A paint sprayer (Model MA 1000, Campbell Hausfeld, Harrison, OH) was selected for its availability. An air brush (Model Wren 56-10004"B", Binks Manufacturing, Chicago, ILL) was selected for its compactness. A Jet Pack (Crown Industrial Products Co., Hebron, ILL) was selected because it was inexpensive.

Small Scale Generators

The main small scale generator was a standard laboratory Collison nebulizer, designed to deliver fine particles (May, 1973). Other fine sprayers examined were represented by a Hudson medical aerosol generator (Model 1700, Hudson Oxygen Therapy Sales Co.,

Wadsworth, OH) and a Fison nebulizer, labeled as "nebulizer" for this report (Model Vaponefrin, Fisons Corp., Bedford, MA). Their flow rates were typically 1-10 mL/min at 20 psi.

Aerosol Chamber

Aerosols were contained in a chamber which covered 28 sq meter of floor space enclosing 90.5 cu meter of air space (Ho, 1989). The aerosol generating device under test was placed in the middle of the room (1.5 m above the floor). Two table fans assisted in even aerosol dispersal. A high speed venting fan connected to overhead duct cleared the chamber of test aerosols after each test run. Exhaust air was filtered (HEPA filter model 7C23-SLCCD, Flanders Filters Inc. Washington, NC) to eliminate potential cross contamination between experiments. Temperature (20° C) and relative humidity (20%) were held constant throughout the experiments. Numerous sampling ports of different diameters were installed in one wall of the chamber to facilitate aerosol sampling.

Aerodynamic Particle Measurement

Aerosol particles were characterized by an aerodynamic particle sizer (model PS 3300, TSI Incorp., St. Paul, MN 55164) as previously described (Agarwal et al. 1982). The instrument was calibrated using standard latex particles (Duke Scientific, Palo Alto, CA 94303) by the method of Chen et al. (1985). The instrument was connected to an IBM PC compatible microcomputer which performed data conversion and storage as number and mass concentration files. The APS measured aerodynamic diameter as well as particle numbers. Particle volume was calculated from the usual formula using APS measured diameter while mass was obtained as the product of volume and density (1 gm/cc was used as the approximate density of BG spores). Statistical analysis and graph

plotting were done with a scientific spreadsheet (RS/1 Release 4, BBN software Products Corporation, Cambridge, MA 02138). Error bars indicate standard error of the mean of 20 replicate data sets.

Biological Aerosol Sampling

Two dichotomous samplers (DS) were operated simultaneously for collecting particulate aerosols (model 245, Andersen Samplers Incorp., Atlanta, Ga). The inlet of each instrument was connected directly to a sampling port by a short length of tubing (3.2 cm ID, 1 meter long) through which aerosols flowed (17 L/min). The virtual impactor separated particulates aerodynamically into two size groups; greater than 2.5 μm (coarse) and less than 2.5 μm (fine), each collected on a different set of glass fiber filters. Sampling (2 min) of aerosol was initiated after the volume of liquid slurry was completely exhausted from the generator (zero time). Time series samples were taken at zero, 10, 20 and 30 minute.

Assay of Viable Cells

Glass fiber filters on which particulate aerosol samples were collected were inserted into capped glass tubes (nonsterile). Distilled water (20 mL) was added to each sample tube. The capped tubes were then shaken for 10 minutes by a wrist action shaker (model 75, Burrel Corp., Pittsburgh, PA) which broke up the glass fiber filters, resuspending the particles. Solutions containing glass fiber slurry were strained through wire gauze disks to recover clarified filtrate containing biological particles. Viable organisms were enumerated from the filtrate by the spiral plating technique (Hedges et al. 1978). Liquid samples were applied to standard nutrient agar plates with a spiral platter (model CU, Spiral Systems Instruments Inc., Bethesda, MD). The plates were incubated over night at 30°C.

A laser-based spiral colony counter with an integrated data processor (model 500A and model 800 respectively, Spiral Systems Instruments Inc.) was used to calculate the number of viable spores in the original sample.

RESULTS

BG suspension

Full strength (100% source) BG slurry was diluted using distilled water to make working suspensions of decreasing concentrations. Viable spore counts for each concentration were determined and as expected (Fig. 1), an increase in source content was followed by a corresponding increase in viable spores. Exactly 100 mL of each suspension was used in the Micronair to generate an aerosol which filled the test chamber. Aerosol samples were collected with the dichotomous sampler and results from the coarse and fine filters were plotted. As shown in Figure 1, only the coarse fraction contributed significantly to the total mass of each sample. Also, there was a linear relationship between source concentration and coarse aerosol concentration.

Aerosol From Micronair

Figure 2 shows the particle size distribution for a 50% BG slurry source. In the number concentration plot a prominent peak in the 1-2 μm size range was accompanied by a broad shoulder extending well past the 2.5 μm region. In contrast, the mass concentration plot showed minimal mass content below the 2.5 μm particle diameter range and gradually increasing to a broad peak in the 6-8 μm region. The particle mass content was higher from successive BG slurries of greater source strength as shown in Figures 3 and 4. In each case, most of the mass content was found in particles greater than 2.5 μm.

To illustrate dynamic characteristics of BG aerosol particles in an enclosed chamber, samples were taken at various times after dispersal. Figure 5 shows that the total suspended aerosol (as determined by viable spore count) generated from different source strengths decreased with time. This decrease was apparently related to a concomitant drop in mass content as calculated from APS data (Fig. 6). At the beginning of an experiment, the proportion of coarse aerosols was greater than 98% and after 30 min. this had dropped to about 80% (Fig. 7). In the dry environment of the test chamber, sample loss could be due to particle adherence to wall surfaces although this has not been substantiated by experimental data.

Aerosol From Paint Sprayer

Particle size analysis of BG particles from a 50% source suspension showed significant number concentration in the 1-2 μm range. However, mass measurement showed that most of the mass content was in particles greater than 2.5 μm (Fig. 8). Again, most of the viable spores were found in the coarse fraction while the proportion coarse decreased with time, a rate of decrease comparable to that from the Micronair (Fig. 9).

Aerosol From Air Brush

The air brush created an aerosol with abundant particle numbers sized between 1-2 μm (Fig. 10). However, the bulk of mass appeared above 2.5 μm, forming a peak around 10 μm. Unlike the paint sprayer, which produced significant mass up to 14 μm size region, this device produced relatively less material with large diameters. This mass concentration distribution spectrum resembled a skewed bell-shaped curve with a left hand tail extending to the less than 2.5 μm size region.

Both coarse and fine viable spore aerosols from this device decreased in concentration over time (Fig. 11). Although the total viable aerosol concentration had decreased by a factor of 10, the percentage of coarse faction remained high at the end of the experiment.

Aerosol From Jet Pack

This device produced an aerosol with number concentration spectrum similar to those from others devices with a large peak in the 1-2 μm range (Fig. 12). Part of the mass distribution spectrum registered in the less than 2.5 μm region while most of the material was found at the higher diameter end. Similar coarse and fine aerosol characteristics were also observed with large coarse fraction greater than 80% (Fig. 13).

Aerosol From Nebulizer

As a small scale and fine sprayer, this device put out an aerosol with a narrower number concentration distribution and a peak centered at about 1 μm (Fig. 14). The mass distribution showed an interesting peak and shoulder at 1-2 μm region with the bulk of mass content appearing above 3 μm, gradually increasing in quantity all the way up to 15 μm. In contrast to the medium and large scale generators, this device produced less coarse particles, about 50-80% of total (Fig. 15).

Aerosol From Collison

As another example of a fine sprayer, the number concentration spectrum from this device resembled that of the previous one, with a narrow peak in the 1 μm region (Fig. 16). Similarities can be seen in

the mass spectrum which has characteristic peak and shoulder in the lower size ranges with a valley around 3 μm followed by gradual increase up to 15 μm. As expected, the percent coarse aerosol fraction as determined by viable spores was less than 80%, but still well above 75% (Fig. 17).

Aerosol From Hudson

Typical of the small scale devices, the Hudson produced a number concentration distribution of narrow range with a peak at 1 μm (Fig. 18). The mass distribution however, was unique in that there was a major broad peak at 2-3 μm region and minor one around 8 μm (Fig. 18) with minimal contribution from particles greater than 9 μm. Similarly, the range of coarse fractions measured between 70-90%, unaffected by different relative humidity levels (Fig. 19).

DISCUSSION

An overall view of aerosol characteristics from a variety of devices is summarized in Table I. The Micronair produced better than 98% of total output as coarse particles. This device is representative of large scale aircraft-based disseminators used in agricultural applications. Micronair devices are commercially available in different output ranges, using the same spinning cage principle for breakup of liquid droplets. More than one device can be installed for simultaneous operation, providing a range of concentration requirements. This instrument exhibits typical aerosol characteristics suitable for threat analysis of large scale disseminators.

The medium scale devices produced coarse particles fairly efficiently, well above 80%. Aerosols generated by any of these will be easily collected by virtual impactor-based samplers. These devices

depend on an air stream to produce liquid droplets and are representative of most compressed air driven aerosol generating systems. This may include jet exhaust driven devices which may be scaled up by using multiple jets to increase output volume. Thus aerosol characteristics demonstrated for these devices may be used to model threat from pressurized liquid delivery disseminators.

In the laboratory, to produce a monodisperse aerosol, a specially designed particle impactor which greatly restricts output, must be attached to a Collison generator to trap and remove particles with diameter greater than 2 μm (May, 1973). However, used without the impactor, the results reported here confirm those of May (1973) who also found 70% of particles greater than 2.5 μm MMAD. This example illustrates the technical complexities required to produce monodisperse fine particles. It partially explains the incorrect belief that the Collison, and by association other generators, are able to produce monodisperse aerosols and perhaps, may have led some to assume that all BG or biological aerosols are inherently monodisperse at below 2.5 μm size range. This misconception is apparently substantiated if biological aerosols are represented solely by their number concentration spectra which appear to exhibit monodisperse characteristics. However, in the present context, where BCD IN design is in question, the mass concentration characteristics determine the ultimate sampling efficiency due to the virtual impactor limitations.

Compared to the large and medium scale devices, results summarized in Table I suggest that small scale devices tend to produce comparatively smaller fraction of particles greater than 2.5 μm. From having examined just a small number of devices, there appears to be a trend which suggests that large scale out put is associated with abundance of particles with MMAD greater than 2.5 μm. Conversely, small output devices produce greater fraction of fine particles. At

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least, in the laboratory, when small scale devices are used to generate aerosols, consideration must be given to the probability that as low as 50% of the particles may be not be sampled by a virtual impactor-based sampler. If the output range of the aerosol generating device is known, the data in Table I may be used as a guide in modeling potential losses of sampling efficiency.

Similar findings have been reported for medical aerosol disseminating devices (generically called nebulizers) based on comparable operating principles. Mercer (1981) examined particle characteristics of a number of pneumatic nebulizers and reported a diameter range of 3-8 μm (volume median diameter). He also studied a number of ultrasonic nebulizers which produced aerosols in the 3.7-10.5 μm range. In a recent review, Payne (1989) reported the MMAD of particle size distribution from a metered-dose inhaler as 1.5-4.3 μm. These examples illustrate that most small scale devices do not produce aerosols of MMAD less than 2.5 μm in significant quantities.

CONCLUSION

Aerosol characteristics from these studies provide evidence to suggest that none of the devices studied is capable of generating threat aerosols exclusively below the 2.5 μm diameter size range. Indeed, only laboratory grade research instruments (vibrating orifice generator and spinning disc generator) are commercially available for producing small quantities of monodisperse aerosols of less than 2.5 μm (Pui and Lui, 1988). Because of their low output characteristics and complex electronic technologies, these instruments are not considered suitable for producing aerosols in quantity. Also demonstrated is a trend which suggests that the MMAD of aerosol particles is related to the output volume of the disseminating device. Detection systems based on virtual impactor type nozzles will be able to collect aerosol particles generated from most common aerosol disseminators in use today.

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TABLE I

SUMMARY OF AEROSOL CHARACTERISTICS SURVEY OF TYPICAL GENERATORS

DEVICE	SCALE	OUTPUT	% PARTICLES $>2.5\ \mu m$*
Micronair	Large	>1 1/min	>98
Paint Sprayer	Medium	10-100 ml/min	90-98
Air Brush	Medium	10-100 ml/min	90-95
Jet Pack	Medium	10-100 ml/min	80-90
Nebulizer	Small	<10 ml/min	50-80
Collision	Small	<10 ml/min	75-80
Hudson	Small	<10 ml/min	70-90

*Mass median diameter 50% cutoff using Dichotomous Sampler

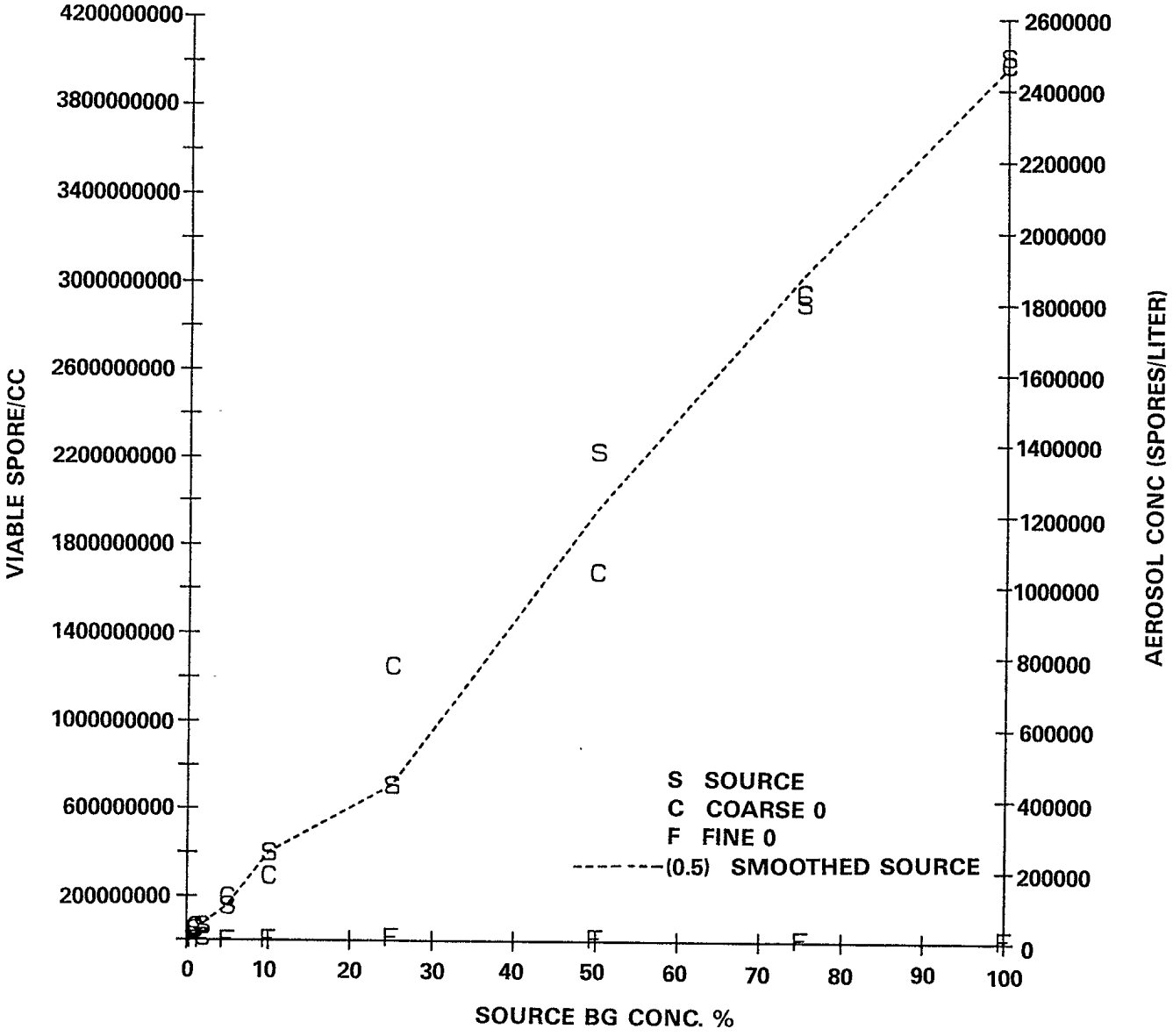

Figure 1

VIABLE SPORES IN SOURCE SUSPENSIONS

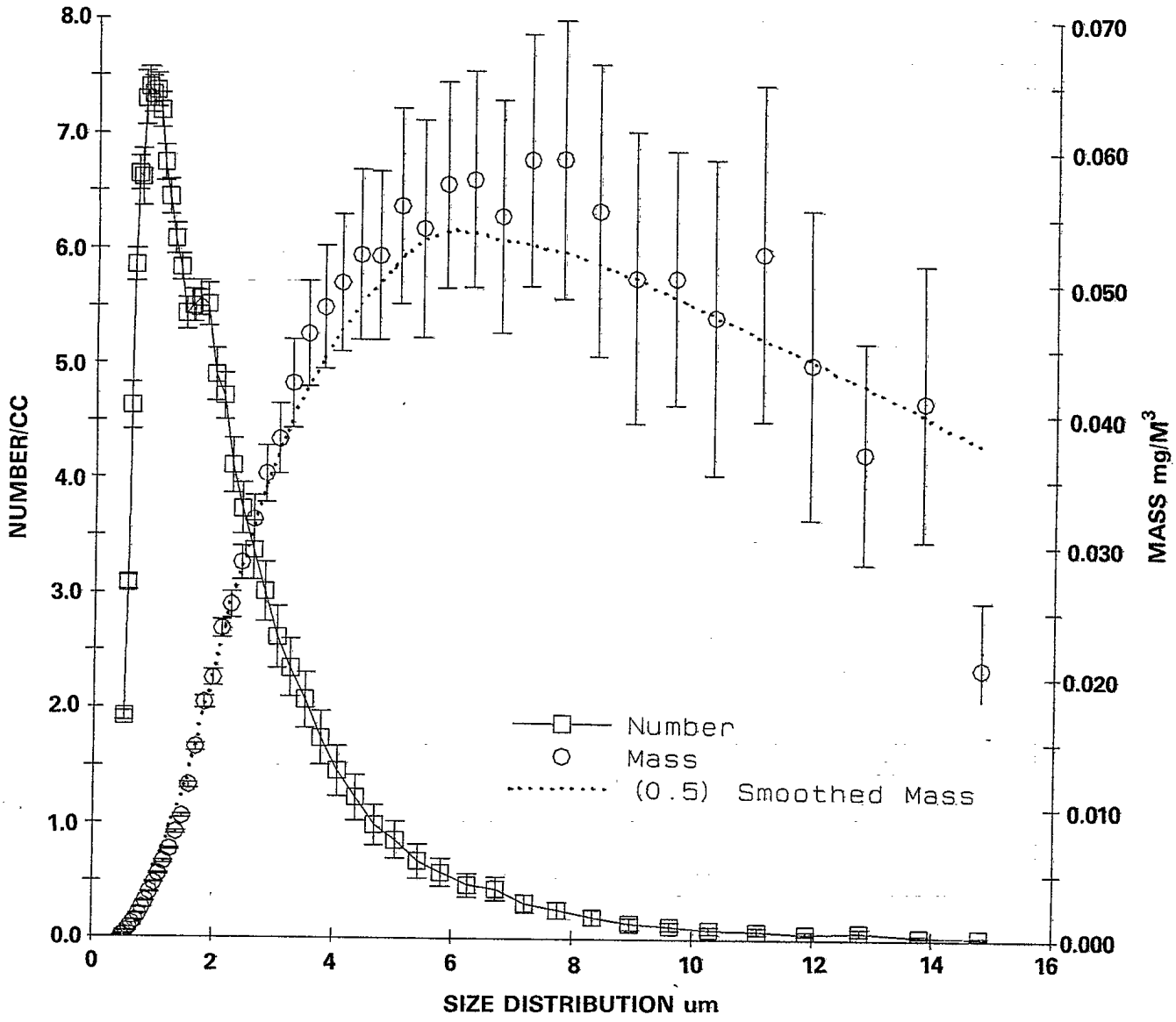

Figure 2

MEAN AND SEM PLOT FROM 50% BG MICRONAIR SPRAY

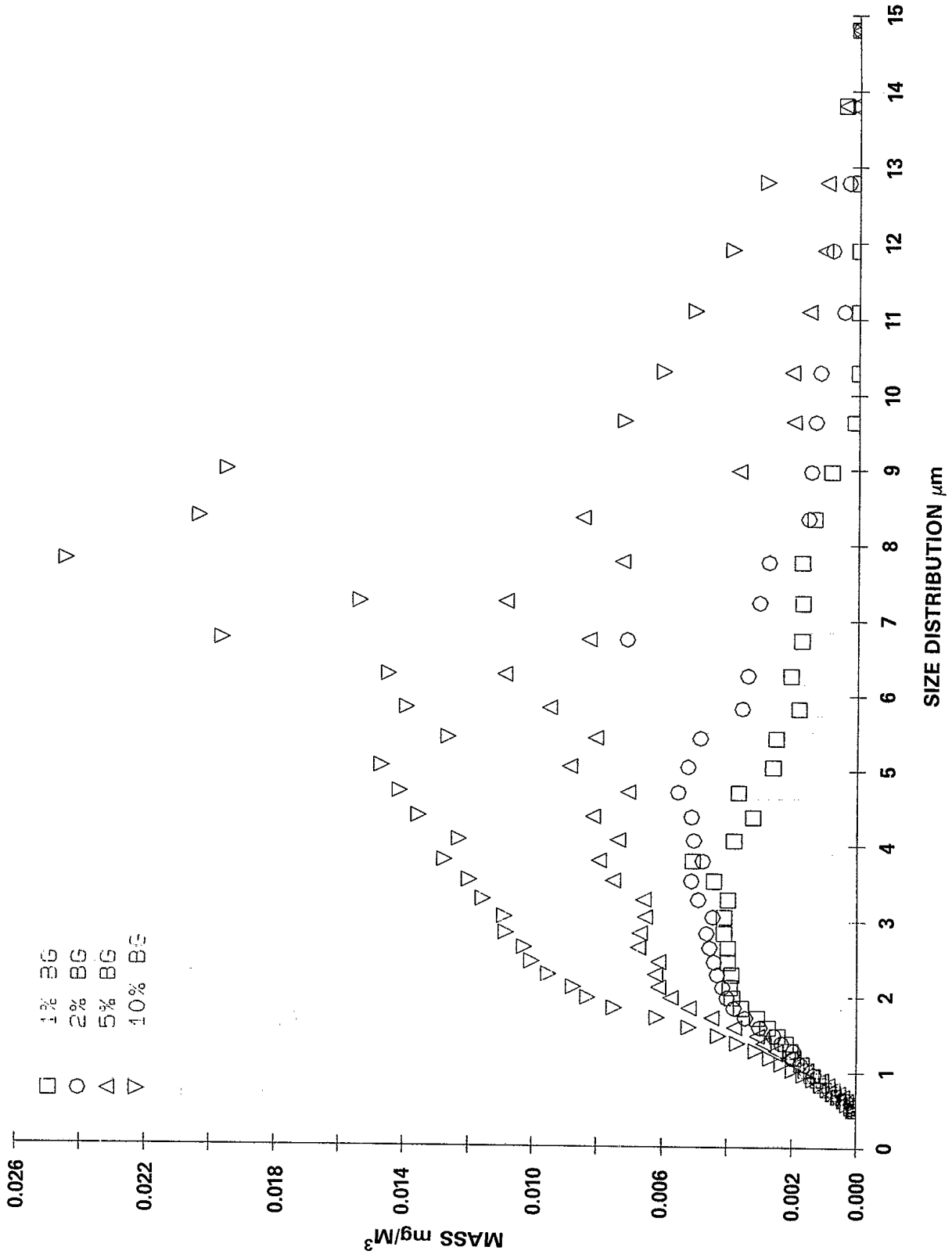

Figure 3

SUMMARY OF MASS SIZE DISTRIBUTION FROM MICRONAIR SPRAY (LOW SUSPENSION CONCENTRATIONS)

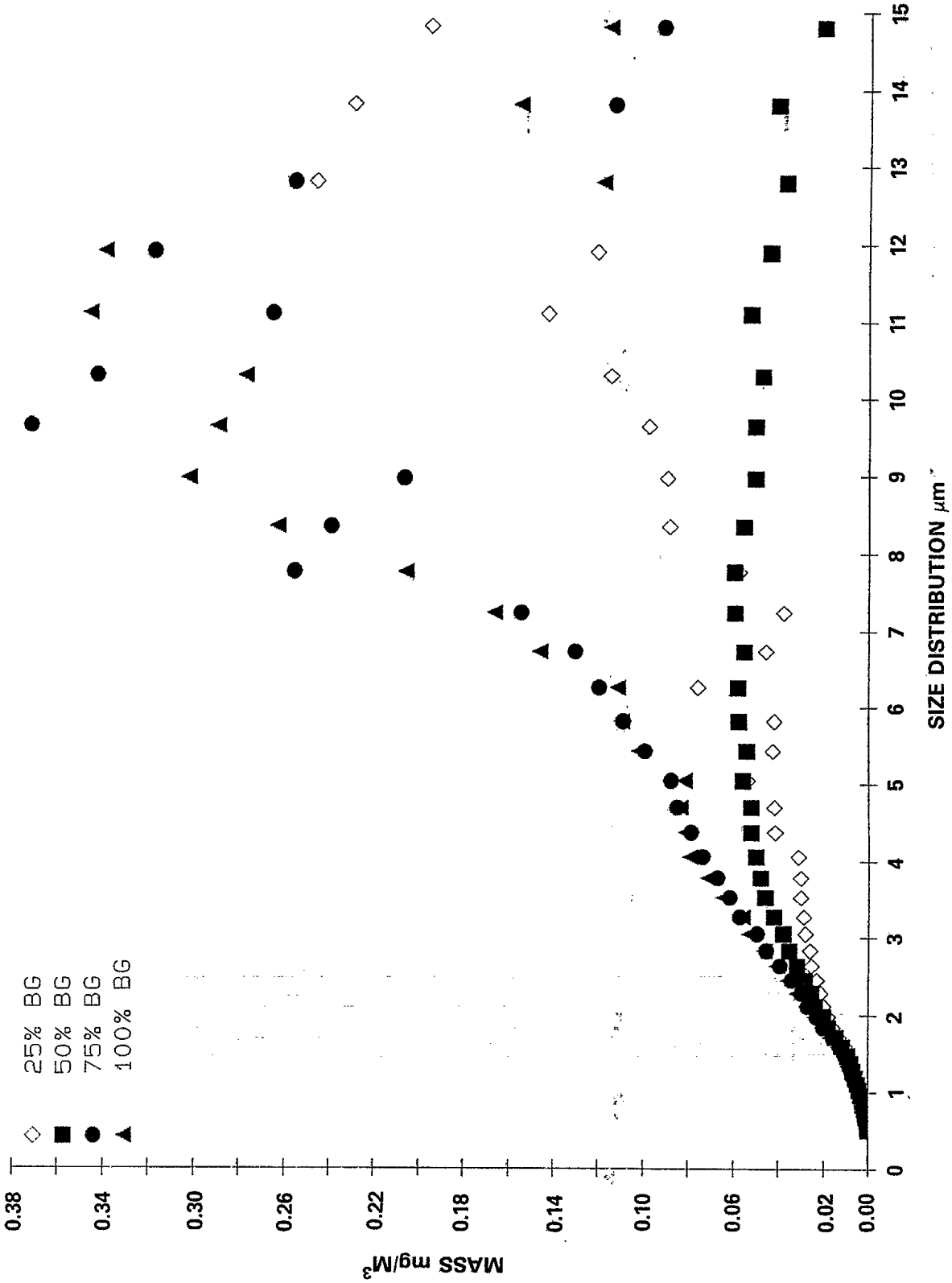

Figure 4

SUMMARY OF MASS SIZE DISTRIBUTION FROM MICRONAIR SPRAY (HIGH SUSPENSION CONCENTRATIONS)

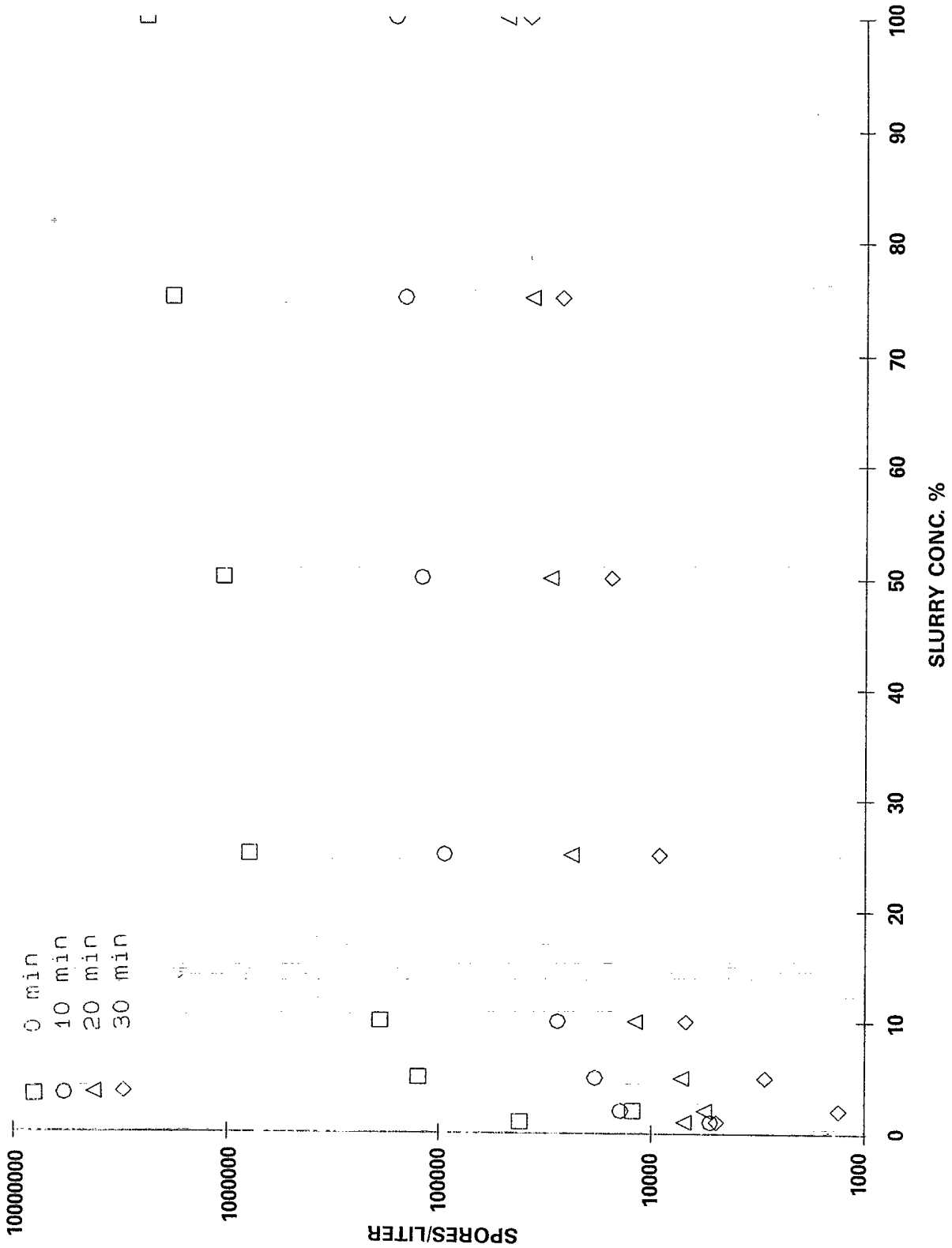

Figure 5

SUMMARY OF VIABLE SPORE NUMBERS IN AEROSOL DISPERSED BY MICRONAIR GENERATOR

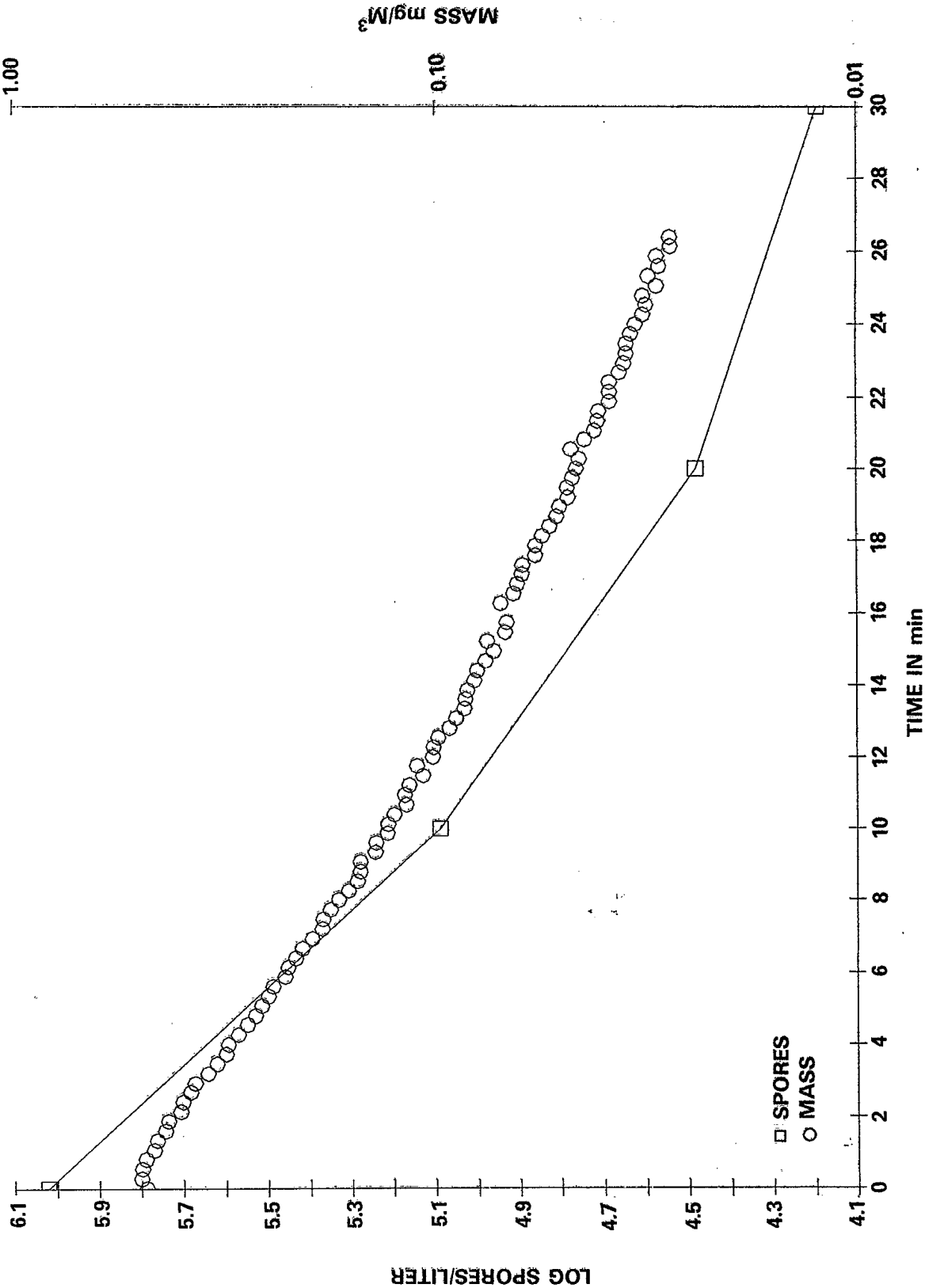

Figure 6

DECREASE IN MASS AND VIABLE SPORES WITH TIME (50% BG)

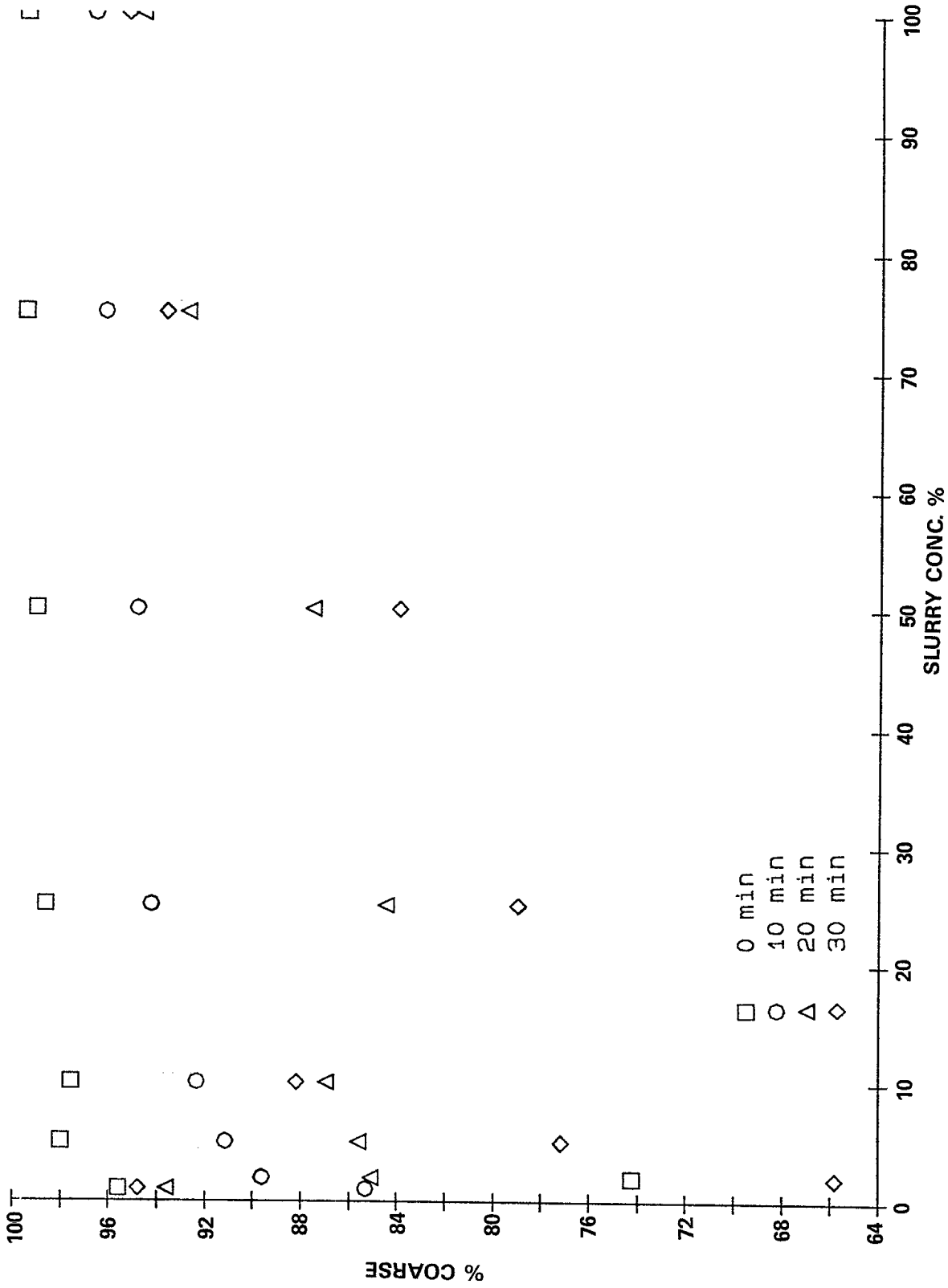

Figure 7

COARSE FRACTIONS FROM MICRONAIR

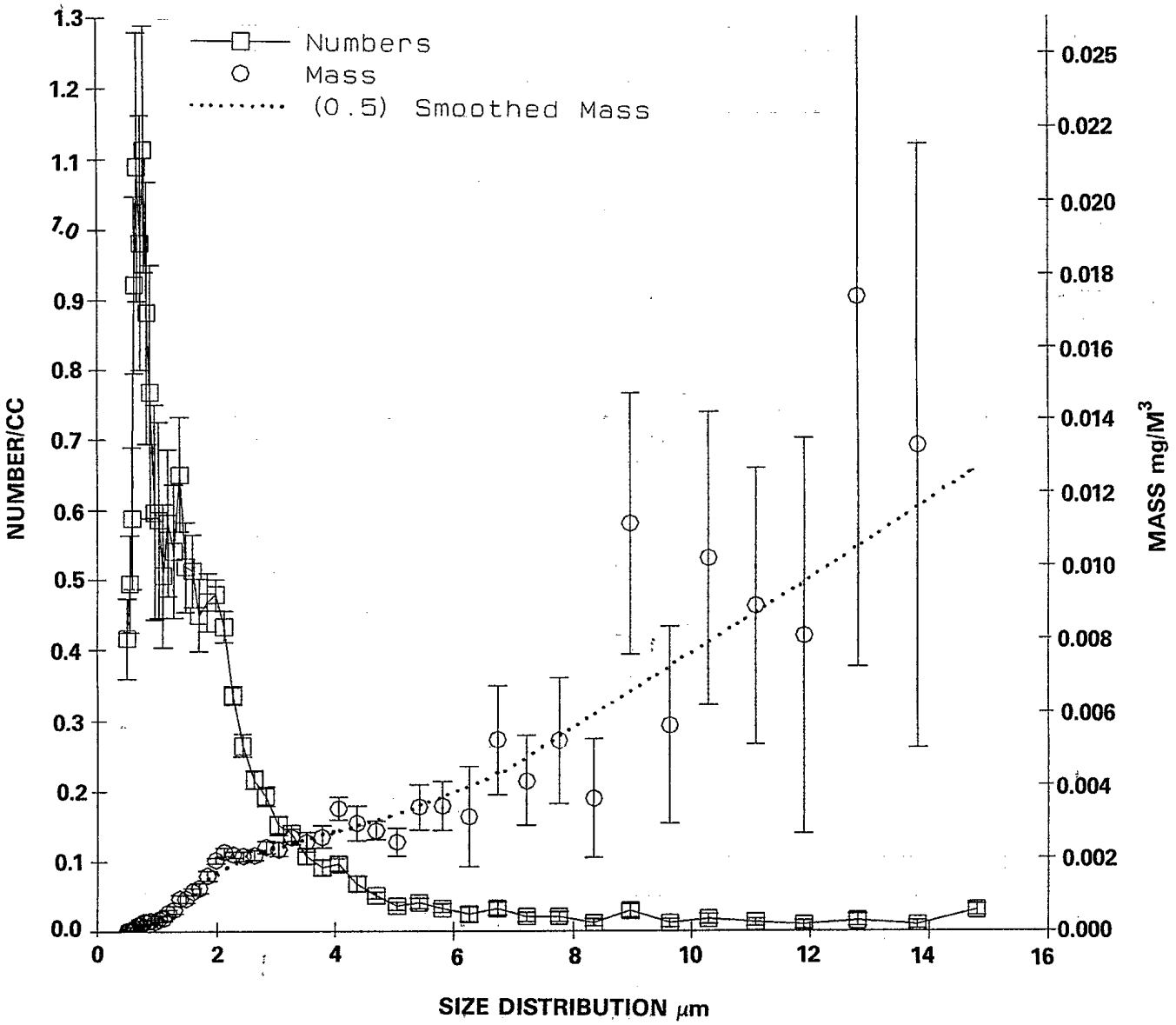

Figure 8

MEAN AND SEM PLOT OF PAINT SPRAYER OUTPUT (50% BG)

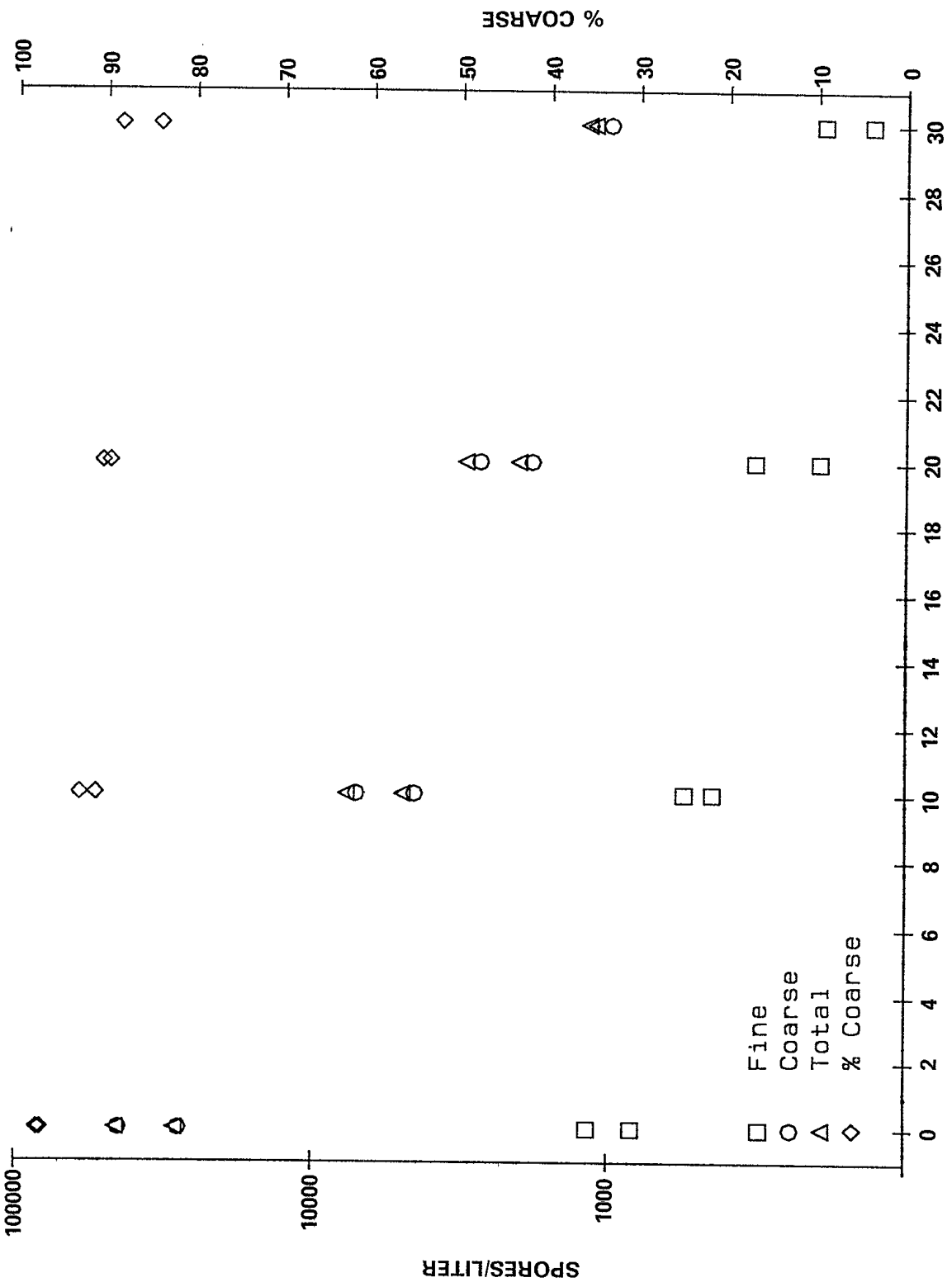

Figure 9

VIABLE SPORE AEROSOL FROM PAINT SPRAYER (50% BG)

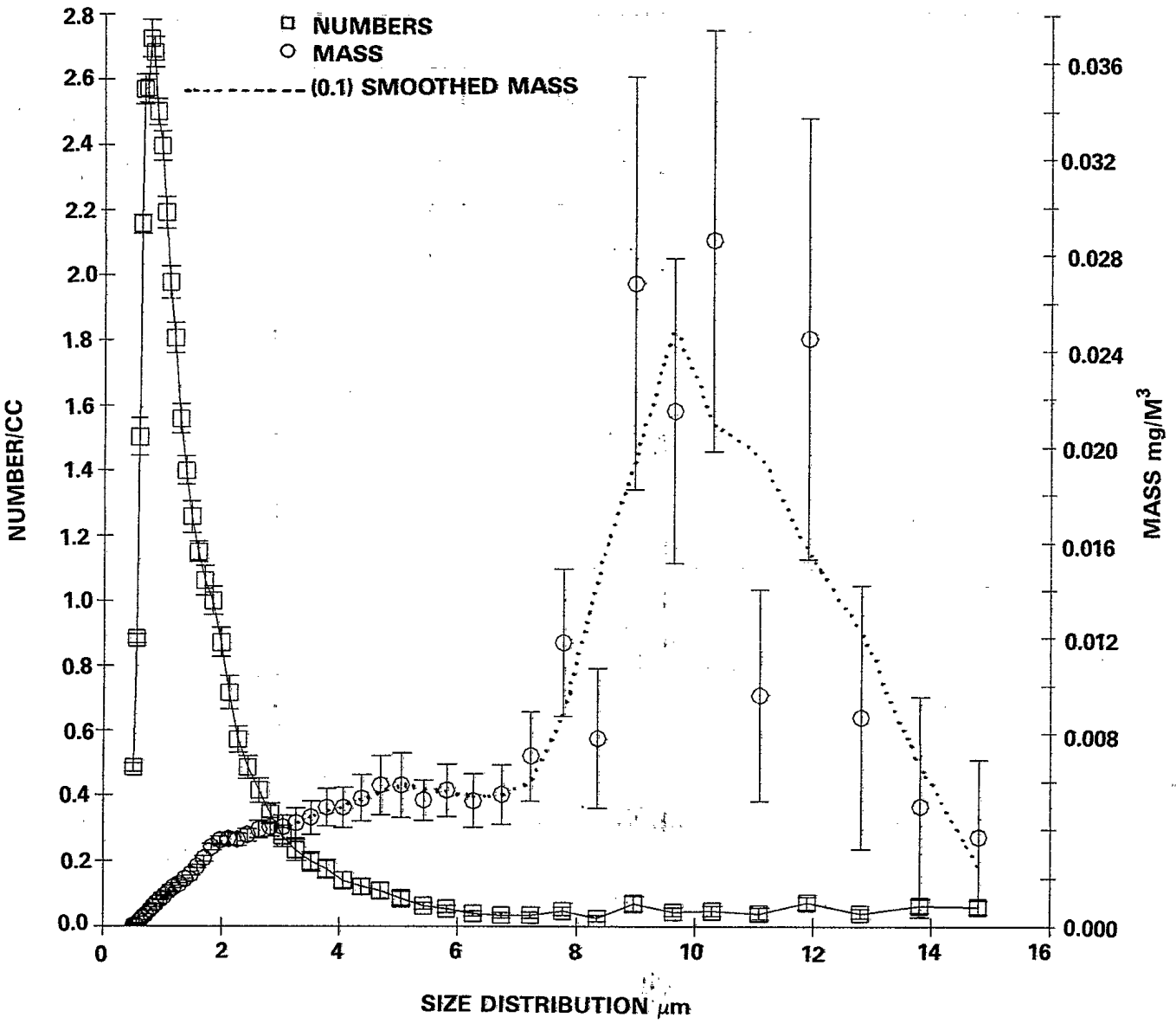

Figure 10

MEAN AND SEM PLOT OF AIR BRUSH SPRAY (50% BG)

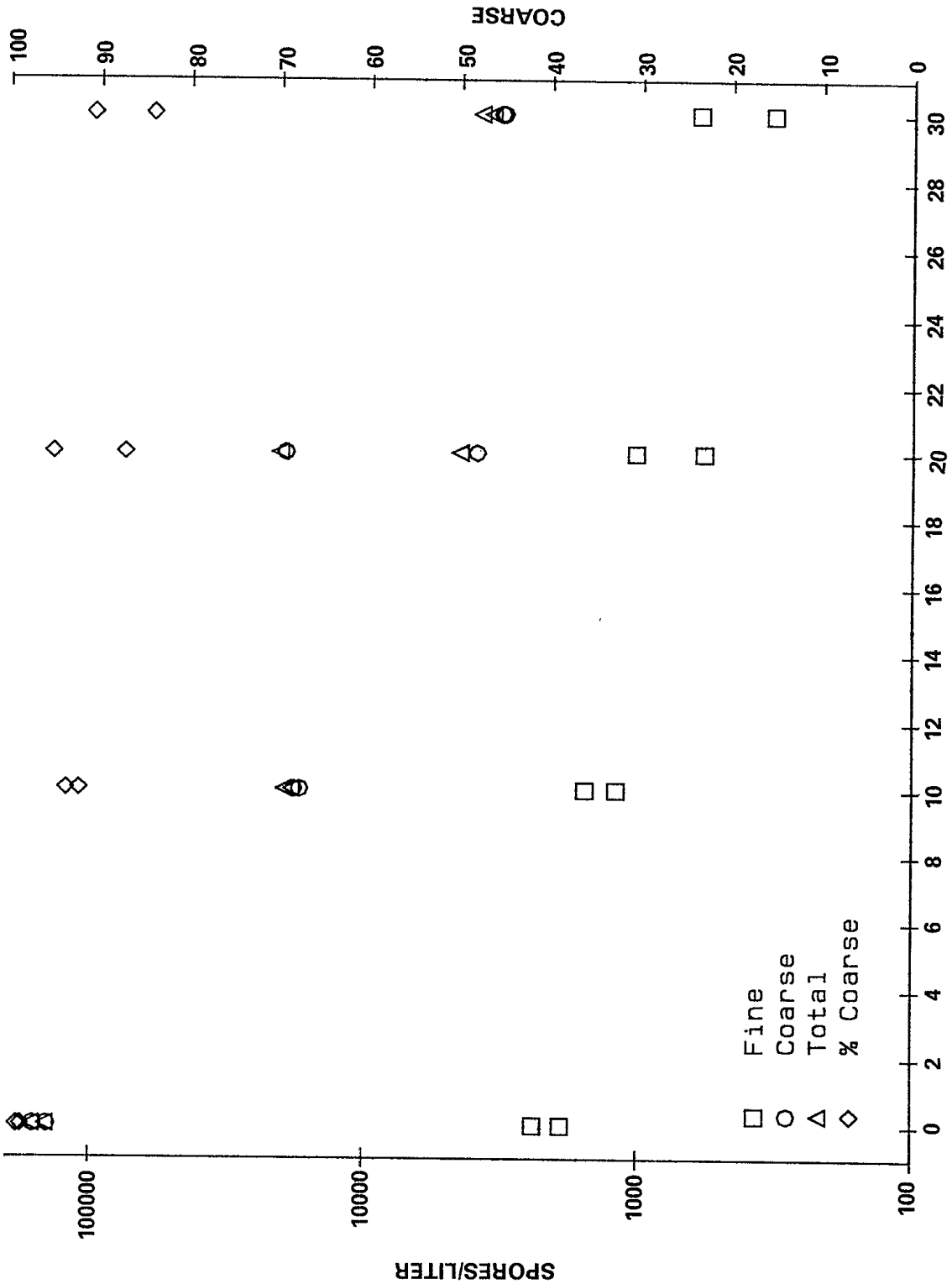

Figure 11

VIABLE SPORE AEROSOL FROM AIR BRUSH SPRAY (50% BG)

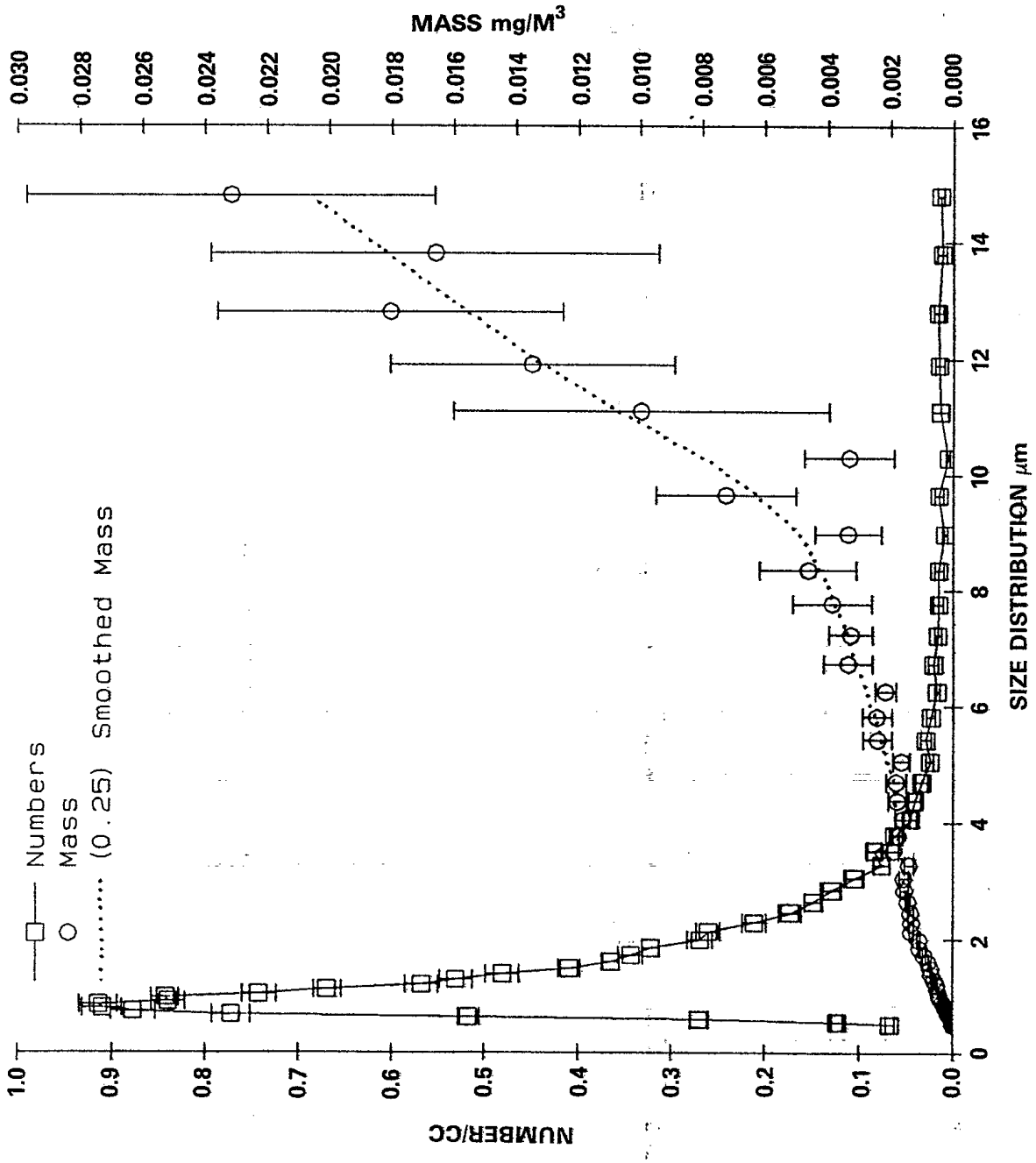

Figure 12

MEAN AND SEM PLOT OF JET PACK SPRAY (50% BG)

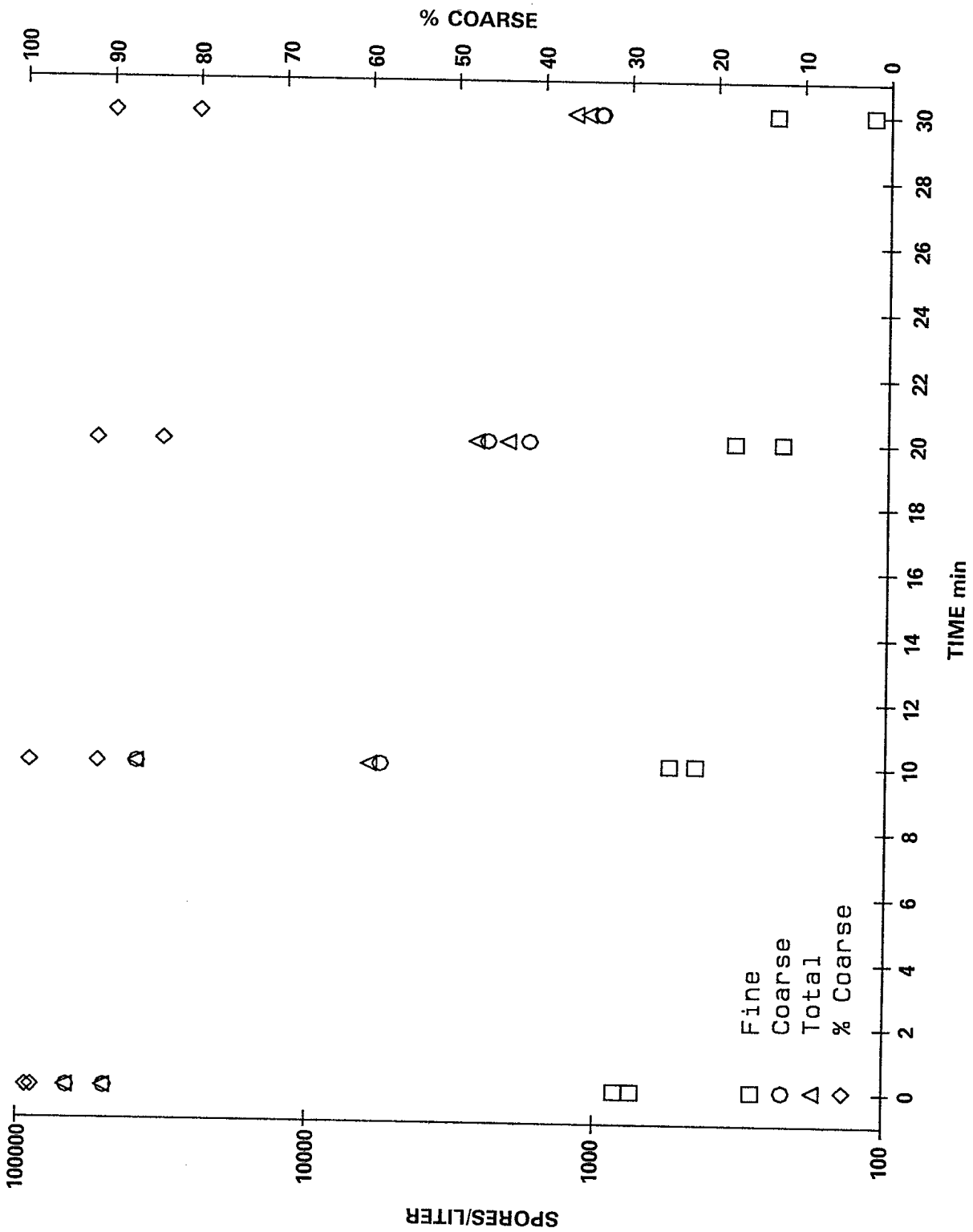

Figure 13

VIABLE SPORE AEROSOL FROM JET PACK SPRAY (50% BG)

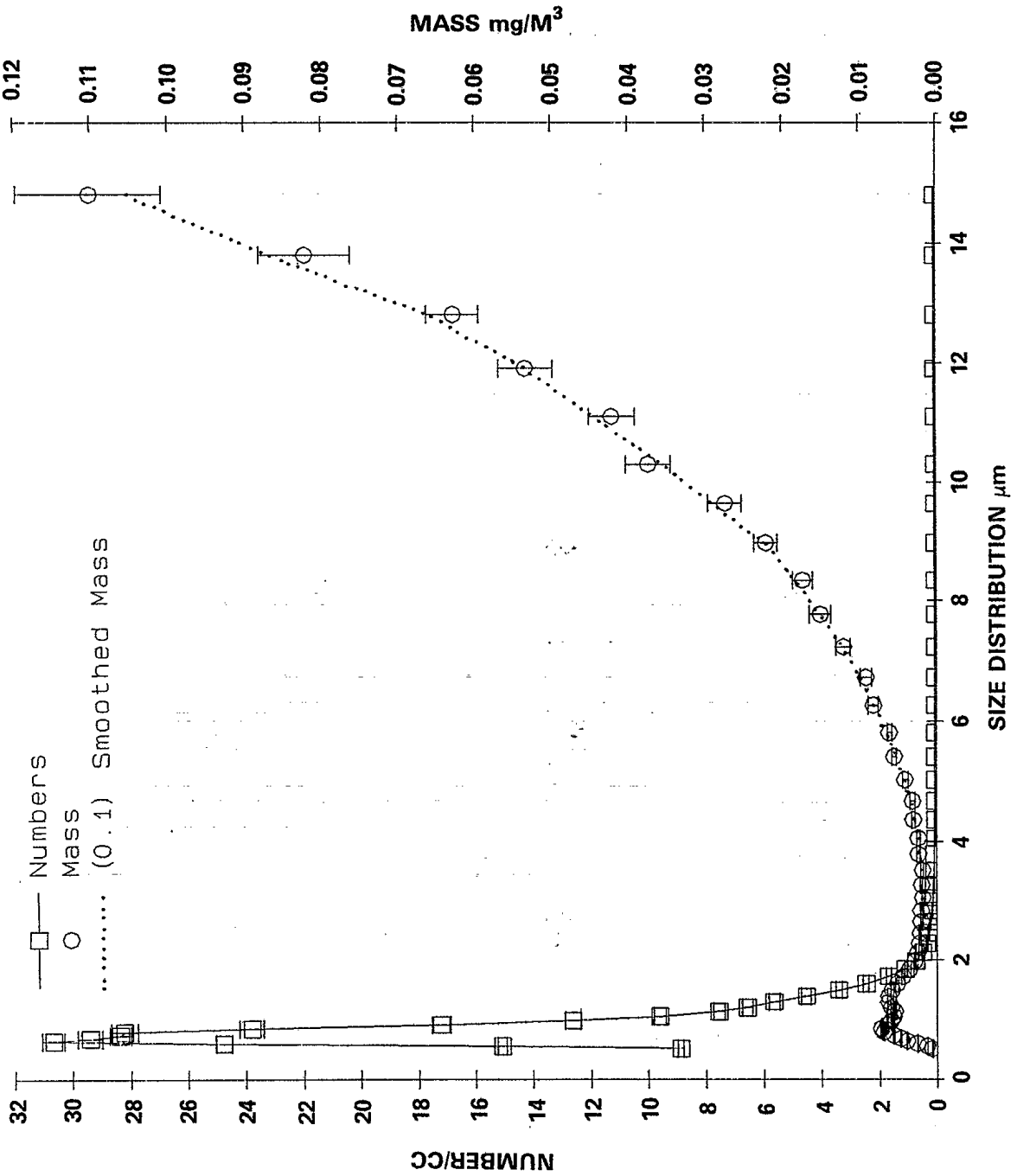

Figure 14

MEAN AND SEM PLOT OF NEBULIZER SPRAY (50% BG)

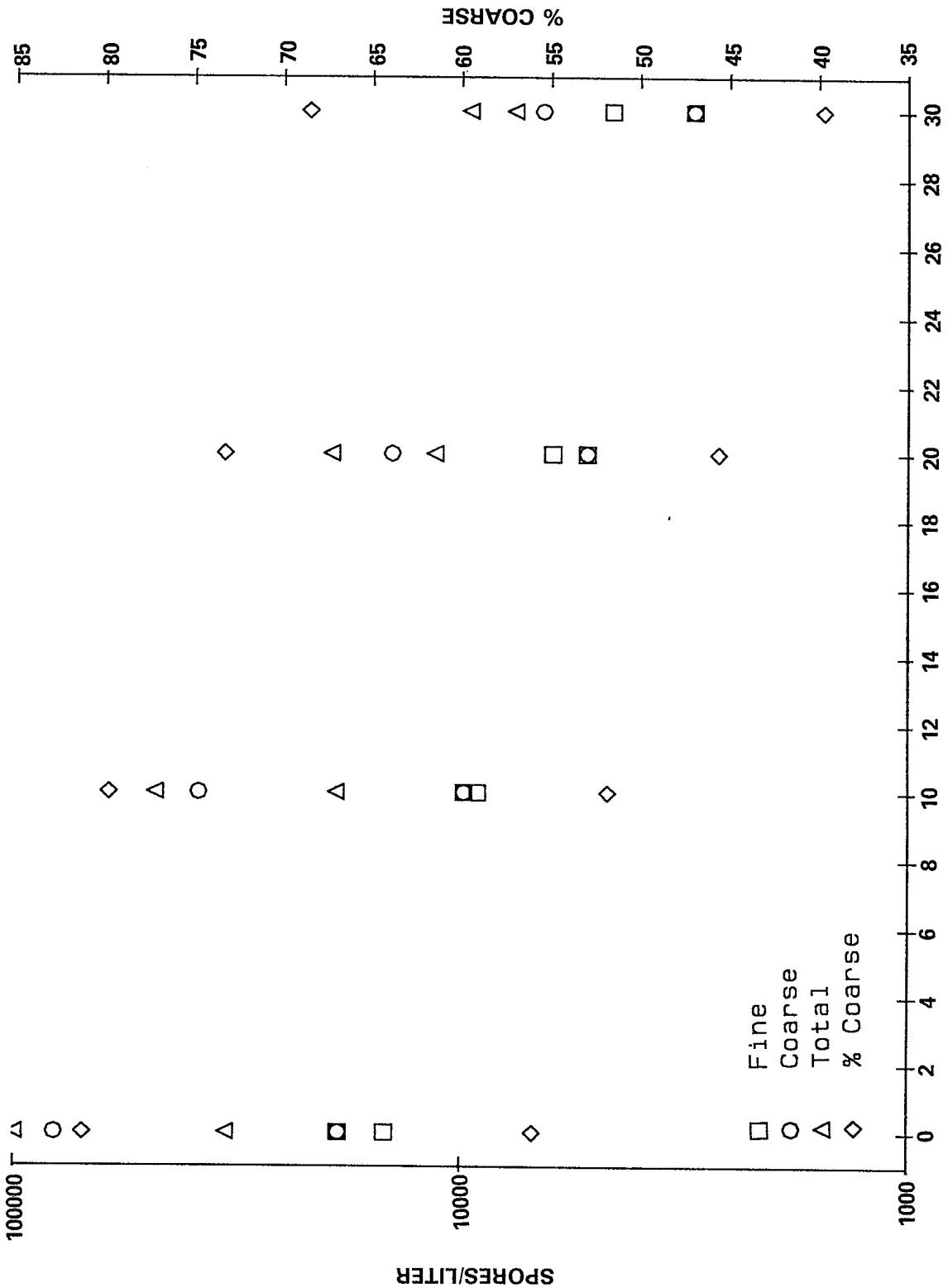

Figure 15

VIABLE SPORE AEROSOL FROM NEBULIZER SPRAY (50% BG)

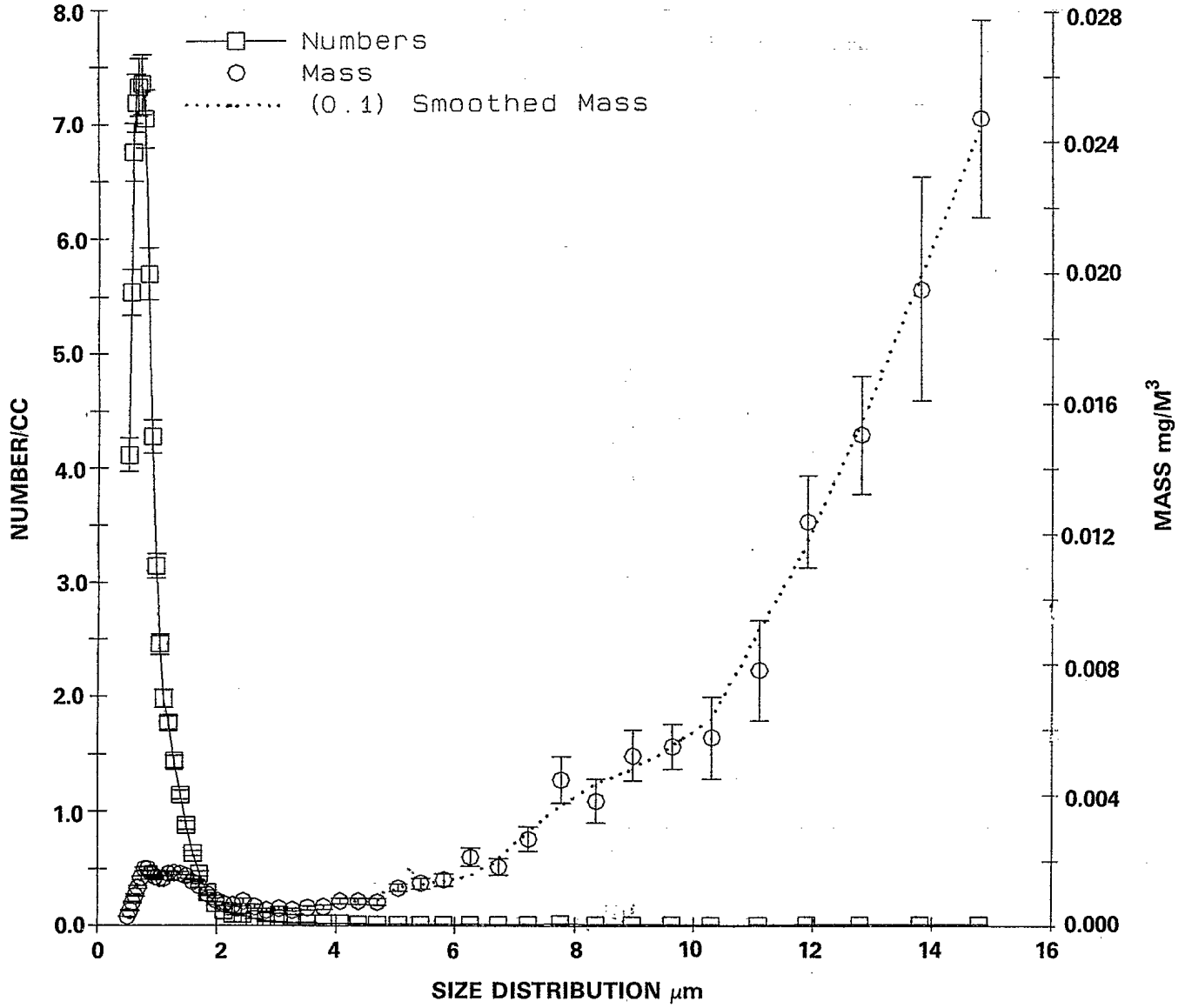

Figure 16

MEAN AND SEM PLOT OF COLLISON SPRAY (50% BG)

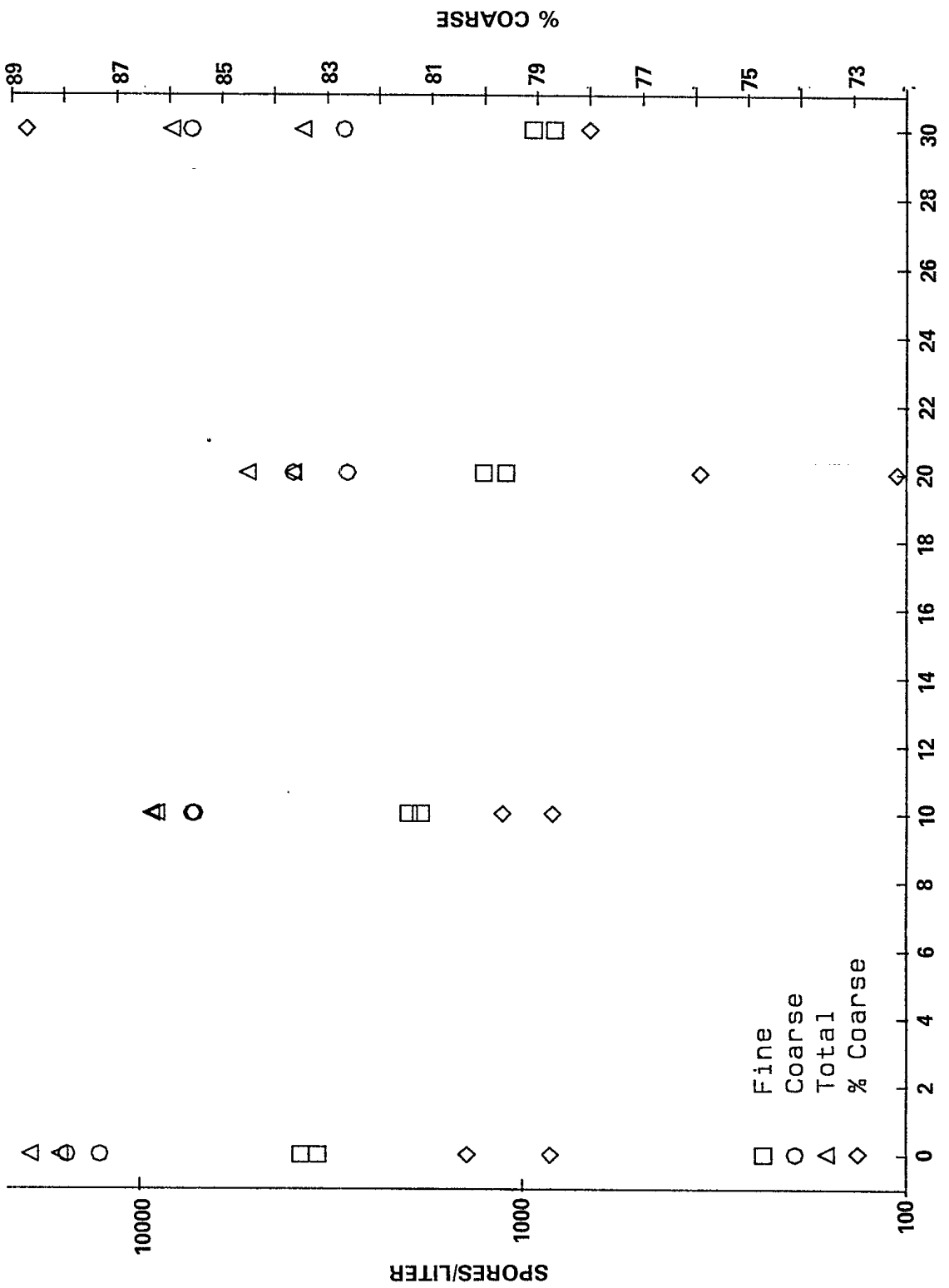

Figure 17

VIABLE SPORE AEROSOL FROM COLLISON SPRAY (50% BG)

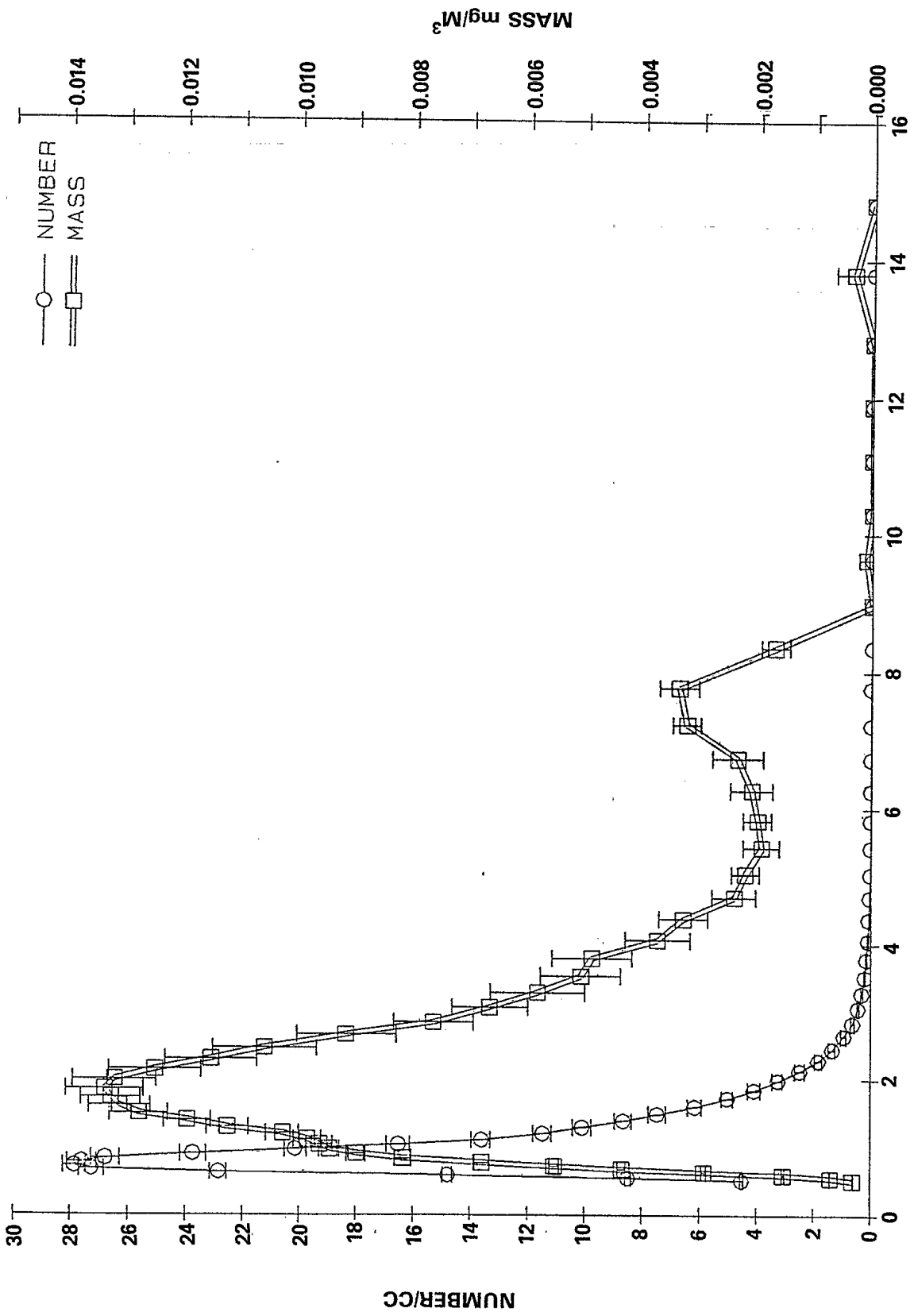

Figure 18

MEAN AND SEM PLOT OF HUDSON SPRAY (50% BG)

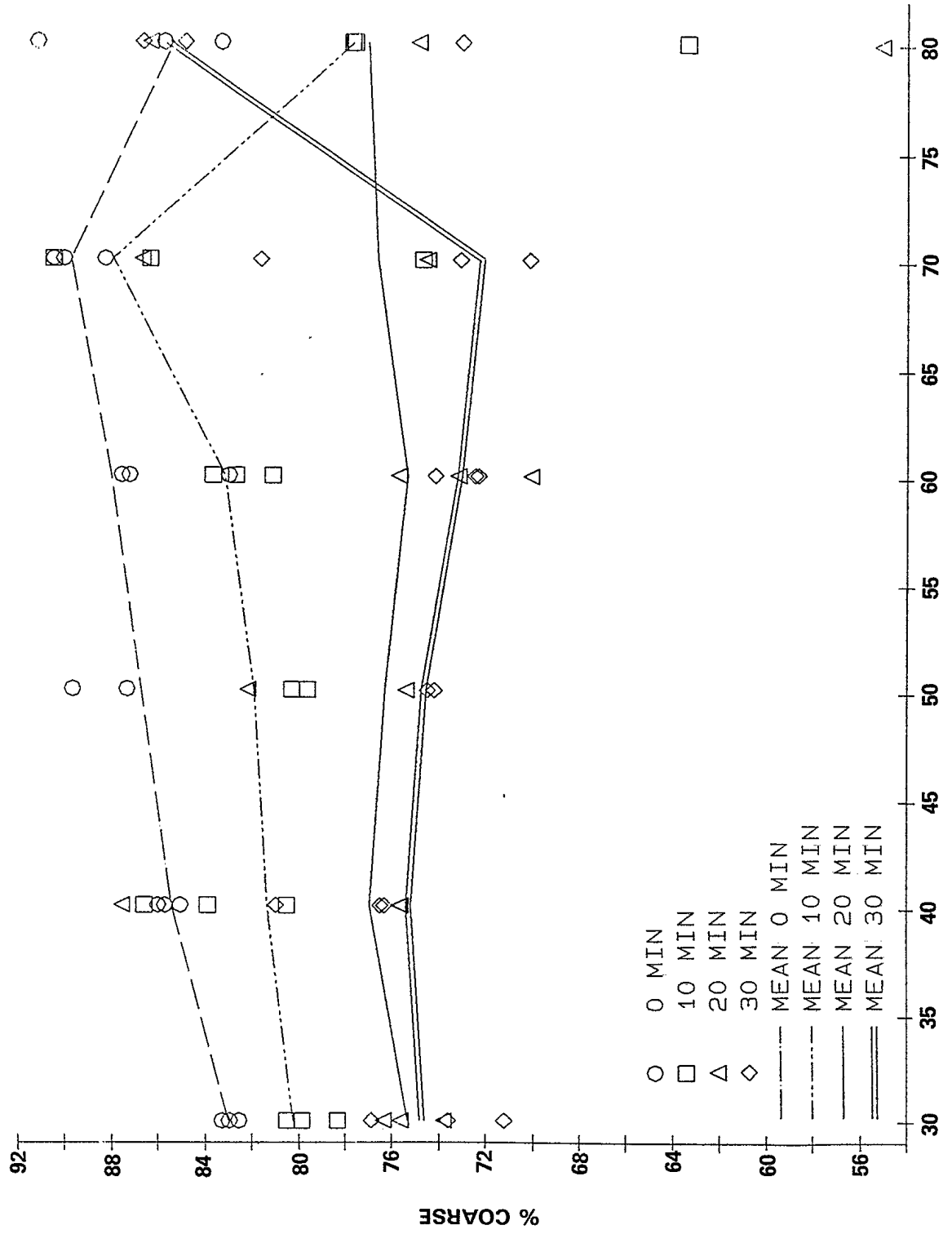

Figure 19

FRACTION OF COARSE AEROSOLS FROM HUDSON SPRAY

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(U) The successful operation of the Biochemical Detector (BCD) system depends on the concentration capabilities of the inlet nozzle component. This device was designed to concentrate the contents in 100 L of air into 100 μL of aqueous suspension, providing a 10^6 concentration factor. However, preliminary studies have indicated that only particles with diameters greater than 2.5 μm diameter were effectively concentrated. This observation implies that the BCD will not detect aerosols of diameter less than 2.5 μm. This limitation is a major concern as it is believed that biological warfare agent aerosols might have significant amounts of material in particles with size ranges below 2.5 μm. The characteristics of biological simulant aerosols were studied to determine if the 2.5 μm BCD concentrator cut-off limit created a significant detection problem. Second, a number of aerosol generating devices designed to produce fine particles were studied in order to determine if aerosols from these could be collected by the BCD inlet nozzle. The results of these measurements revealed that typical large to medium scale aerosol generators produced about 90% of total particulate material within the collection range of the BCD concentrator. The corresponding result for small scale fine particle generators is about 50-80%. Studies on a variety of aerosol generating devices revealed that their output aerosols fall in the range of the design specifications of the BCD inlet nozzle.

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Threat assessment; aerosol generators; aerodynamic diameter; biological aerosols; inlet nozzle; biochemical detector; Micronair; dichotomous sampler; biological detection.