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FIELD MEASUREMENTS OF PARTICLE SIZE DISTRIBUTION WITH INERTIAL SIZING DEVICES

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I. INTRODUCTION

The purpose of this research contract is to devise and evaluate various techniques for field measurements of the fractional efficiency of particulate control devices. The primary particle size range of interest is from 0.2 to 2.0 μm diameter but techniques for measuring larger particles are also being evaluated. Inertial classification is the basic sizing technique that is being considered under this contract. Most of this report is devoted to a description of a comprehensive particle size measurement program that was conducted at a coal-fired electric generating station earlier this year. The report also includes some information that was obtained from other field tests and from laboratory work so that it provides a summary of the most significant work during the first funding period of the contract.

II. BACKGROUND

Because of the current interest in the control of small particles, the emphasis in this work is on the development of measuring techniques suitable for the 0.2 to 2.0 μm* particle size range. Under the proper operating conditions, inertial sizing devices such as cascade impactors and multiple cyclones can be used to measure the size distribution of particles in the general size range of interest for air pollution work. Research

*All references to particle size in this report are given as particle diameter in μm (microns).

is in progress by others[1,2] to develop cascade impactors that will measure the particle size distribution down to about 0.02 μm. A minimum particle size of 0.3 μm is the approximate lower limit for all existing impactors that are suitable for field work. Most of our work has been devoted to improving field measurement techniques with cascade impactors.

Inertial sizing devices do not give real-time particle size information and particle size errors can result from reentrainment and other factors; however, inertial sizing devices have many features that make them worthy of consideration; these devices are useful over a wide range of particle sizes and concentrations; the aerodynamic size distribution obtained with cascade impactors is useful for the evaluation of most control devices; if needed, physical size can be computed from average particle density and shape information; the measured sizes are not affected by the optical or electrical properties of the particles; and, finally cascade impactors frequently can be used to provide mass concentration data, "grain loading", simultaneously with particle size data.

The work has been a combination of laboratory and field work with emphasis on field measurements made on a variety of stationary emission sources.[3] As a result of work on this project and several other recent and current Institute projects, which had a requirement for particle size determination, measurements have been made on the following emission sources: a kaoline kiln with a pilot-scale, gravel bed filter; two sulfate pulp mills with direct contract evaporators both equipped with a combination venturi scrubber and cyclone; a sulfate pump mill without direct contact evaporation equipped with an electrostatic precipitator; and eight coal-fired electric generating stations all equipped with electrostatic precipitators.

Most of this report is devoted to a summary of a comprehensive field test conducted over a period of about three weeks at a coal-fired electric generating station.

III. THE TEST CONDITIONS, PROCEDURES, AND EQUIPMENT

General Description

Between January 10 and January 24, 1973, particle size measurements were made at the inlet and outlet of an electrostatic precipitator that was being used on a coal-fired electric generator rated at 68 megawatts full-load output. A mechanical collector was in use upstream of the precipitator. The efficiency of the mechanical collector was approximately 75% so that the grain loading in the large particle size range was reduced and cyclone precollectors were not needed ahead of the impactors.

Five sampling ports were installed in both the inlet and outlet ducts of the precipitator. These ports were 0.15 m (6 inches) in diameter.

Particle size measurements were made with inertial classifiers built by six different manufacturers. Including modifications and prototype designs that resulted from work done on this project, a total of eleven (11) different sizing devices were evaluated. These devices are listed below and the stage size cut points, D_{50}*, for some of the devices are shown in Figure 1.

1. A Battelle CIS-6 impactor which had been modified by Battelle to include an additional stage with a D_{50} of about 0.25 μm. (Battelle)†

2. A parallel cyclone sizing device designed and built by McCrone Associates. (McCrone)†

3. A University of Washington Mark III Source Test Cascade Impactor manufactured by Pollution Control Systems, Inc. (U. W. Mark III)†

4. A conventional Brink BMS-11 sampling kit manufactured by Monsanto Environchem. (Brink BMS-11)†

5. & 6. Two Brink impactors that have been modified to provide size information for particles larger than those caught in the stage of the commercially available device. These modifications include an additional stage and cyclone precollectors. (Brink)†

7. A TAG sampler (multiple slit cascade impactor) manufactured by Environmental Research Corporation. (TAG)†

8. An Andersen Stak Sampler (Andersen Model II)†

9. A modified Andersen Stak Sampler with glass fiber filter substrates (Andersen Model III)†

10. A second modified Andersen Stak Sampler with glass fiber filter substrates and cyclone precollector. (Andersen III-cyclone)†

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*D_{50} is the particle size (aerodynamic diameter in μm) collected with 50% efficiency by the inpactor stage.

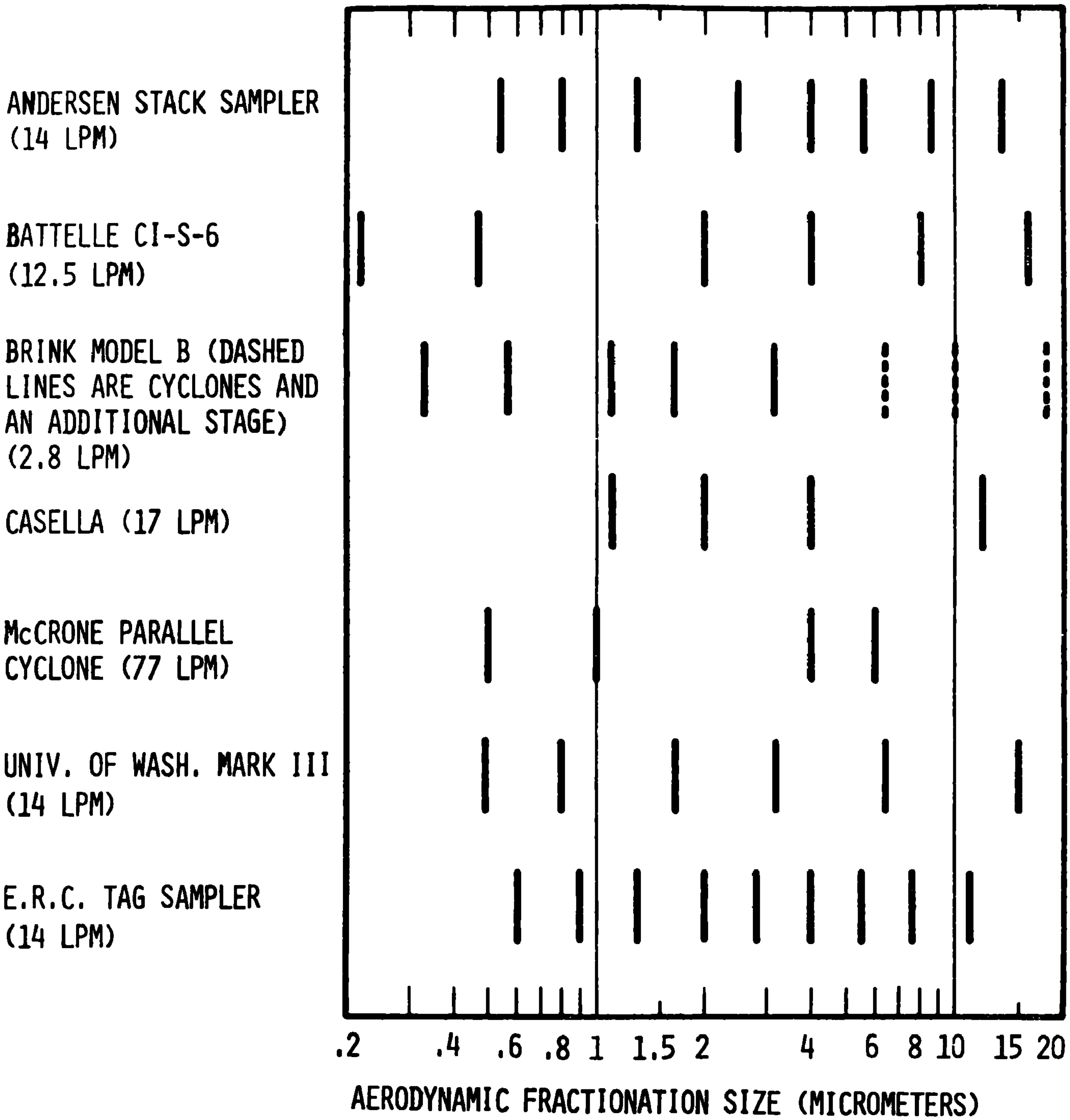

Figure 1. Comparison of Fractionation Sizes (D_{50}) for Seven Inertial Separators. (The Sizes Indicated are the 50 Percent Stage Penetration Points [at Typical Flow Rates] for each Stage of Fractionation.)

11. An instack version of the Andersen Non-Viable Sampler using glass fiber filter substrates. (Andersen Model IV)†

Test Procedure

Upon arrival at the steam plant, a laboratory was set up in the plant results laboratory. Two balances were used in this test. A Cahn Electrobalance was used for weighing the filter and foil substrates, as well as the other catches of less than about 30 mg. The Cahn weighing accuracy, as used for these tests, was about ±0.02 mg. For the heavier cyclone catches, a Ventron pan balance with a sensitivity of about 0.1 mg was used. Due to vibrations from the turbines, generators, motors, etc., the pan balance was moved out of the steam plant to one of our motel rooms. The Cahn balance is insensitive to vibration and was used in the plant laboratory.

To reduce the tare weight of the impactor stages, glass fiber filter or aluminum foil collection substrates were used for many of the impactor tests. The substrates were cut, disiccated and weighed prior to their placement in the appropriate device. The Andersen Model II and McCrone were the only devices which were not tested with the substrates on at least some of the tests.

After preparation of the impactor, an appropriate nozzle and sampling probe were chosen. The inlet and outlet ducts to the precipitator were approximately 2.5 m (8 ft) in depth with the air flow in a horizontal direction. When sampling with the instack samplers—Andersen, Brink,U. W. Mark III, and TAG—probes were used that placed the inlet to the impactor about 1.5 m (5 ft) from the top of the duct. The McCrone, Battelle, and Brink BMS 11 sampled through conventional probes and nozzles. These probes were approximately 1 m (3 ft) long. The Battelle was operated in the heated enclosure that was used for the McCrone; the same probe used for the McCrone was used for the Battelle.

A wide aray of nozzle sizes were available to permit near isokinetic sampling at fixed flow rates with each impactor. During each test, the Brink impactors were run in the vertical position while the Andersen, U. W. Mark III and TAG were usually run in a horizontal position. On a few occasions, buttonhook nozzles were used and the latter impactors were operated in a vertical position. It was found that operation in the vertical tended to result in less material being dislodged from the plates during removal from the duct.

†Key words shown in parentheses have been used throughout this report to simplify the identification of the various sizing devices.

With the Battelle, there was evidence of material lodging in the long probe without getting to the impactor. This problem was evident in low grain loadings at all sizes based on calculations to compare the data obtained with the Battelle to the other impactors. The average mass concentration obtained from the Battelle data was also lower than that measured with the full traverse ASME stack sampling procedure. The extent of the probe losses for out-of-stack samplers appear to be related to flow rate, loading, and particle size distribution. It is interesting to note that data obtained with the McCrone parallel cyclone used out of the stack and under about the same conditions as the Battelle showed general agreement with the data obtained with the instack samplers. The important difference was that the sampler probe flow rate for the McCrone was much higher than that used for the Battelle.

For the Brink tests, the only auxiliary equipment used were nozzles, a vacuum pump, manometer, and a stopwatch. The flow rate needed to achieve isokinetic sampling, based on average gas velocities, was maintained by monitoring the pressure drop across the impactor. For the Andersen, U. W. Mark III, and TAG impactor tests, a vacuum pump, a gas meter, an orifice for monitoring instantaneous flow, and stopwatch were used. The McCrone system was equipped with two gas meters, pumps, and flow metering controls as necessary, in a self-contained unit. The flow rate for the Battelle impactor was determined with a conventional dry gas meter.

During some of the early tests with the U. W. Mark III, TAG and Andersen impactors, it was noticed that material was accumulating on the underside of the plates at locations where material would not be deposited by such things as particle bounce, etc. These deposits appeared to be related to the large negative pressure in the duct (relative to ambient pressure) which caused a reversed air flow through the impactors when the vacuum pumps were turned off. This caused loose material in the impaction deposits to be reentrained and impacted on the underside of the plates. Competely sealing the flow system at the end of a sampling run seemed to solve this problem.

As soon as possible after the impactor was removed from the duct, the impaction substrates were removed from the impactor and desiccated overnight before weighing. Handling of backup filters proved to be a problem. On approximately half of the tests these filter weights were negative, even when it was visibly evident that material had accumulated on the filter. This problem was observed on all of our tests and appears to be related to the design of the filter holder; that is, some of the filter material is lost when the filter is removed from the holder. On about 50% of the tests, the last stage showed weight losses when greased substrates or glass fiber filter substrates were used. It should be noted that the correct weight gain of the final stages and filter is typically quite small; however, the weight losses that were observed appear to be due to handling problems more than weighing accuracy.

IV. TEST RESULTS

The McCrone Parallel Cyclone Inertial Sizing Device

Six tests were performed with the McCrone parallel cyclone, all at the precipitator inlet. Because no outlet measurements were made, fractional efficiencies could not be obtained solely from McCrone data. The McCrone device consists of 6 major pieces; two condensing units, two gas pump and metering boxes, the enclosure for containing the Parallel Cyclone, and the sampling probe. The cyclone enclosure and probe are maintained at stack temperatures by means of appropriate heaters. Due to the bulk and weight of the device, it would be extremely difficult to run inlet and outlet tests on the same day with only one system.

The parallel cyclone assembly consists of a large scalping cyclone, three smaller cyclones, and a filter all sampling from a manifold at the outlet of the scalping cyclone. Each small cyclone has its own back up filter. The D_{50}'s for the four cyclones are reported to be 6.0, 4.0, 1.0, and 0.5 µm when operated under the conditions used for these tests. Thus in the 0.2 to 2.0 µm range of particle sizes, the McCrone unit provided only two fractionation points. It would be possible, however, to modify the McCrone to provide additional size cuts in the particle size range of interest.

For these six tests, sampling times were from 9 to 15 minutes which resulted in sample volumes between 0.6 and 1.3 m^3 (22 to 45 ft^3). The total volume sampled with the impactors in comparison was typically about 0.03 m^3 (1 ft^3). During operation, it is the increasing pressure drop across the cyclone back up filters that limits the sampling time. It is worth noting here that when the McCrone system was operating, the pitot tube built into the probe consistently showed a 10% velocity increase over the value obtained with the sample flow off.

The McCrone sampling probe extended about 1 m (3 ft) into the duct. The connection from the stack to the sampling box was not heated. We did not directly measure probe losses; however, the grain loadings computed from the cyclone and filter catches agreed very well with those determined by conventional methods and the size distributions were found to agree reasonably well with those obtained with the instack classifiers. Cumulative size distributions for representative McCrone runs are shown in Figure 2.

Prior to each run, four filters were desiccated and weighed, then placed in their holders. The cyclones were then heated to stack temperature after which sampling was started with flow rates set by cyclone and metering orifice pressure drops. (The flow rates must be held constant.) As the test continued, the back up filters began to clog and after some time, the filter pressure drops exceeded the pump capacities at which time sampling was terminated. The 47 mm filters used in the present unit limit the sampling time rather than the capacity of the cyclone reservoirs. After cooling, the cyclone catches and back up filters are removed, desiccated, and weighed. There was some problem in removing the filters from their holders. On many occasions, a considerable amount of the filter material stuck to the filter holder. As mentioned previously, this was a common problem with back up filters for all the devices tested which used rubber rings to seal the back up filter.

Differential size distributions for each run were obtained by numerical differentiation of cumulative size distributions. For example, Figure 3 shows the differential distributions obtained from the cumulative data shown in Figure 2. Each curve tends to agree fairly well with inlet distributions obtained with the other devices. Below 0.5 μm, the differential distributions shown are extrapolations based on an analytical curve fitted to the cumulative distribution data points.

For all differential distributions given in this report, the ordinates have the units of mass concentration; that is, the "M" in the expression $\frac{dM}{d \log D}$ has the units of g/m^3 or gr/ft^3. Since the main interest here is in the shape of the various distributions rather than the actual value of the points, all of the differential distributions in this report are shown with the more familiar units of gr/ft^3. For conversion to metric units, the number in gr/ft^3 should be multiplied by 2.288 to obtain g/m^3.

The lack of information in the particle size range of interest, 0.2 to 2 μm, makes it difficult to compare data obtained with the McCrone with the other devices which provide a greater number of size cuts. The large size and weight of this prototype

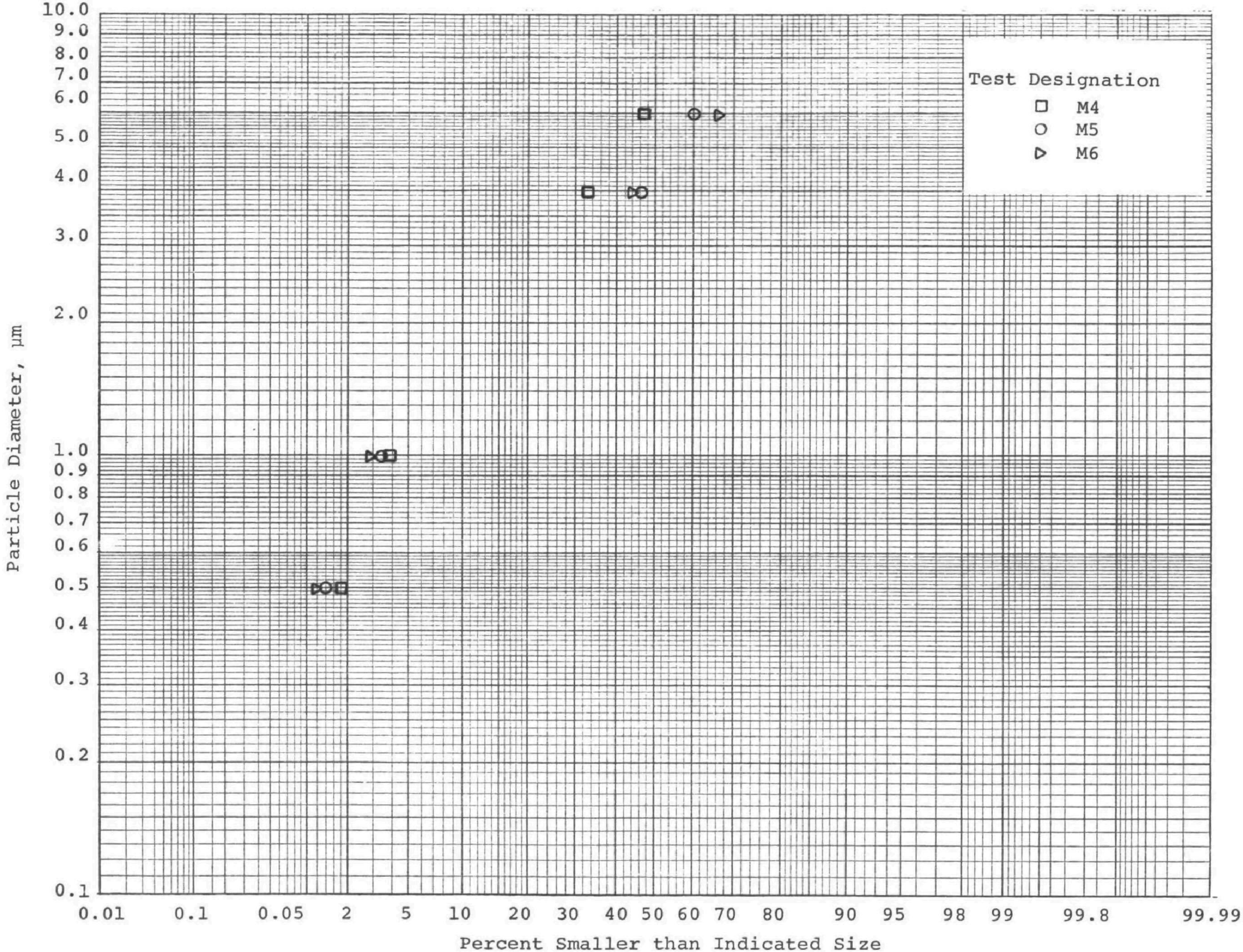

Figure 2. Representative Cumulative Size Distributions Obtained with the McCrone Parallel Cyclone Sampler.

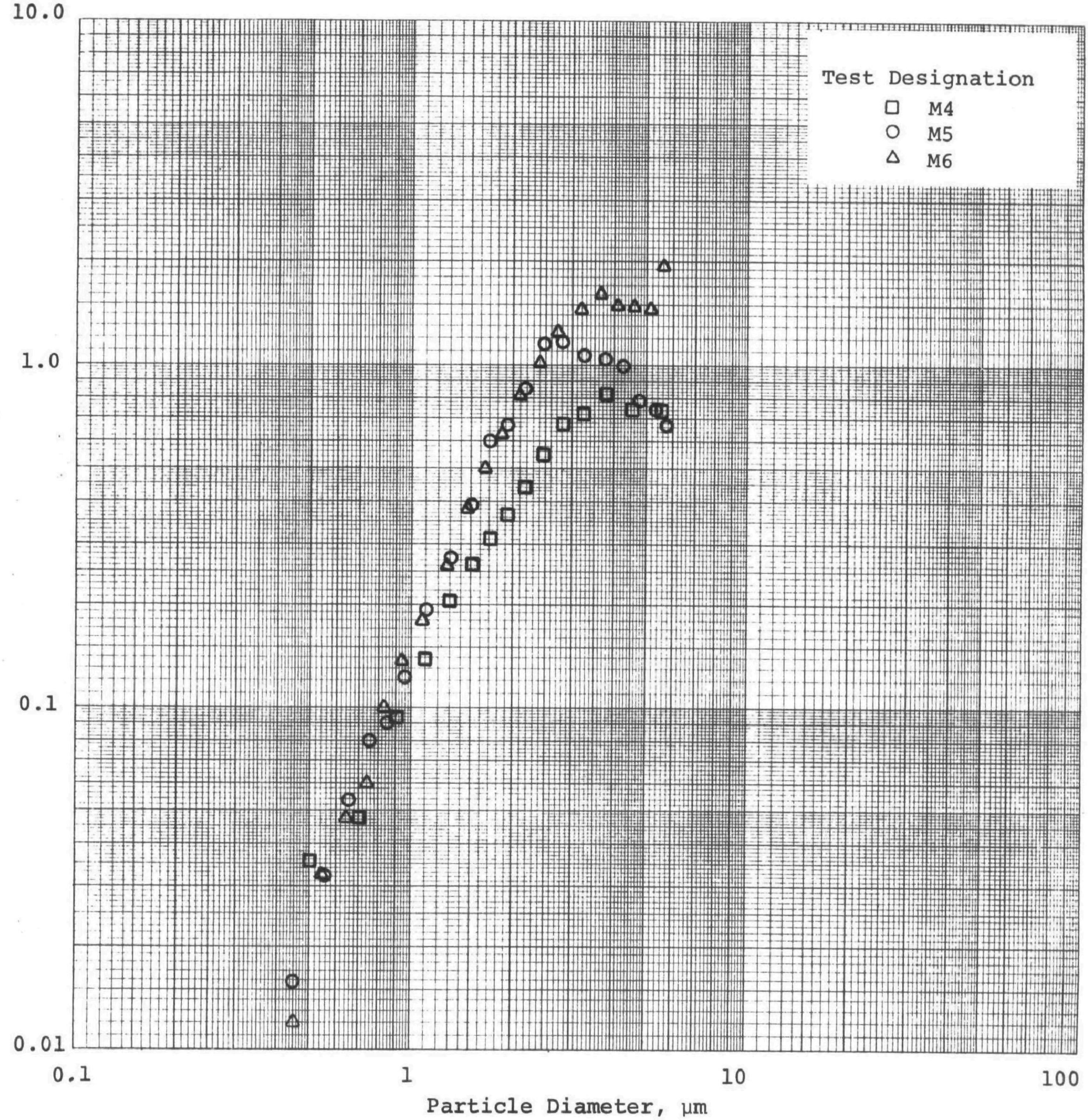

Figure 3. Differential Mass Distributions Obtained from the Cumulative Distributions shown in Figure 2.

model of the McCrone made this particular device a poor choice for the measurement of fractional efficiencies. The concept, however, appears to have merit and the prototype devices tested here may in fact be useful for determining efficiencies from 0.5 to 10 μm, especially where inlet grain loadings are very high and sampling times for impactors are impractically short. During these tests, the parallel cyclone was able to sample for about 2 to 6 times as long as the impactors and sampled 20 to 50 times the gas volume sampled by the impactors. The sampling time could be substantially increased by using back up filters with a larger surface area.

Battelle CIS-6 Cascade Impactor

Five tests were conducted using a Battelle CIS-6 cascade impactor. The model used in these tests had been modified to include an additional multiple orifice stage which was reported to have a D_{50} of about 0.25 μm. The Battelle was mounted external to the duct and the McCrone probe and heater were used. The impactor was heated to stack temperature before the sampling was started. Since the entire seven stage impactor would not fit in this enclosure, stages 1 and 2 were removed and not used for four of the five runs. On the fifth run, stage seven was omitted and stage two was used. This omission caused a loss of information at some sizes but in this case the information was of small consequence because of the mechanical separator upstream of the sampling location. Furthermore, the fractionation sizes for the stages omitted were much larger than the upper limit of our primary range of interest.

To improve weighing accuracy by reducing the tare weight of the collection surfaces, foil substrates were used rather than the glass plates supplied with the impactor. On four of the five runs, grease was used on the foils.

Particulate mass concentrations calculated from the Battelle data do not agree with measurements obtained with the other devices. The fact that these results are very low indicates a possible loss of material in the sampling nozzle and probe. This may have been aggravated by a relatively low gas velocity that must be used in the probe. Differential mass distributions determined from the Battelle data show pronounced deficiencies at larger particle sizes. This occurred in spite of the use of an oversized inlet sampling nozzle which should have resulted in some over sampling of large particles. Differential size distributions as measured with the Battelle impactor are shown in Figure 4.

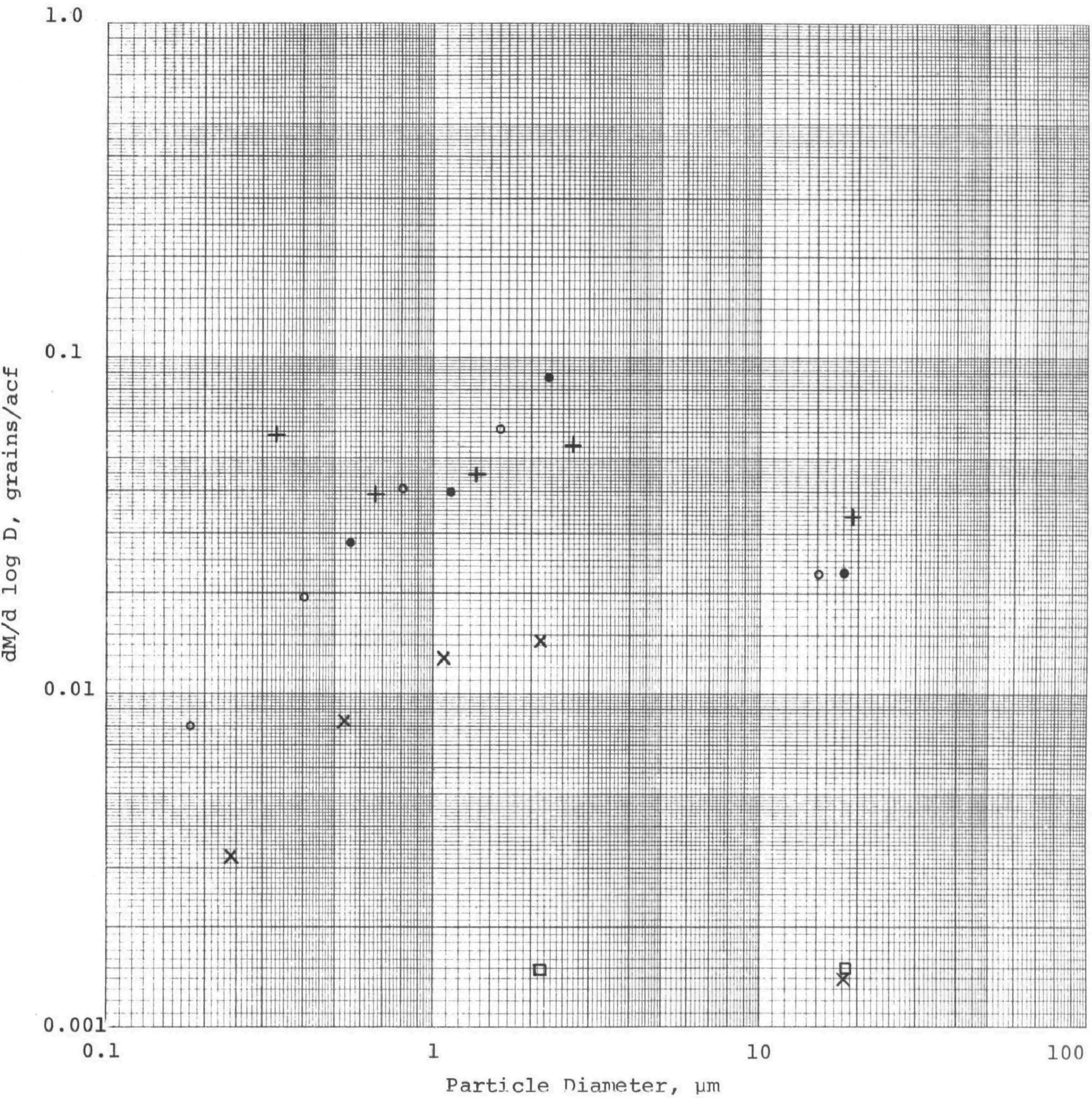

Figure 4. Differential Inlet Mass Distribution Obtained with the Battelle CIS-6 Impactor.

TAG Multiple Split Cascade Impactor

The ERC TAG impactor consists of 10 impaction stages and a back up filter. Each stage weighs about 20 g. This is too heavy for use with the high precision balance; therefore, for heavily loaded stages, the material was removed from the plates and transferred to a small foil boat for weighing. ERC recommends the use of grease on stages 1 and 2; however, these stages are for particle sizes outside the range of interest for our work so these stages were not weighed. Based on visual appearance and weighing, stages 7, 8, 9, and 10 showed poor particle retention. For this reason, the bare metal substrates were covered with foil substrates that had been coated with a thin layer of grease for most of the runs. It appeared that the use of foil on stage 10 was probably the only way to accurately determine the catch on this stage by use of gravimetric methods.

As shown in Figure 5, the data from the six inlet runs with the TAG tend to agree fairly well with that obtained with the remaining devices in the 0.2 μm to 2.0 μm range. In general, they do lie a little lower in this range.* In the region above 2.0 μm, the differential distributions obtained from TAG data were low when compared with the distributions obtained with the other devices.

Figure 6 shows the results of several tests at the precipitator outlet that were made with the TAG during times when the generator was operating at 94% load. General agreement was found with the other impactors in the range from 0.2 μm to 2.0 μm; however, above 2.0 μm there was very poor agreement; the TAG data generally gave loadings above 2 μm that was lower than the other sizing devices.

Figure 7 shows the results of measurements made with the TAG when the generator load was 85% and another performed with 100% load. There does not appear to be enough data from these individual tests to make a meaningful comparison with the other devices tested during these load conditions.

University of Washington Mark III Source Test Cascade Impactor

Figures 8 and 9 show the data from the U. W. Mark III inlet runs with and without greased foil substrates. Four runs were performed with grease on stage 1 only. Thirteen runs were performed with grease and foils on all stages. It can be seen that the apparent loading at sizes from 0.3 μm to 2.0 μm

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*Subsequent to the preparation of this report a revised calibration was obtained which reduced but did not entirely eliminate the difference between the TAG and the other impactors.

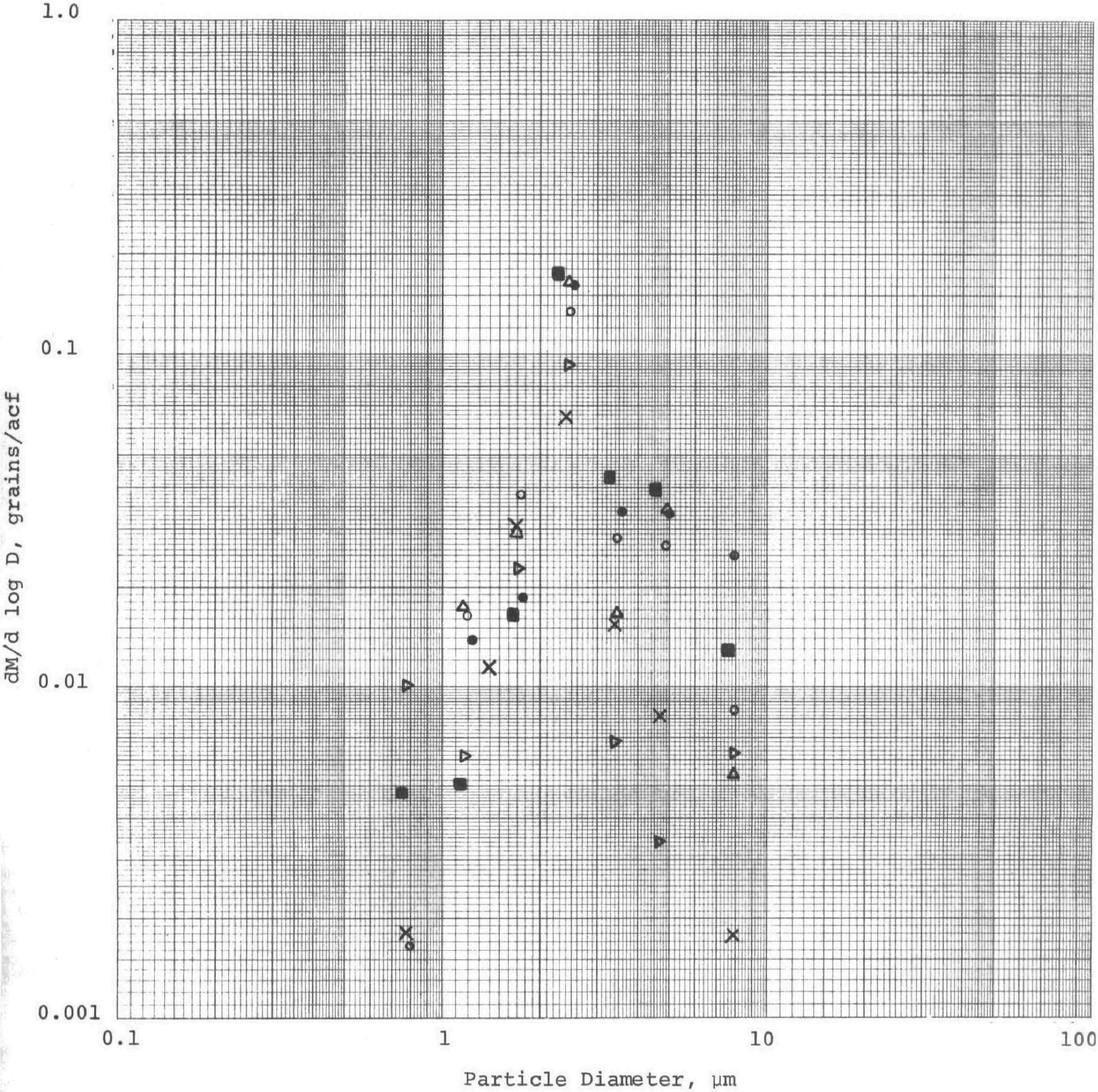

Figure 5. Differential Inlet Mass Distribution Obtained with the ERC TAG Sampler.

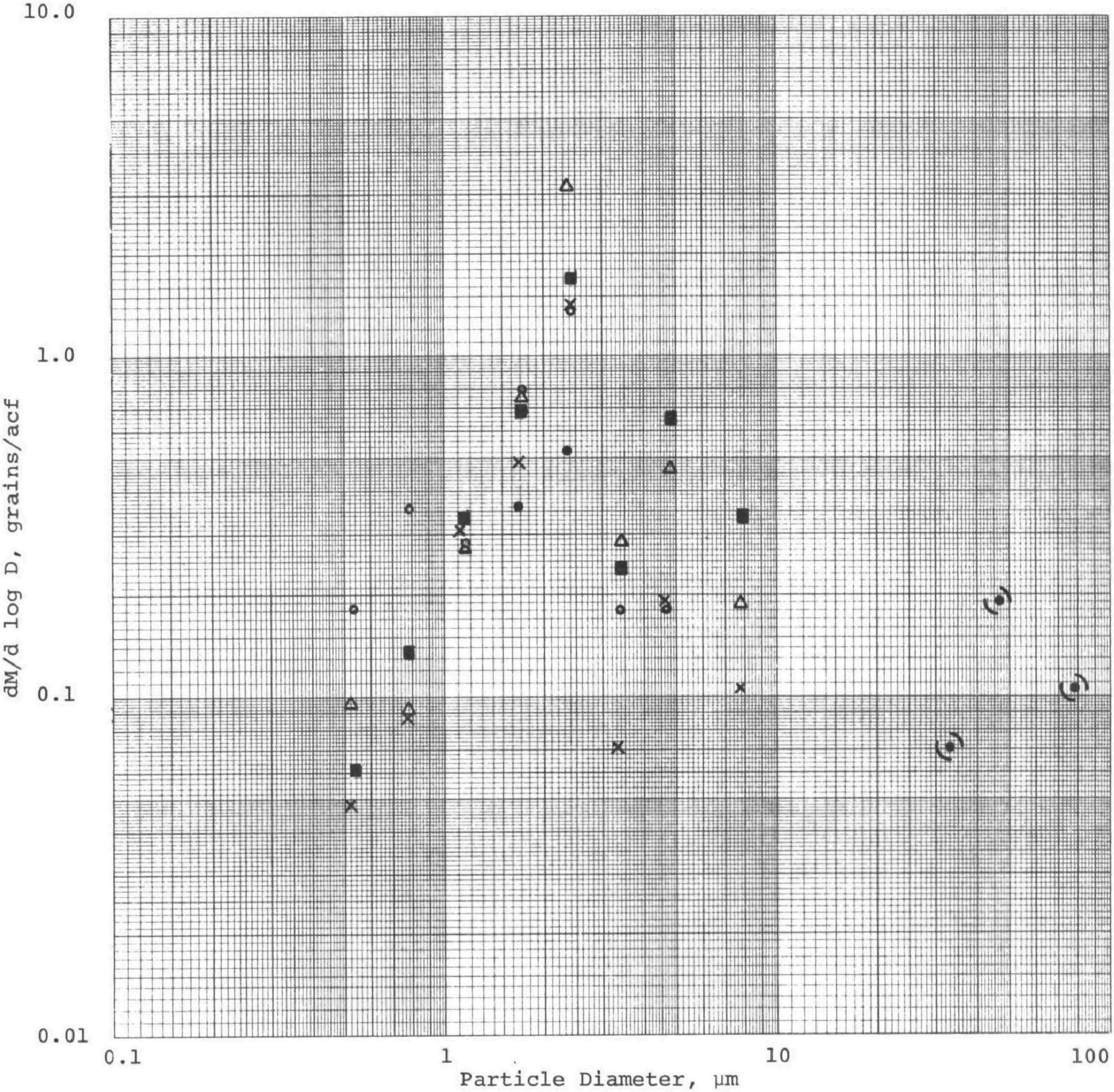

Figure 6. Differential Outlet Mass Distribution at 94% Load as Obtained with the ERC TAG Sampler.

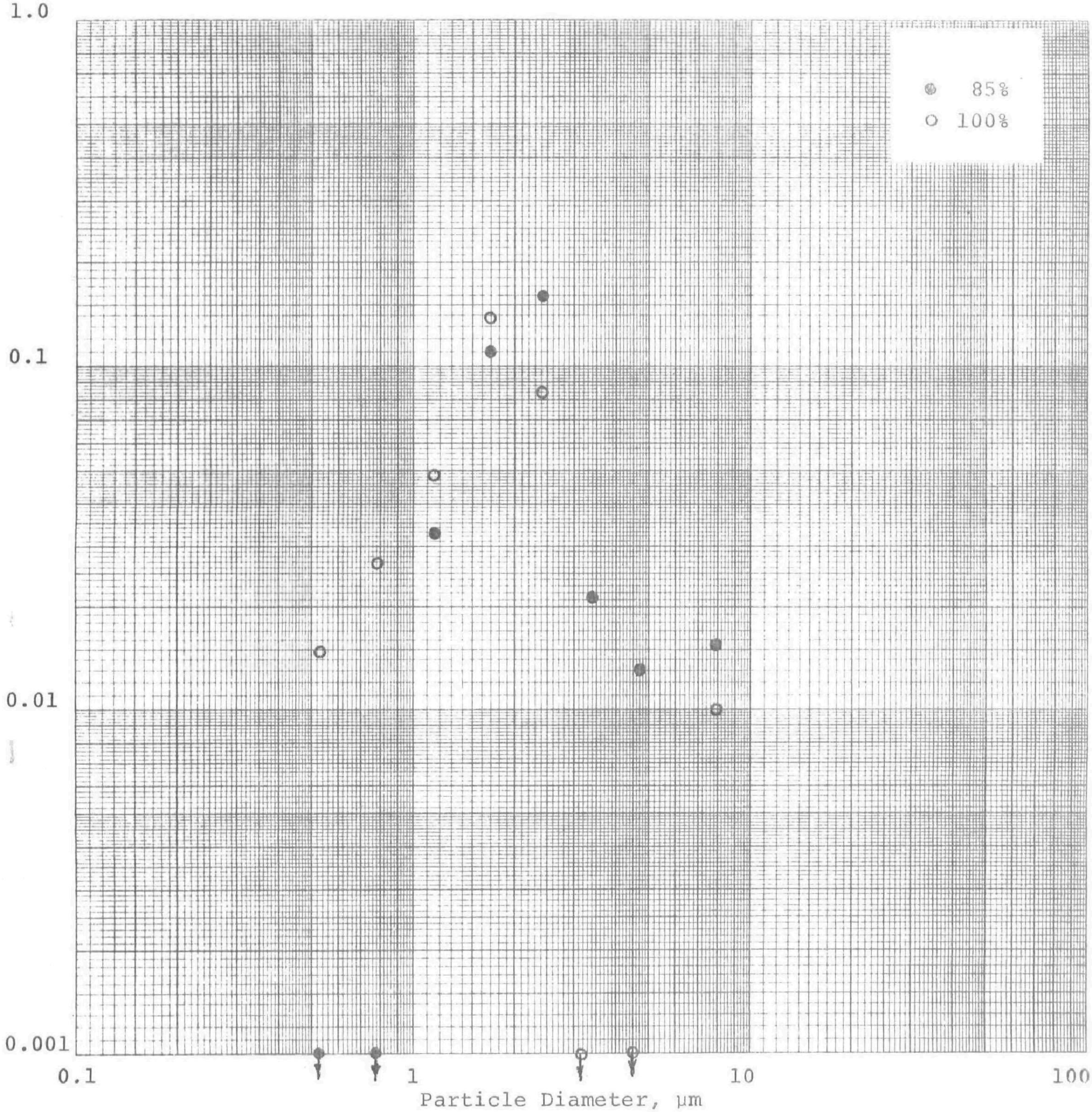

Figure 7. Differential Outlet Mass Distributions Obtained with the ERC TAG Sampler at Loads of 85% and 100%.

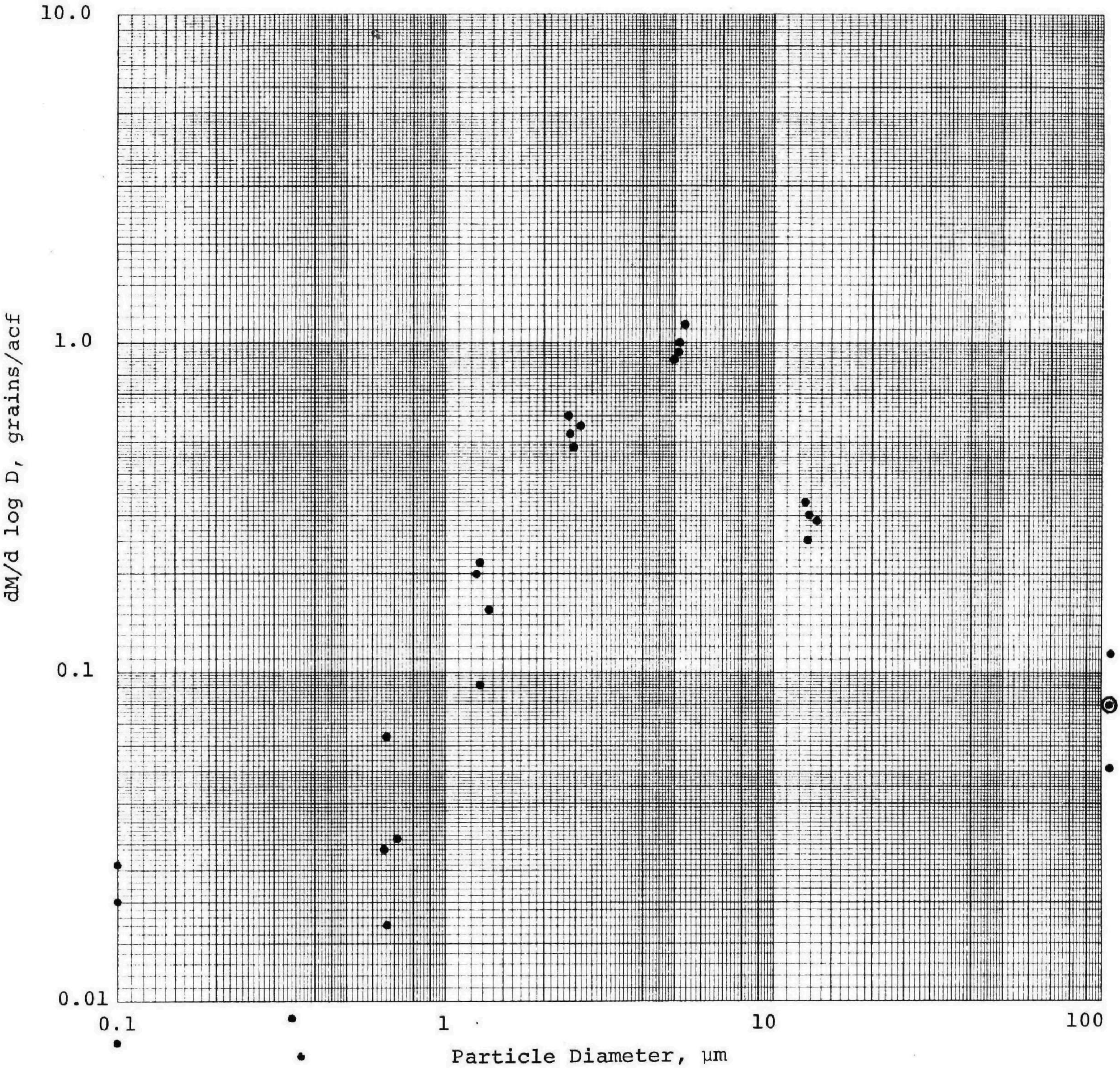

Figure 8. Differential Inlet Mass Distributions Obtained with the U. W. Mark III Impactor with Ungreased Substrates.

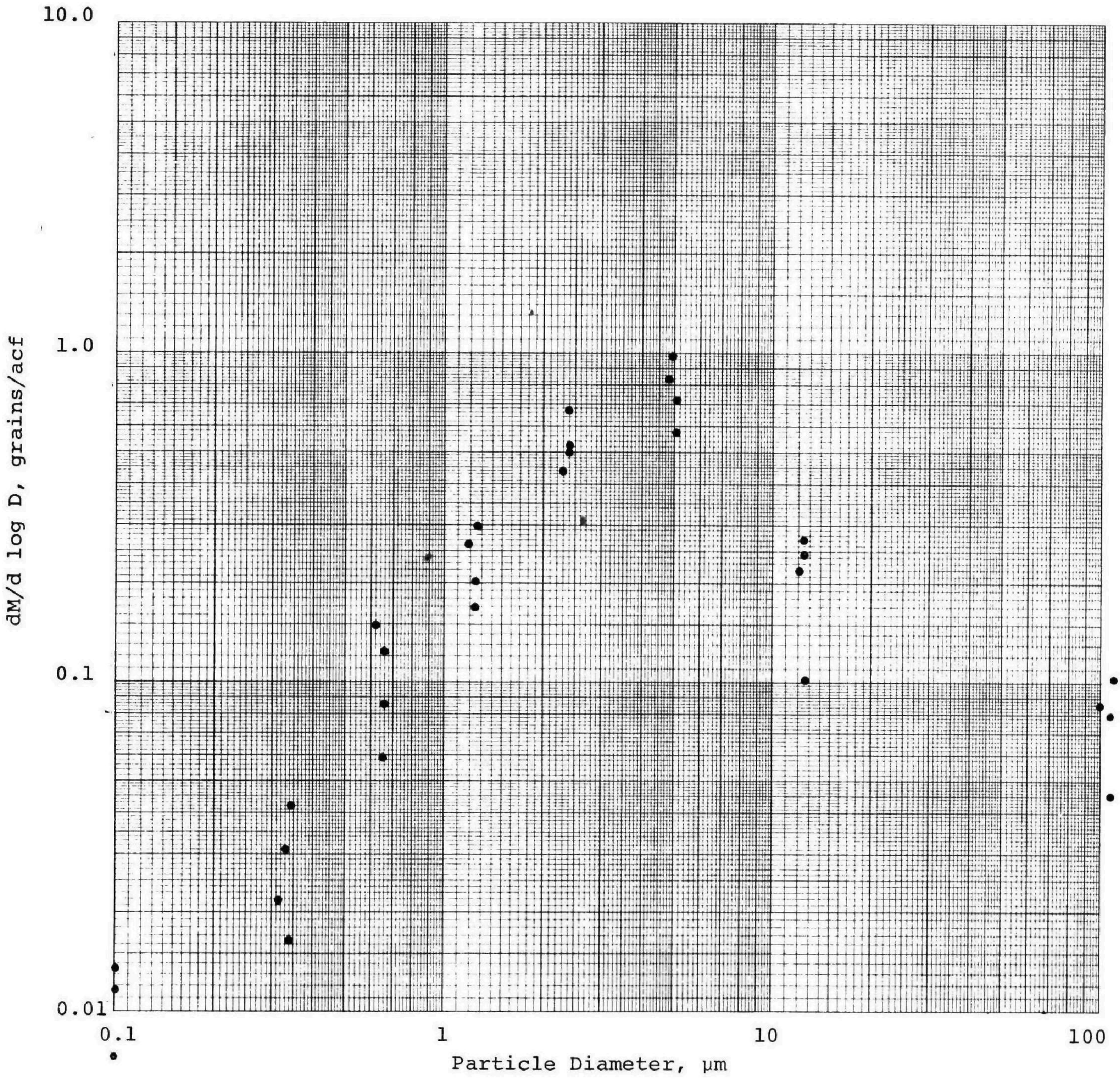

Figure 9. Differential Inlet Mass Distributions Obtained with the U. W. Mark III Impactor with Greased Substrates.

increased substantially when greased substrates were used. At the same time, there was much better agreement with the other devices when grease was used. The difference in fine particle load, the change in weight gain and appearance of the filter, and the change in appearance of the impactor deposits, all indicated that, without grease, particles were bouncing off the last few stages and ending up on the filter.

The grease used was a Dow-Corning high-vaccum silicone grease suitable for temperature up to 200°C (400°F). The pregreasing and preweighing required careful handling of the impaction substrates, especially when foil substrates were used, so that grease is not lost due to poor handling.* The donut shaped foils that were required on stages 2 through 7 are somewhat difficult to put in place when greased. The foils must be cut a little larger than the final diameter of the substrate to allow for forming a small lip. This lip holds the foil in place when the impactor is assembled. Care must be taken to contour the foil to the shape of the plate to insure proper stage to plate spacing. Although use of the foils is time consuming, the increased weighing accuracy appears to justify the additional time.

During all runs, the impactor was held in a horizontal position parallel to the gas stream, pointing downstream during the 20 to 30 minute warm up period and upstream during the test.

Figure 10 gives the results of additional tests that were conducted with the generator at 94% of full load. Within the scatter of the data, these size distribution data obtained at the precipitator outlet with the U. W. Mark III impactor agree with that obtained with the other devices, in the 0.2 μm to 2.0 μm region.

<u>Andersen Stak Sampler - Model II</u>

Four runs were performed with the Andersen Model II. (Three inlet tests and one outlet test.) The only way to accurately weigh the stage catches was to try to brush the material into a foil cup. This proved unsatisfactory because of poor transfer efficiency. Using the Ventron pan balance to weigh the catch by determing the weight gain of the plates

*The results of laboratory work after the field tests have shown that evaporation of the silicone grease at high temperatures (200°C) can produce a weight loss of 1-2% during the first hour of operation. This loss can be significant in the fine particle stages but it can be reduced by baking the greased foils for one hour at 200°C before the test.

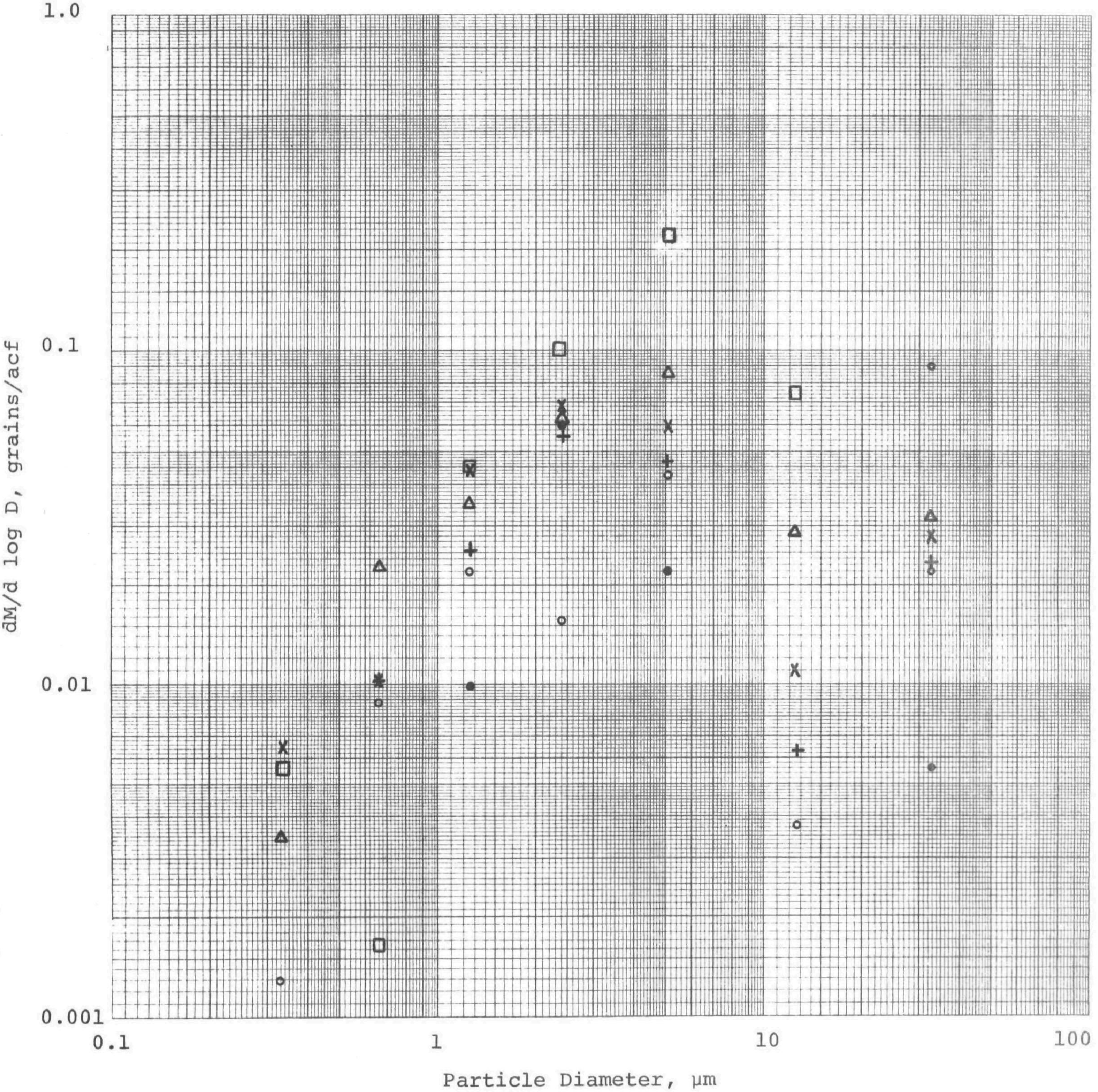

Figure 10. Outlet Differential Mass Distributions Obtained with the U. W. Mark III Impactor at 94% Load.

was unsatisfactory because of insufficient sensitivity and accuracy in weighing the small catches on the last few stages. Because of these problems and the difficulty in using grease to minimize bounce and reentrainment in the impactor very few tests were performed with this device.

A sampling method similar to the U. W. Mark III was used. The impactor was held in a horizontal position, 1.5 m (5 ft) into the duct. Care had to be taken to not jar the device after a run and to clean the nozzle properly after each run.

Figure 11 shows the three inlet tests with the Model II Andersen. Effects of reentrainment and bounce are evident in the relatively low loadings for sizes caught on the first stages, the broad peak at about 3 μm and the relatively low apparent loadings near 0.4 μm. Figure 12 shows the size distribution at the precipitator outlet at 84% load as obtained with the Model II Andersen. The Andersen Models III and IV, which are described next, are similar to the model II but have been designed to use glass fiber filter collection surfaces.

<u>Andersen Model IV</u>

Figure 13 shows the inlet differential mass distribution data obtained with the Andersen Model IV. The Model IV is an instack version of the Andersen non-viable sampler using glass fiber disks as impaction substrates.

As can be seen by comparing the data shown in Figure 13 with that in Figure 11, the inlet data obtained with the Andersen Model IV does not agree well at all with data from the other devices. It was obvious that severe reentrainment occurred in the upper stages. Visual inspection of the appearance of the deposits on the upper stage impaction substrates indicated that the reentrainment resulted from blow off due to high gas velocities parallel to the surface of the substrates. This reentrainment resulted in a pronounced apparent shift in the measured size distribution toward the lower sizes. Data from samples obtained at the precipitator outlet showed the same effects.

It appears that this particular design, even with the glass fiber inserts, is not suited for sampling aerosols such as fly ash because of this severe reentrainment problem.

<u>Andersen Stak Sampler - Model III</u>

The Andersen Model III is a modified Model II with provision for the use of bulls-eye shaped, glass fiber filter impaction substrates. This particular design was the most useful of the

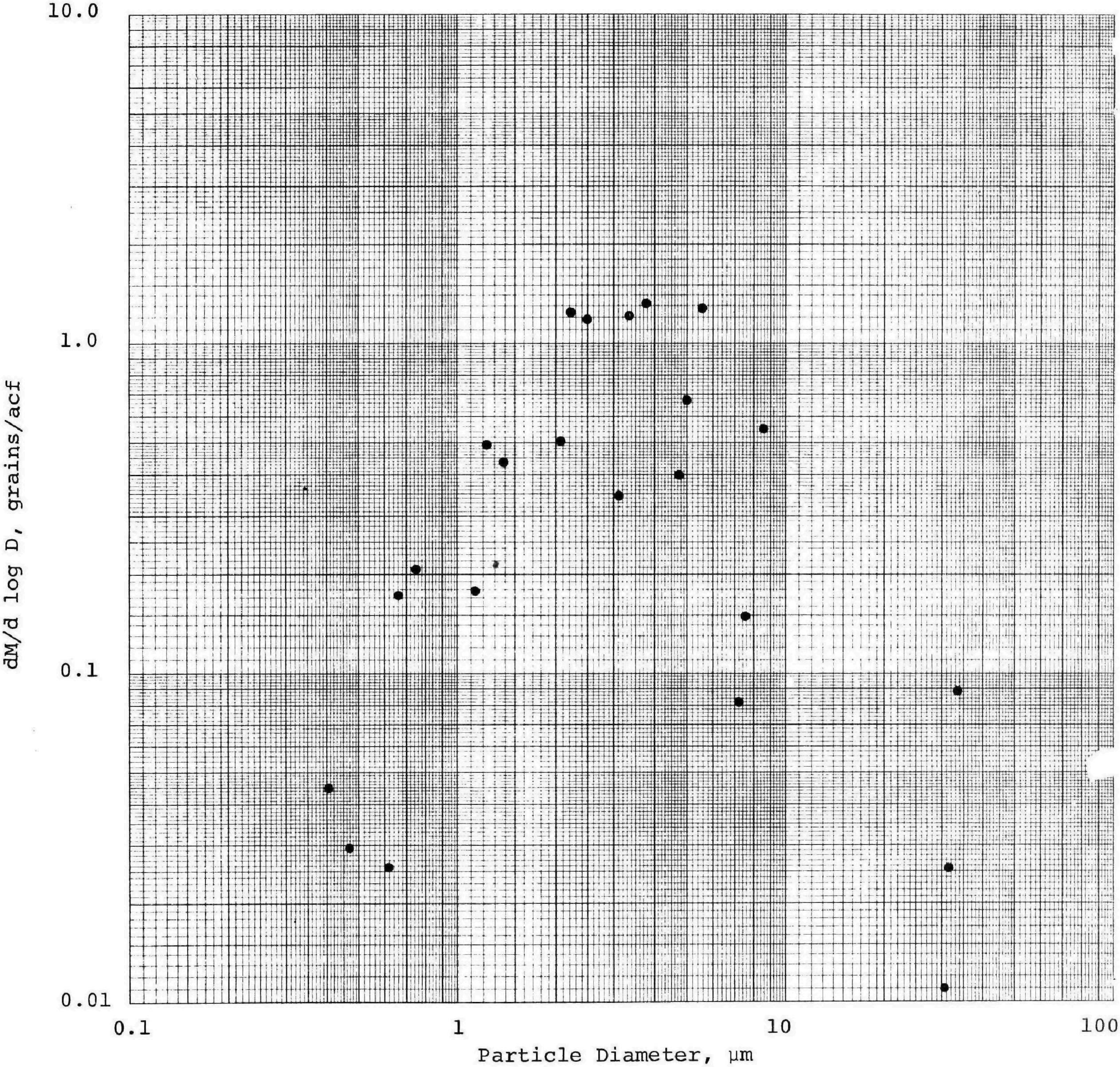

Figure 11. Differential Inlet Mass Distributions Obtained with the Andersen Model II Impactor at 100% Load.

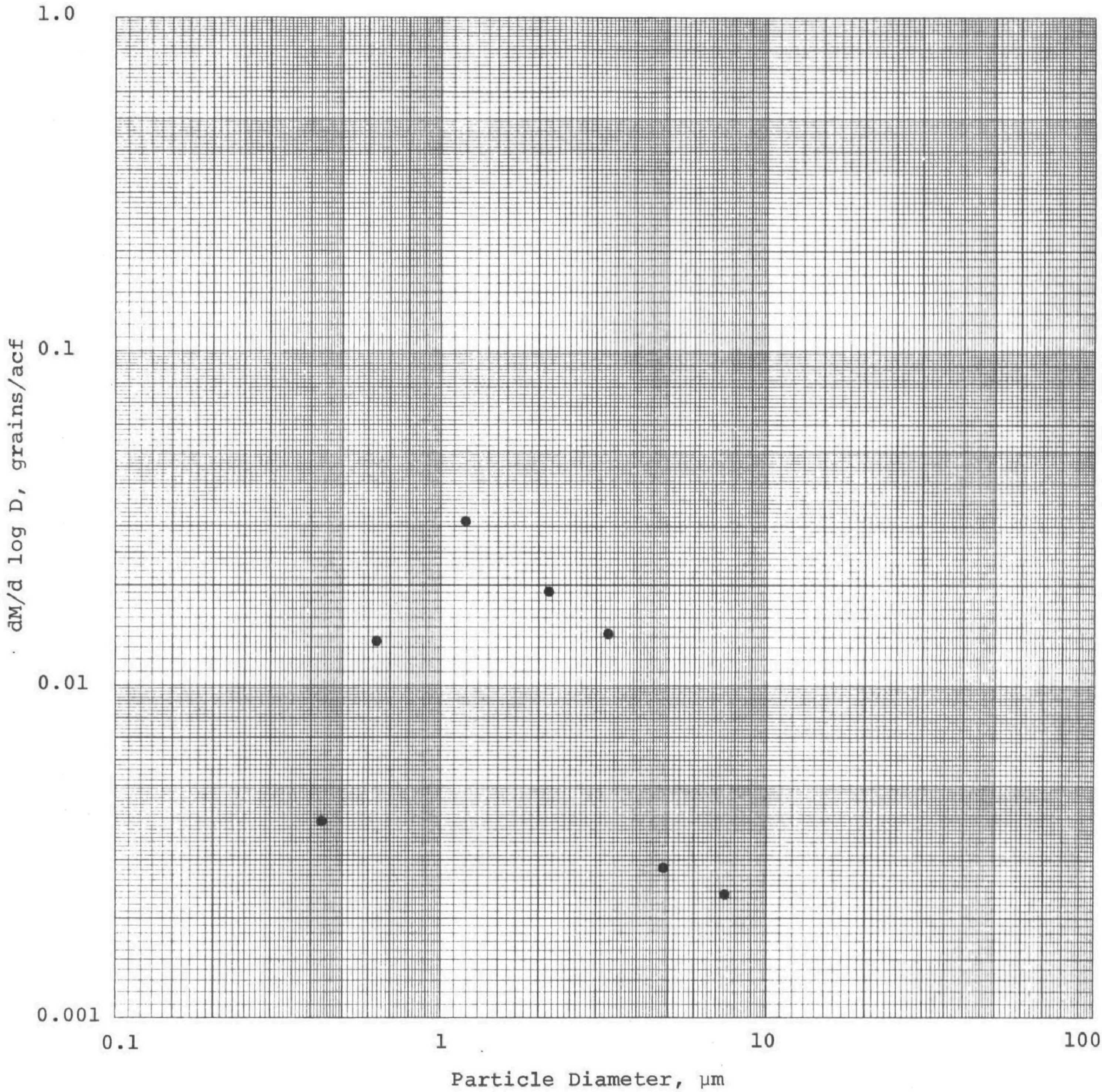

Figure 12. Outlet Differential Mass Distribution Obtained with the Andersen Model II Impactor at 80% Load.

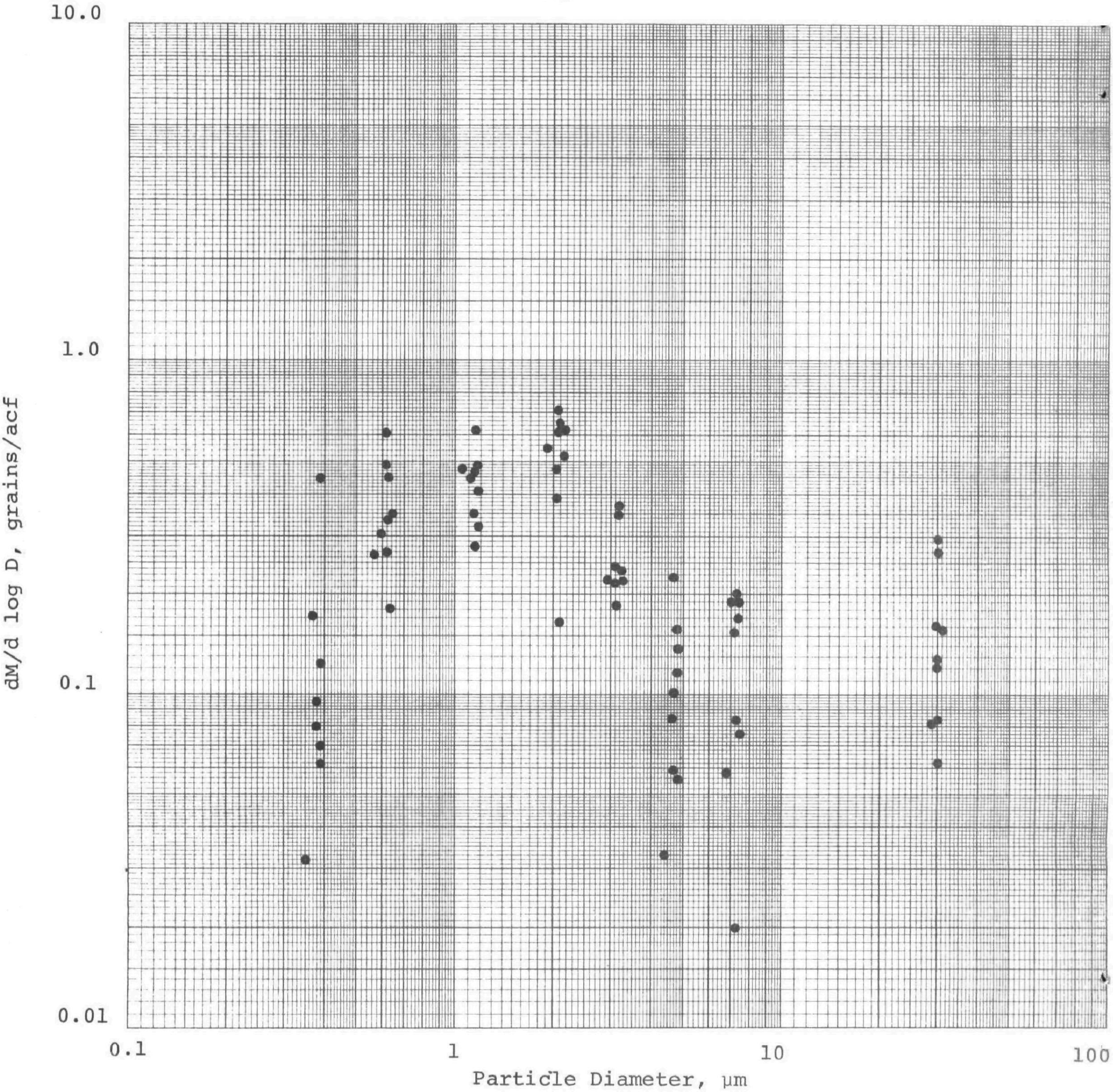

Figure 13. Differential Inlet Mass Distributions as Obtained with the Andersen Model IV Impactor.

three Andersen models tested. The reentrainment problems associated with Models II and IV were not evident with this modification.

Care must be taken in handling the filter substrates. Over tightening of the impactor case during assembly can cause the steel o-rings to cut into the filters. It was found that one of the two possible orientations of the sealing ring was less likely to cut the glass fiber substrates.

As can be seen in Figure 14, the Andersen Model III inlet data agrees very well with that obtained with the other classifiers.

Five inlet tests were also run with the Andersen 2000 Inc. prototype scalping cyclone. Data from these runs are shown in Figure 15. There is no noticeable difference below 6.0 μm in the differential size distributions measured with and without the cyclone. Above this point, the data tends to fall a little lower indicating that some of the material that would have ended up on stage 1 had been caught in the cyclone. In the 0.2 μm to 2.0 μm region, the cyclone has no apparent effect.

The outlet tests using this impactor gave generally good agreement with the other classifiers, although on several occasions not enough data was collected to give a clear comparison. Representative data from outlet runs are shown in Figure 16.

Brink Impactor

This impactor was run in a number of configurations. Four cyclones were used singly or in combination to remove the larger particles when the Brink was used at the inlet to the precipitator. Approximate D_{50}'s for the four cyclones under these test conditions were 11 μm (SRI Model I, C1), 4.32 μm (SRI Model II, C2), 6.44 μm (SRI Model III, in line, C3), and 7 μm (cyclone supplied with the Brink BMS 11 kit). Also an auxiliary stage, "0", was designed and fabricated to obtain a fractionation point at a size about 1.5 times the D_{50} of the standard Brink first stage. The zero stage was generally used in conjunction with the inline cyclone, C3. In addition to three versions of the Brink impactor modified for instack sampling, the Brink BMS-11 sampling kit was mounted external to the duct so that it sampled through conventional probes. Cyclones were not used for outlet runs because of the absence of large particles at the outlet. In addition to tests of the several configurations of the Brink impactor, a limited number of tests were run at both the inlet and outlet using greased impaction substrates.

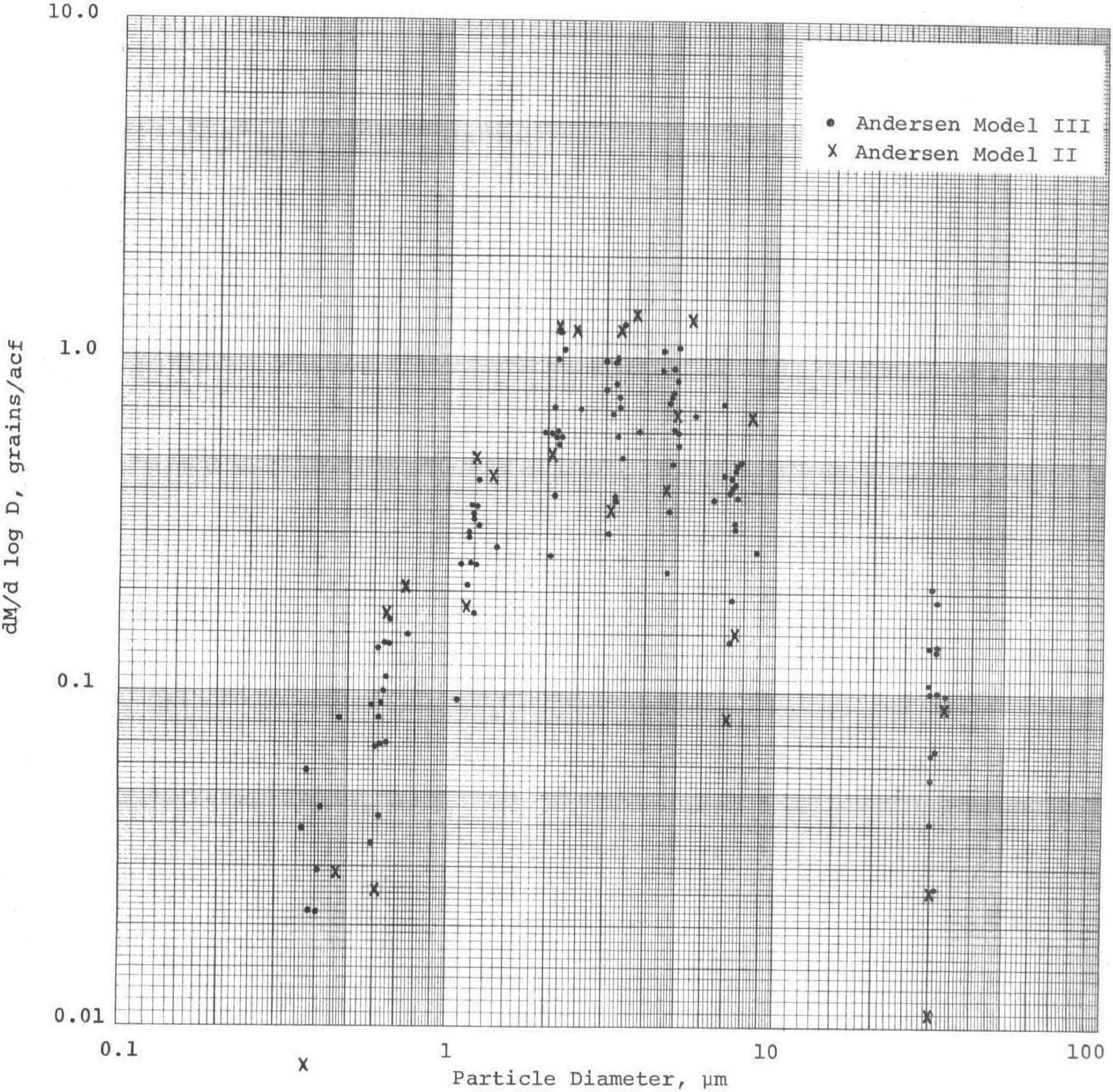

Figure 14. Differential Inlet Mass Distributions Obtained with the Andersen Models II and III Impactors.

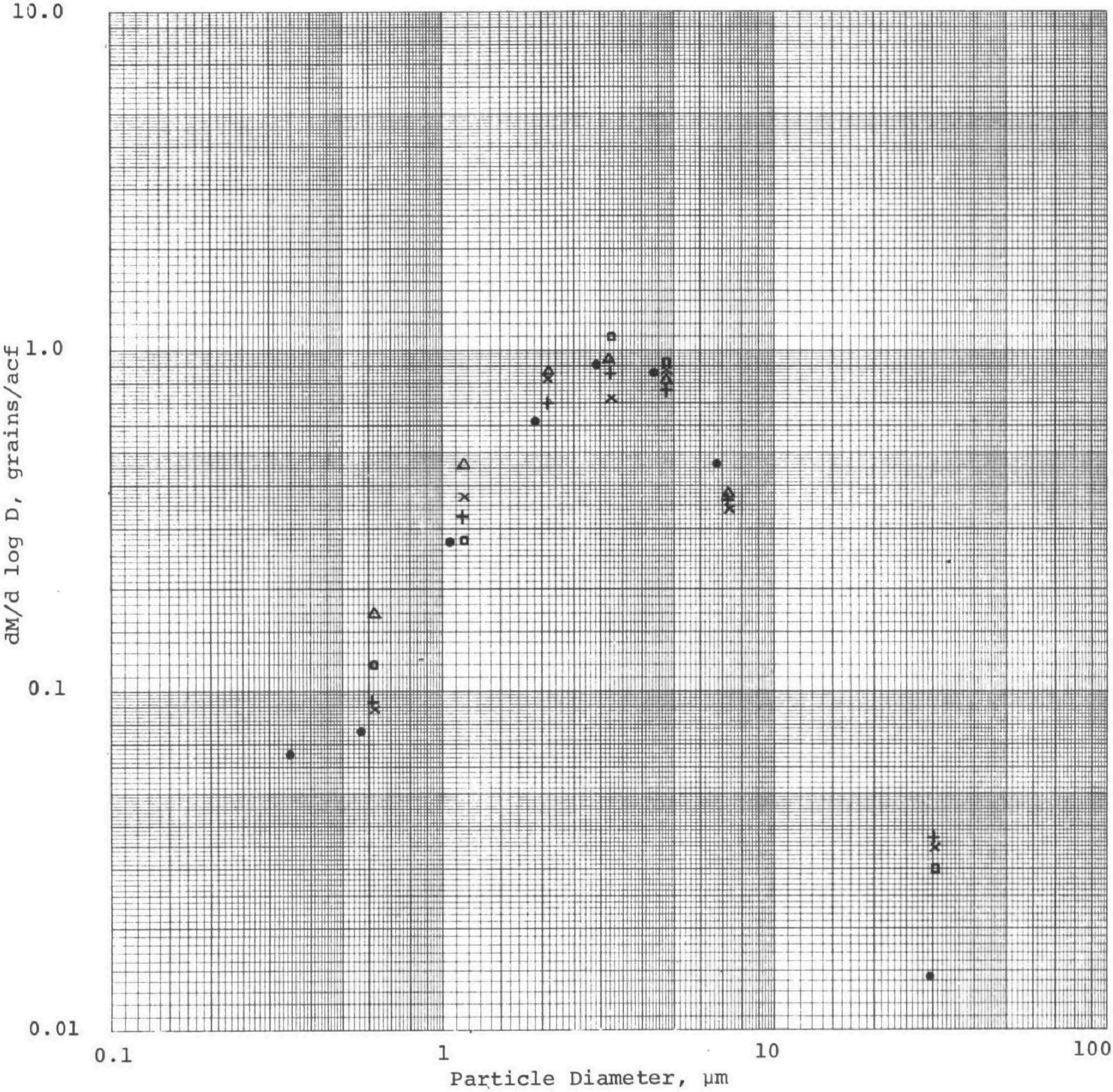

Figure 15. Differential Inlet Mass Distributions Obtained with the Andersen Model III Impactor Preceded by a Prototype Scalping Cyclone.

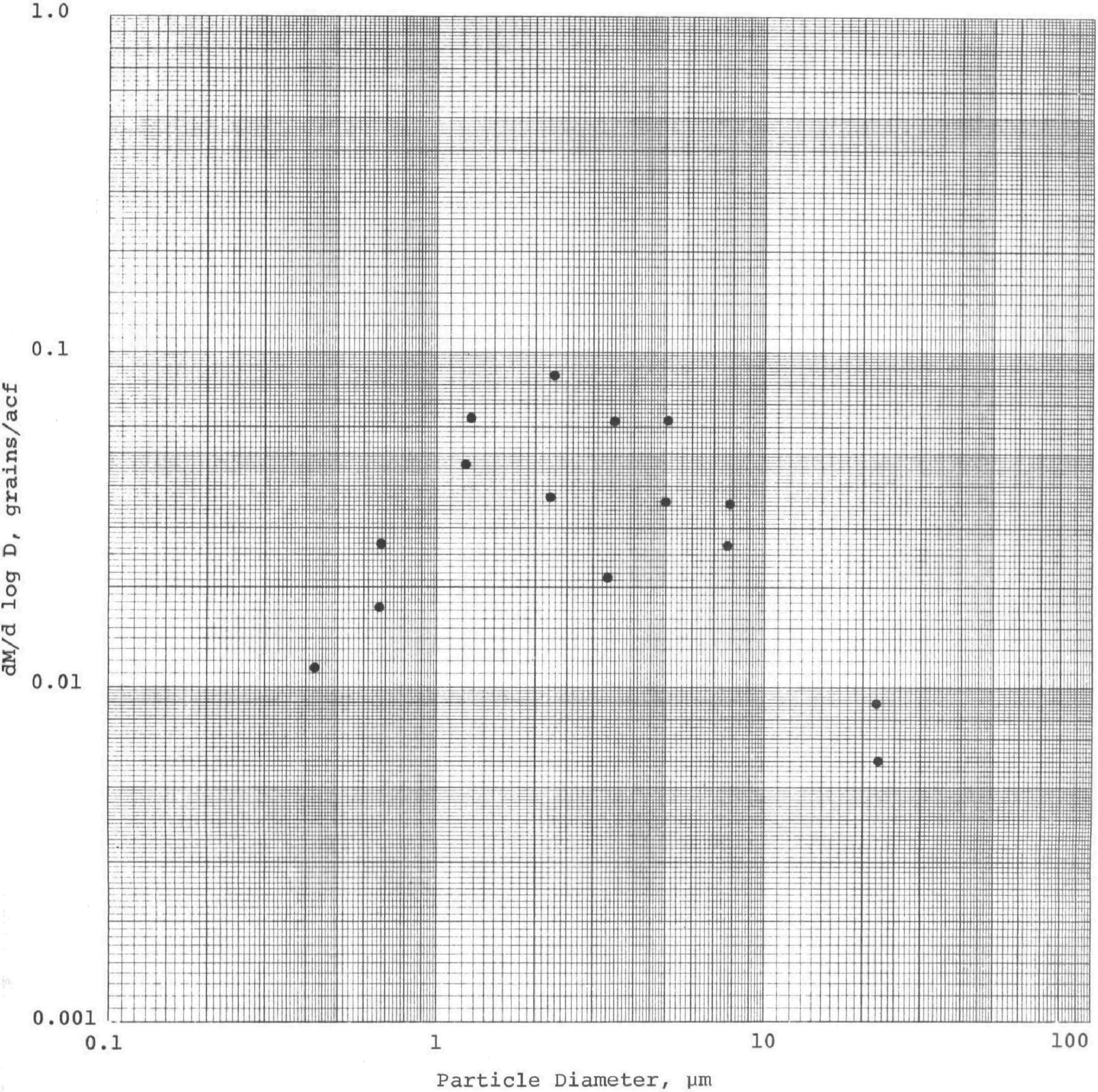

Figure 16. Differential Outlet Distribution at 60% Load Obtained with the Andersen Model III Impactor.

All Brink impactor measurements were made with the impactor in the stack except for the tests using the Brink BMS-11 kit. All tests were run with the impactors in a vertical position with nozzles chosen for isokinetic sampling. Back up filters were used on all runs.

The three cyclones were run in the following configurations at the inlet. (The cyclone designations were explained previously; the numbers 1, 2, 3,... refer to Brink stages; and "F" stands for the glass fiber back up filter)

C1, C2, 1, 2, 3, 4, 5, F

C2, 1, 2, 3, 4, 5, F

C3, 1, 2, 3, 4, 5, F

C3, 0, 1, 2, 3, 4, 5, F

Brink Kit Cyclone, 1, 2, 3, 4, 5, F

Figures 16 through 19 show results for inlet tests with these configurations. As can be seen there were no significant differences in size distribution results for any of these set ups, with the exception of those obtained with the BMS-11 kit. The data obtained with the kit indicated significantly lower loadings for sizes larger than 2 μm as can be seen in Figure 17. In fact, the cyclone collected negligible amounts of material. Presumably most of the material it would have collected was lost in the probe.

One series of tests were conducted to see if the use of foil substrates and grease would cause any significant changes in the Brink data. Figure 20 shows the results of these tests. As expected, the greased foils tend to retain the material better on the small particle stages. The use of grease does not seem to significantly affect retention of particles on the upper stages. Subsequent to the tests, microscopic examination of the particles caught on several sets of ungreased substrates revealed the presence of large quantities of over-sized particles on the substrates of stages 4 and 5, and on the back up filters. It was also noted that particles were not collected immediately under the jet on runs with ungreased substrates for stages having jet velocities greater than 35 to 40 m/sec. No such evidence of bounce and reentrainment were observed when greased substrates were used even with jet velocities as high as 75 m/sec.

The Brink impactors were also used for measurements at the precipitator outlet for a variety of load conditions; these results are shown in Figures 21 through 23. A comparison of

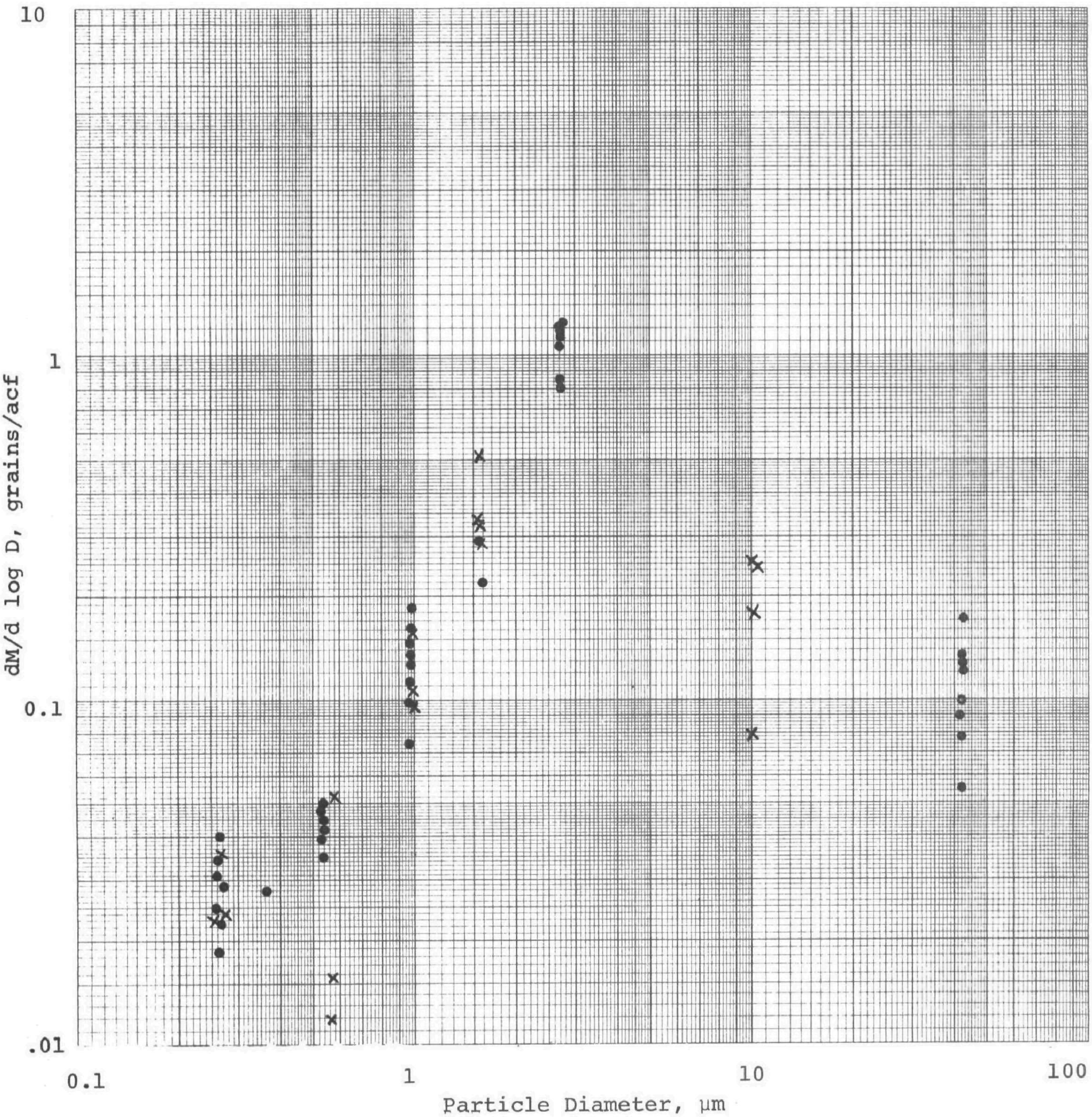

Figure 17. Differential Inlet Mass Distribution Obtained with Brink Impactor Modified for In-Stack Sampling Preceded by Cyclone C2, and Corresponding Data Obtained Using the Brink BMS 11 KIT.

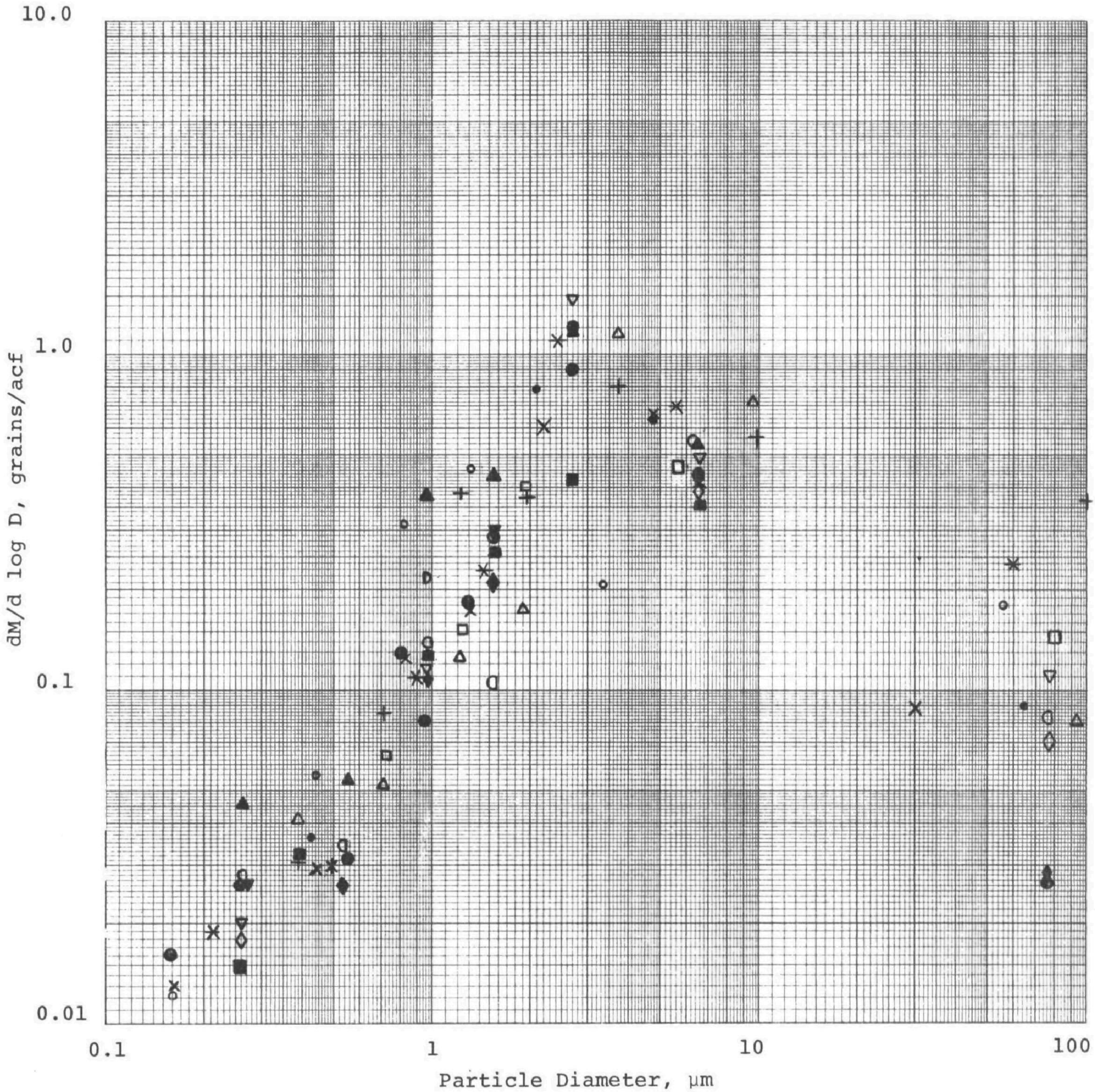

Figure 18. Differential Inlet Mass Distributions Obtained Using Brink Impactors Modified for Instack Sampling Preceded by Cyclones C1 and C2.

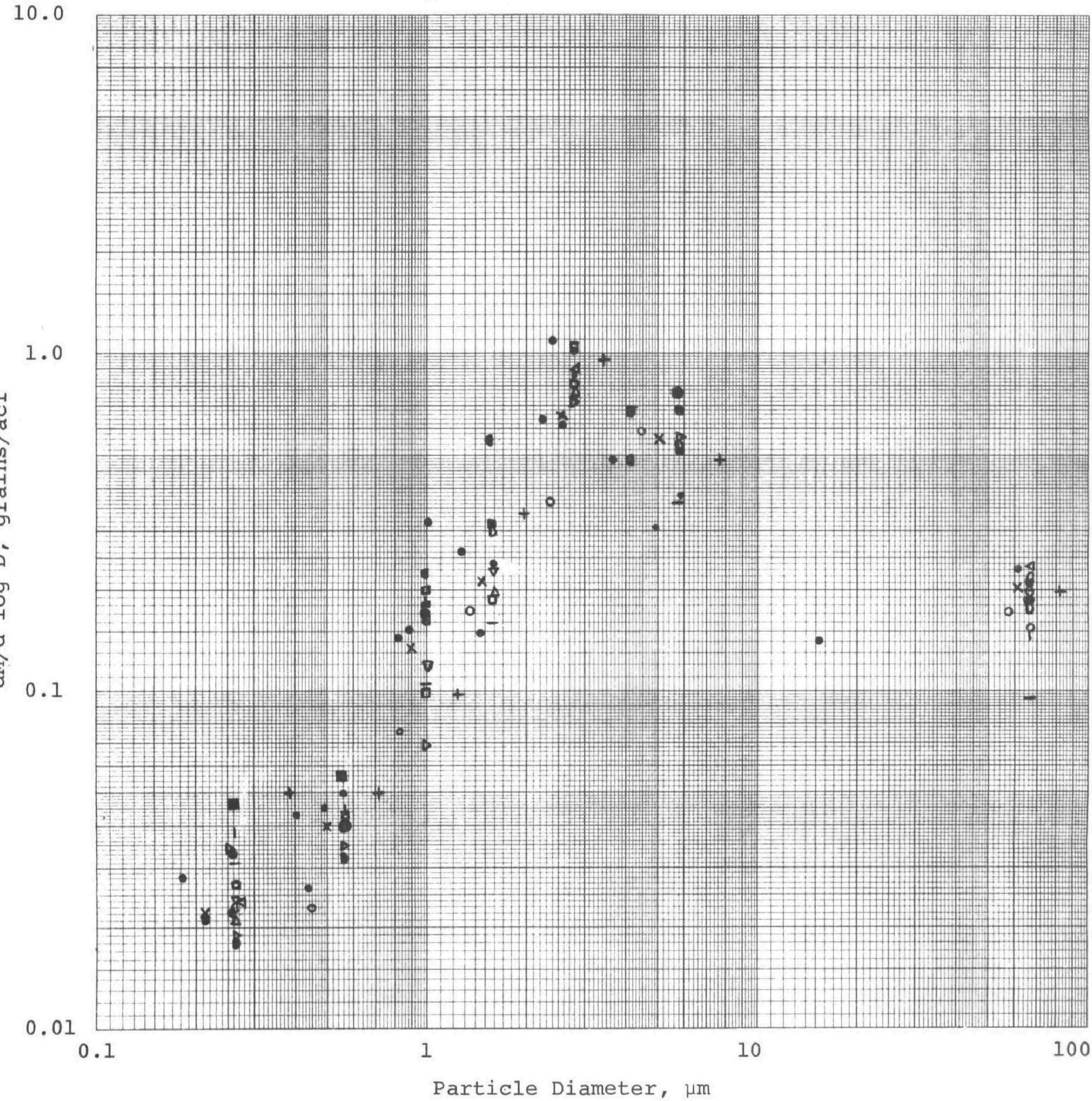

Figure 19. Differential Inlet Mass Distributions Obtained with Brink Impactors Modified for Instack Sampling Preceded by an Additional Stage, SO, and Cyclone C3.

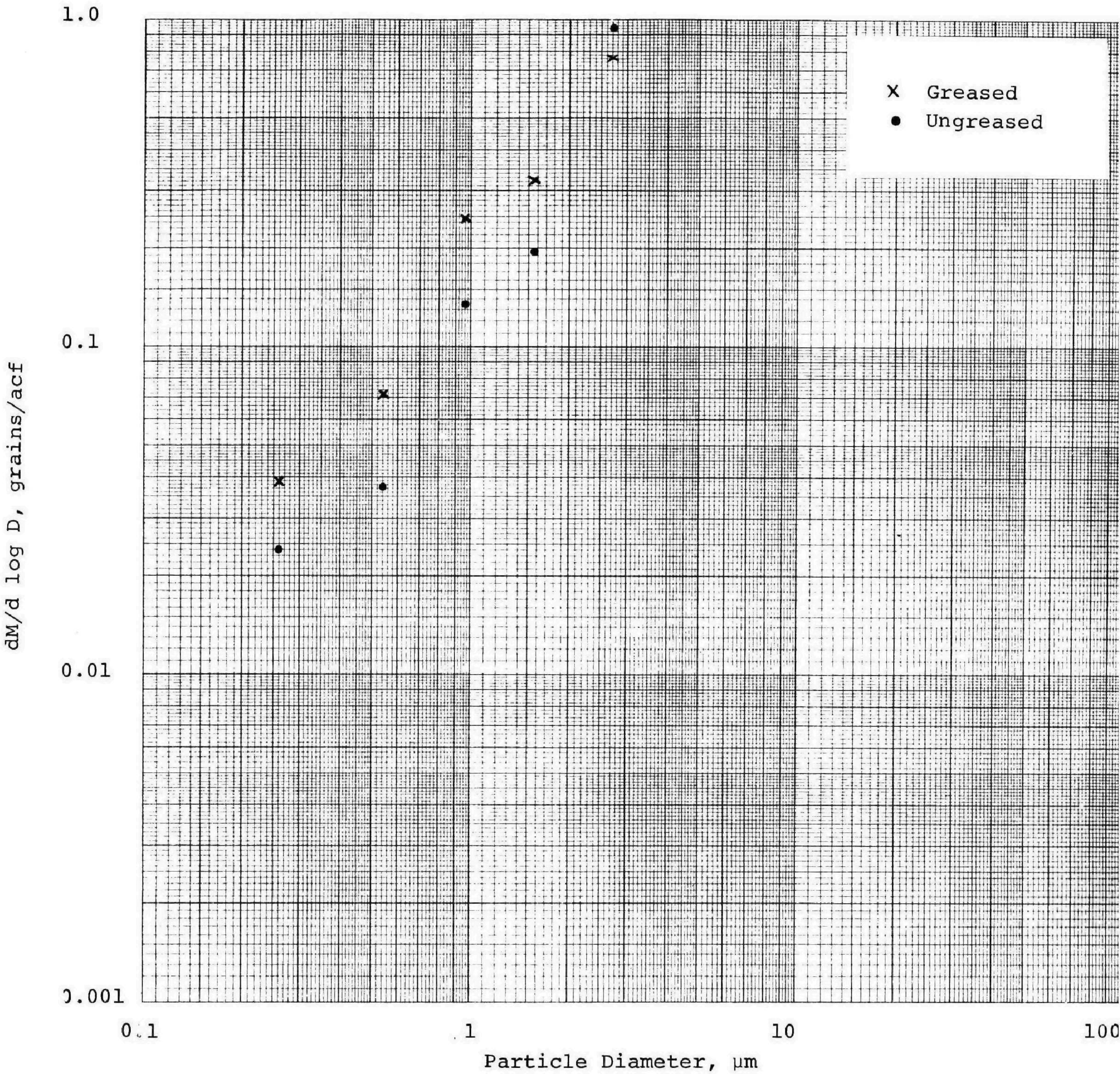

Figure 20. Comparison of Averaged Differential Inlet Mass Distributions Obtained with Brink Impactors Using Greased and Ungreased Impaction Substrates.

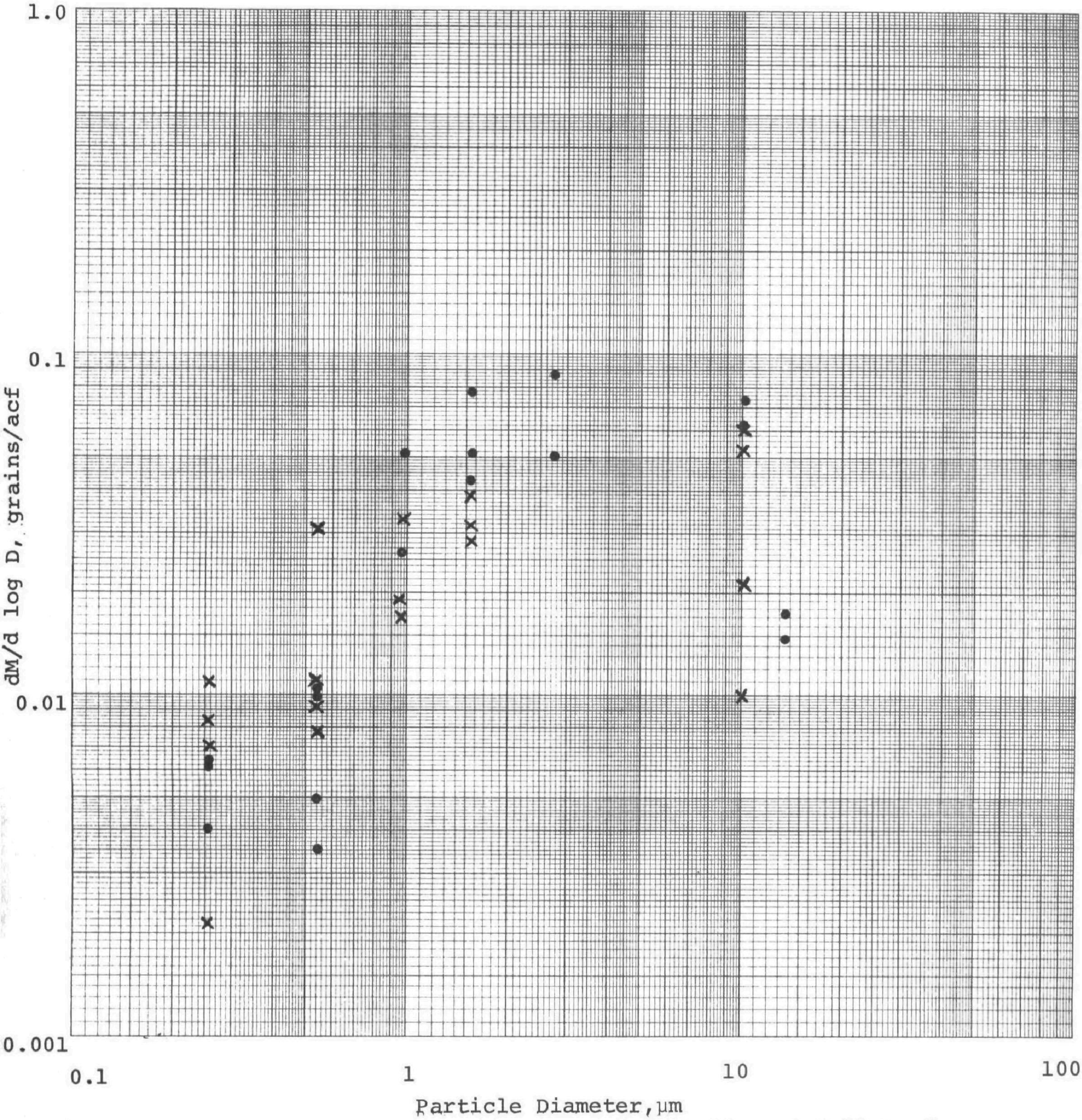

Figure 21. Differential Outlet Mass Distribution at Full Load Obtained Using Brink Impactors Modified for In-Stack Sampling Using Greased and Ungreased Substrates.

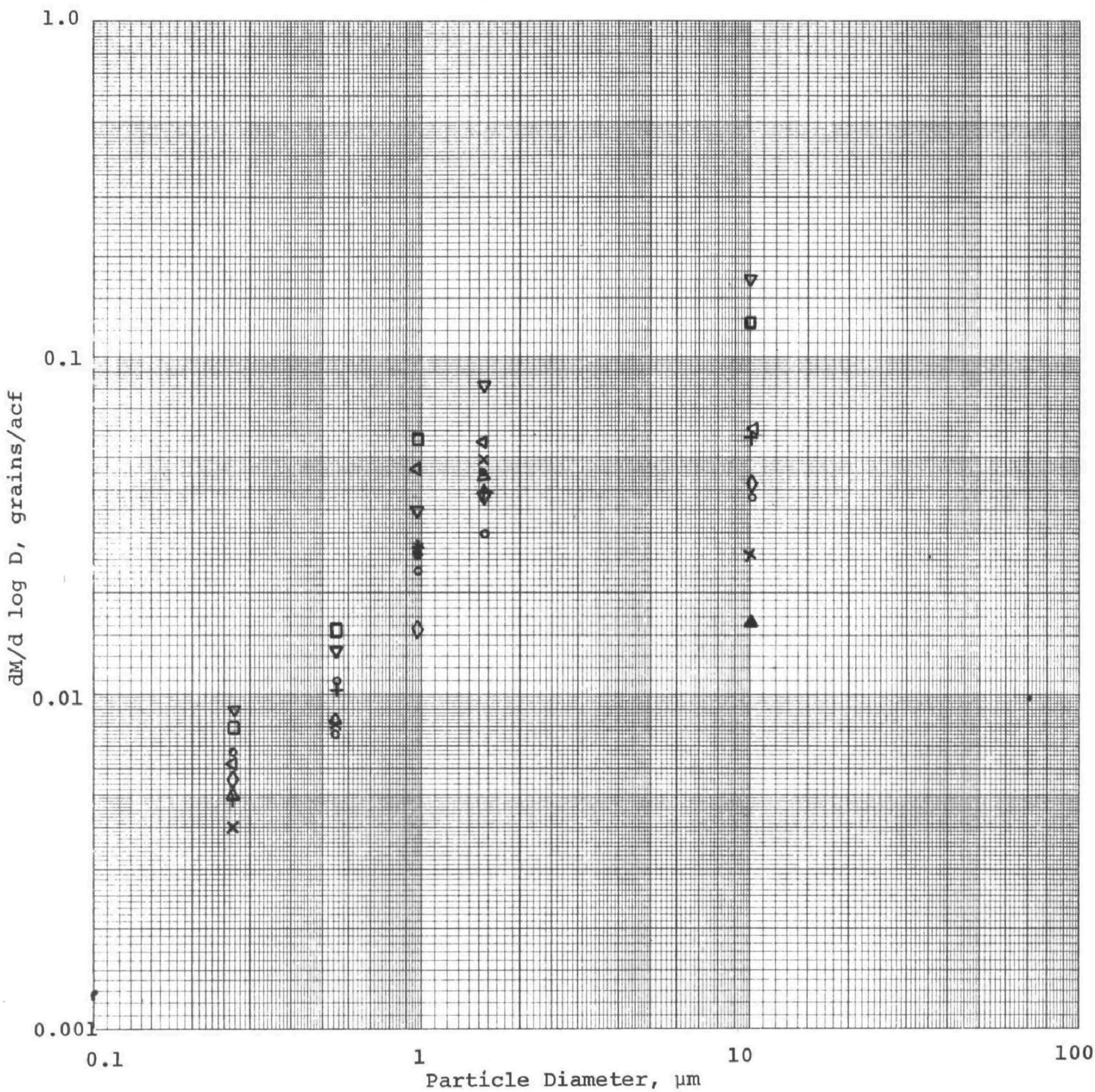

Figure 22. Differential Outlet Mass Distributions at 94% Load Obtained Using Brink BMS 11 Kits and Brink Impactors Modified for In-Stack Sampling.

FIGURE 23

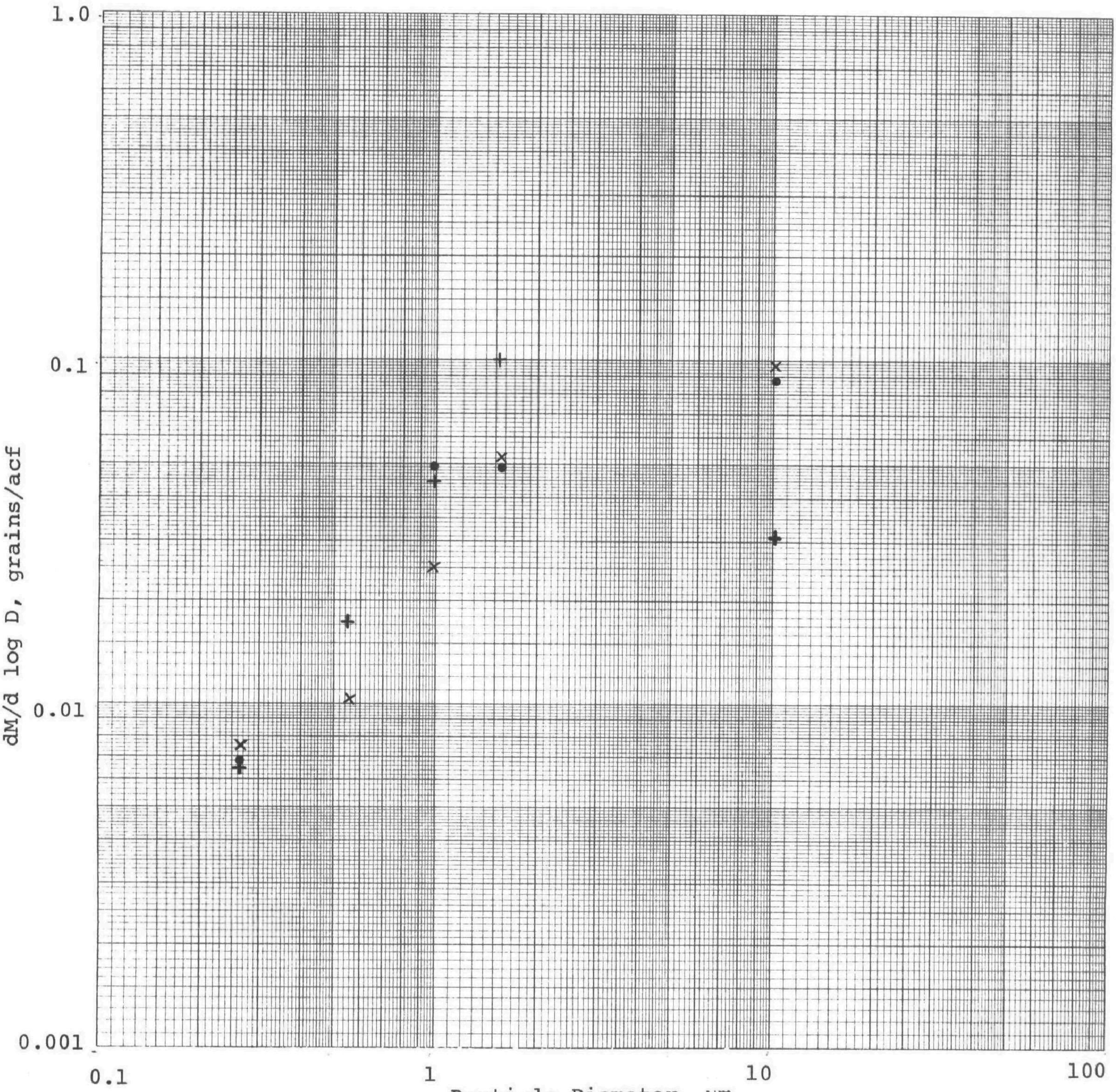

Figure 23. Differential Outlet Mass Distribution at 55% Load Obtained Using Brink Impactors Modified for Instack Sampling.

these results for greased and ungreased foils, under identical load conditions, emphasized the importance of using grease at the outlet as well as the inlet.

Summary of all Impactor Tests

A total of 192 individually evaluated tests were performed at the inlet and outlet of the precipitator in both high and low efficiency modes. The precipitator efficiency was varied by load changes or by addition of fly-ash conditioning agents. This allowed for both course and fine aerosols to be sampled. A list of the number of individual tests using each device and each different combination of stages and cyclones is given below. This list includes only the tests that appeared to be valid; that is, some tests have been deleted because of errors that may have resulted from operational problems, severe reentrainment, etc. Where appropriate, these test results were used to compute the fractional efficiency of the electrostatic precipitator as described in the next section.

Particle Sizing Device	Number of Tests
Andersen Model II	4
Andersen Model III	25
Andersen Model III with Andersen Cyclone	5
Andersen Model IV	18
Battelle - Greased Foils	4
Battelle - Ungreased Foils	1
Brink - C3,0,1,2,3,4,5,F - Ungreased	15
Brink - C2,1,2,3,4,5,F - Ungreased	8
Brink - C2,1,2,3,4,5,F - Greased	2
Brink - C3,1,2,3,4,5,F - Ungreased	5
Brink - C3,1,2,3,4,5,F - Greased	2
Brink - BMS-11-C,1,2,3,4,5,F - Ungreased	8
Brink - C1,C2,1,2,3,4,5,F - Ungreased	13
Brink - C1,C2,1,2,3,4,5,F - Greased	1
Brink - 0,1,2,3,4,5,F - Ungreased	12
Brink - 1,2,3,4,5,F - Ungreased	23
Brink - 1,2,3,4,5,F - Greased	5
McCrone	6
U. W. Mark III - Grease on 1 only	4
U. W. Mark III - Grease and foils on all	13
TAG - Grease on 1 and 2 only	4
TAG - Grease on 1 and 2, grease and foils on 7,8,9,10	9

Total number of valid tests = 187

Fractional Efficiency of the Electrostatic Precipitator

Examples of the efficiency of the precipitator as a function of particle size are shown in Figures 24 and 25 for two operating conditions, 94 to 100% of full load and 55 % of full load. Each set of points shown on these figures represents an average value calculated from inlet and outlet mass-size distributions that were measured with the same type of impactor; that is, one efficiency is as measured with the Andersen, another with the Brink, etc. The data used for Figures 24 and 25 were collected at various times over a period of three weeks and for some of the tests inlet and outlet size distributions were not obtained simultaneously. Based on these facts and the apparent differences in the size calibrations of the various impactors, the fractional efficiencies shown here should be regarded as approximate. There is less scatter of the data for the fractional efficiencies shown in Figure 25 than in Figure 24. The information shown in Figure 25 was all based on measurements made with the Brink and Andersen impactors. More measurements were made with these impactors because more of the impactors were available for these tests. Because of the additional measurements, the efficiencies shown in Figure 25 are probably a better representation of average performance than those shown in Figure 24.

V. CONCLUSIONS AND COMMENTS

Several general conclusions can be drawn from the results of our field evaluation of inertial sizing devices:

A. Of the inertial classifiers tested, no single device was found to be useful over the entire range of particle size and concentration needed for evaluation of a wide variety of particulate control devices. In general, the inertial classifiers designed to operate at low sample flow rates are useful at the inlet of a control device where the particulate loading is high; the low-flow-rates permit reasonably long sampling times to be used. If these same low-flow-rate classifiers are used at the outlet of a control device, the sampling time may be impractically long, so that a high-flow-rate device is usually a better choice at the outlet.

B. One possible solution to the problem of measuring fine particles in the presence of high concentrations of large particles is to use one or more small cyclones in front of the impactor. Modified Brink impactors and the Andersen Model III were successfully used in this manner during our field tests.

C. Most of the impactors have collection stages that are too heavy for obtaining accurate measurements of the weight of particles collected in a size fraction. It is helpful to cover

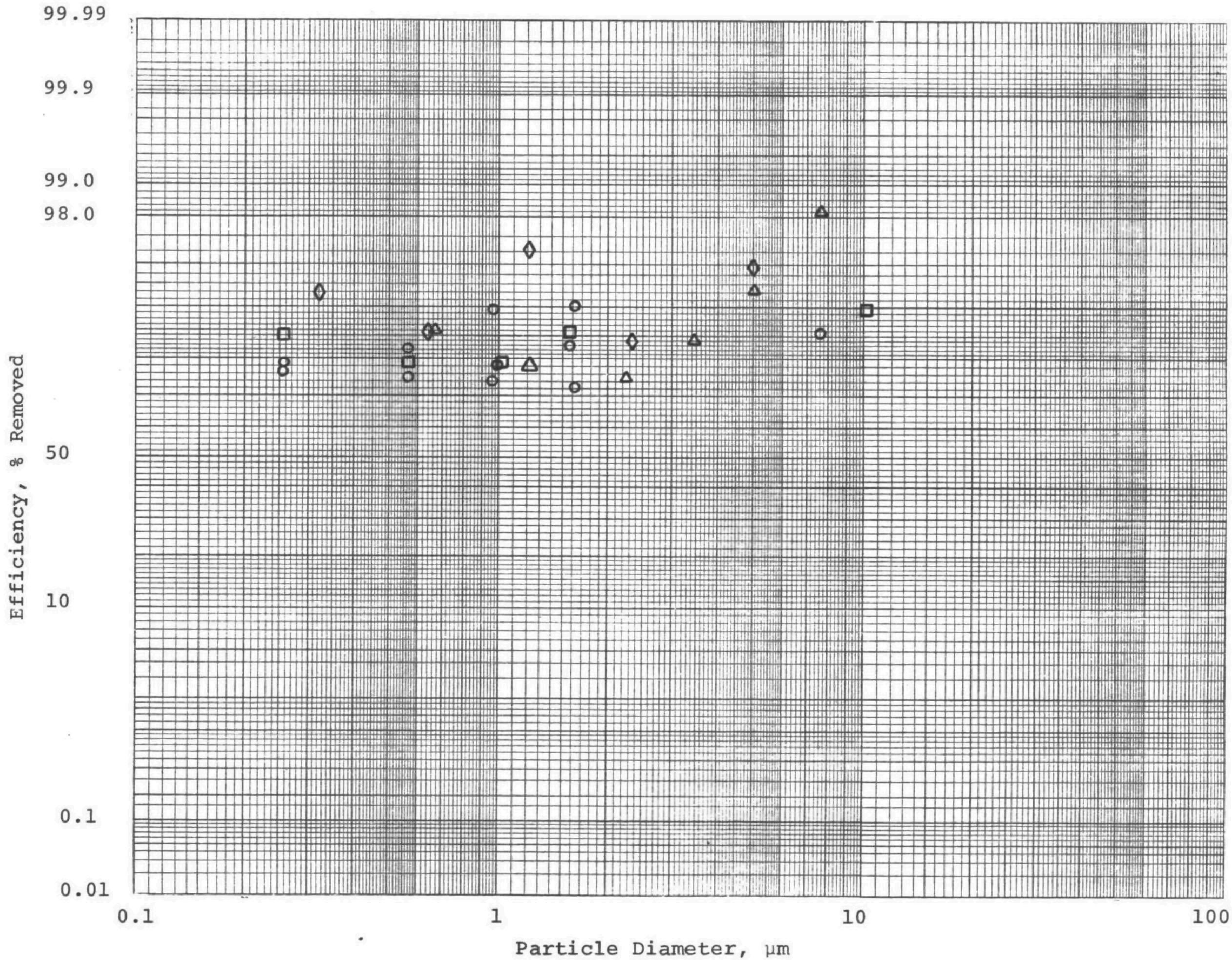

Figure 24. Precipitator Efficiency at 94% and 100% Load as Measured with Modified Brink (o), Brink BMS 11 Kit (□), Andersen Model III (Δ), and U. W. Mark III (◊) Impactors.

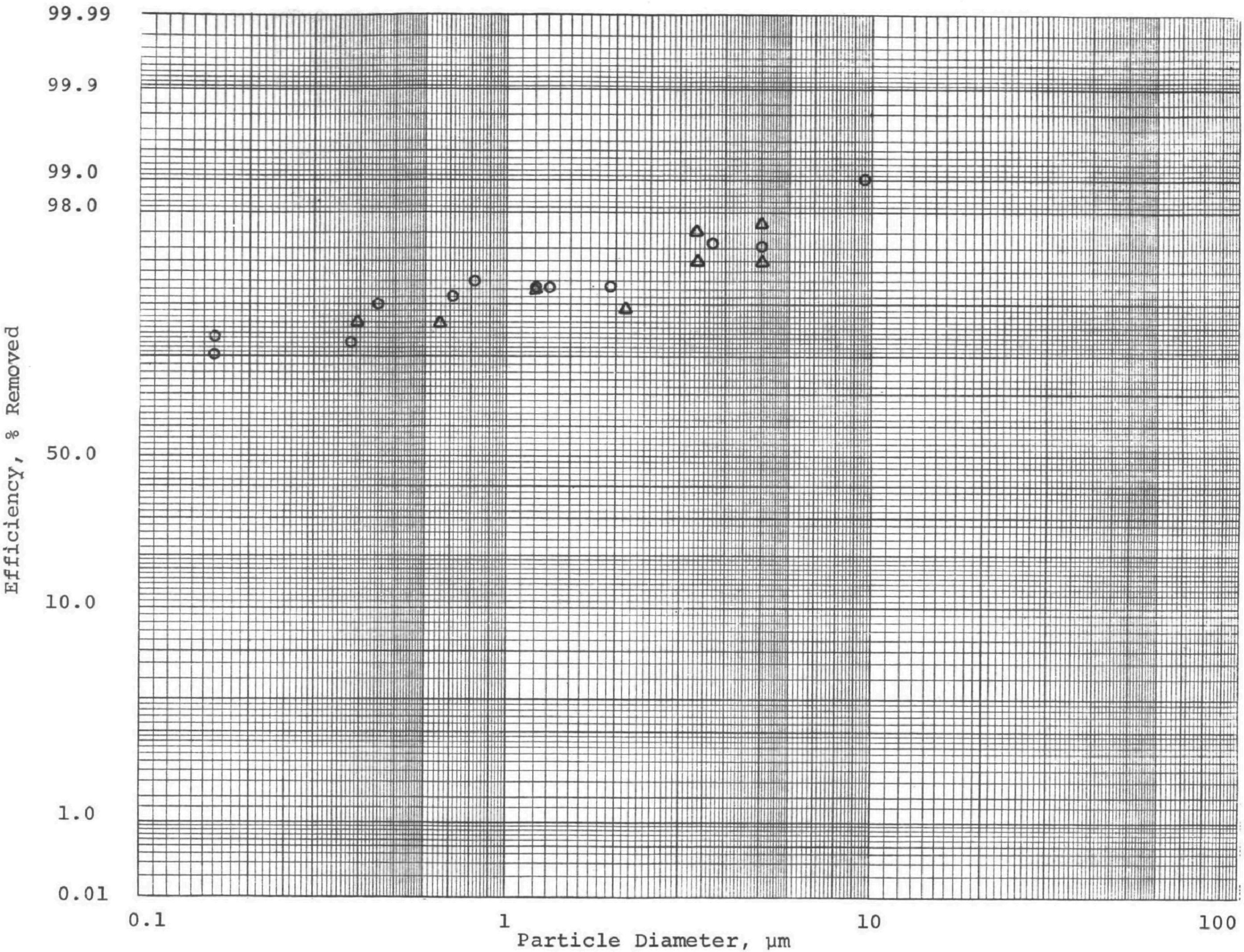

Figure 25. Precipitator Efficiency at 55% of Full Load as Measured with Modified Brink (o), and Andersen III (Δ) Impactors.

the stage with a lightweight collection substrate made of aluminum foil, teflon, glass fiber filter material, or other suitable lighweight materials depending on the particular application. With such an arrangement, it is possible to make accurate weight determinations of collected samples that are small enough to prevent or at least minimize reentrainment. Weighing to a precision of at least 30 μg appears to be required for impactor size determination for submicron particles and 10 μg precision is desirable.

D. When impactors are operated at flow rates higher than some critical value, particle bounce can lead to incorrect sizing with non-cohesive particulates. This is especially true in the lower (fine particulate) stages. In these lower stages, the high jet velocities cause scouring of the plates which are quite noticeable and is an almost certain indication of reentrainment; Figures 26 A and B illustrate this effect. Experience with the University of Washington Mark III and the Brink impactor indicate that the maximum jet velocities that can be used for impaction on ungreased substrates without severe reentrainment resulting from particle bounce is about 40 m/sec. Also, the physical properties of the particles can effect the maximum loading that can be safely obtained on an impaction stage. For example, with some emission sources, a small quantity of cohesive particulate materials will form a pile that will plug the stage orifice. For other types of emission sources with dry particulates, reentrainment and particle bounce problems can be severe. The use of a silicone grease that is stable at high stack temperatures appears to be helpful for measuring dry particulates. It has been our experience that even with this grease, errosion and scouring can occur on the lower stages with high jet velocities, velocities > 75 m/sec. The scouring and reentrainment can be reduced by reducing the flow rate in the impactor. For example, if the Brink sample flow is reduced from the recommended value of 2.8 l/min (0.1 cfm), to approximately 1.4 l/min (0.5 cfm) the scouring effect can be eliminated. This change in flow rate increases the cut point of each size fraction and decreases the amount of information that can be obtained in the small particle size range. These comments are appropriate for the Andersen and other impactors as well as the Brink. However, the addition of an additional stage to the impactor with the proper combination of velocity and jet diameter would make it possible to regain the information lost at the lower flow rate.

E. Glass fiber "back up" filters have generally been used after the final stage in our impactor tests. For some emission sources, the back up filter frequently showed a weight loss instead of a weight gain. This result appears to be related to filter handling problems and poor design of filter retainers and seats. More work is needed to solve this problem.

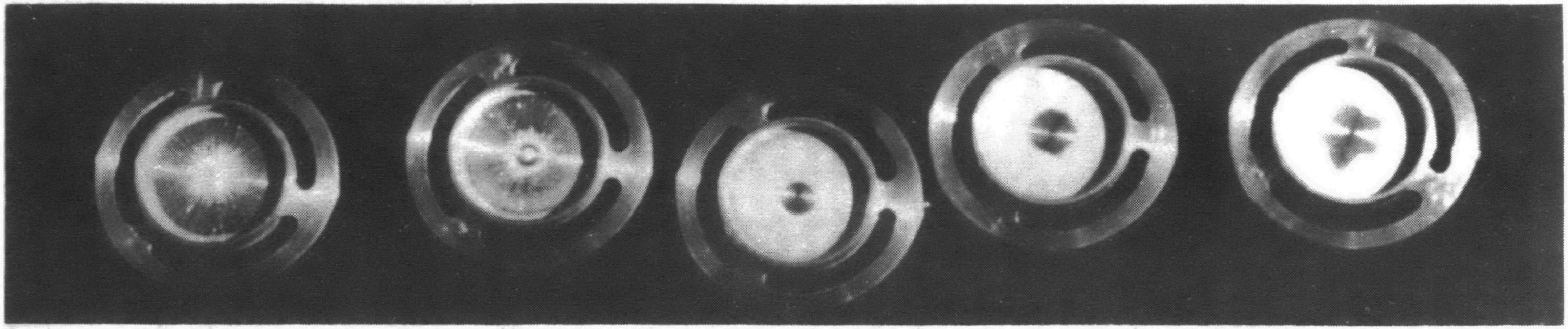

Figure 26A. Fly Ash Deposits on Ungreased Impaction Substrates without NH_3 Injection into Flue Gas. (Effects of Particle Bounce and R-entrainment are Especially Pronounced on the Last Three Stages.)

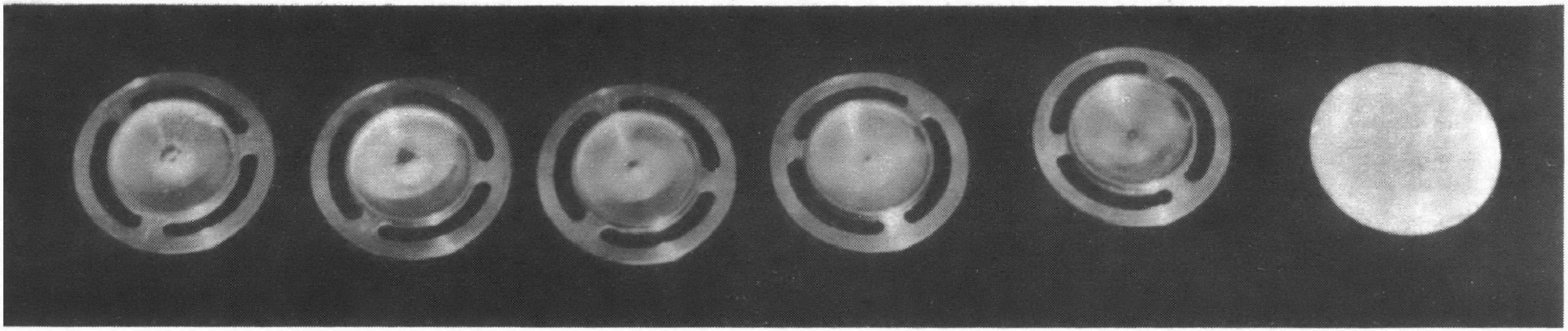

Figure 26B. Fly Ash Deposits on Ungreased Impaction Substrates with NH_3 Injection. (Comparison with Figure 26A Reveals a Pronounced Change in the Adhesive and Cohesive Properties of the Particulate.)

F. Particle size measurements have been made with the impactors mounted outside the stack. Sampling probes and lines were used to transport the sample to the impactor. Based on simultaneous size determination with the instack and out-of-stack sampling arrangements, it seems almost certain that a significant quantity of particles are lost in the probe and sampling lines, particularly in sizes larger than 2 μm. Figure 27 shows average differential inlet distributions as obtained with out-of-stack classifiers and illustrates this effect.

G. A consideration of all of the fractional efficiency curves shows that measurements with the modified Brink impactors, Brink with grease, Brink kit, Andersen Model II, and U.W. Mark III all seem to result in about the same calculated efficiency.

Although most of the classifiers used during these tests show general agreement in the differential size distributions obtained with each, significant differences were noted in detailed comparisons. Figure 28 shows average inlet size distributions as obtained with four instack classifiers. A revised calibration for the E.R.C. TAG sampler was received after the field work and was used in the preparing of Figure 28. Differences of as much as a factor of two in the loading at any one particular size exist between the data obtained with some of the classifiers. These differences appear to be related to the lack of good calibration of the stage penetrations under conditions that are appropriate for field sampling. Simultaneous calibrations under identical conditions, that simulate field measurements, appear to be mandatory if reliable field test results are to be obtained with a wide variety of impactors. This comparison or mutual calibration will be particularly important if two different makes of impactors are to be used in determining the fractional efficiency of a control device. As described previously in this report, the use of two impactors, a low flow rate impactor at the inlet and a high flow rate impactor at the outlet, is often required for measurement of field emissions sources.

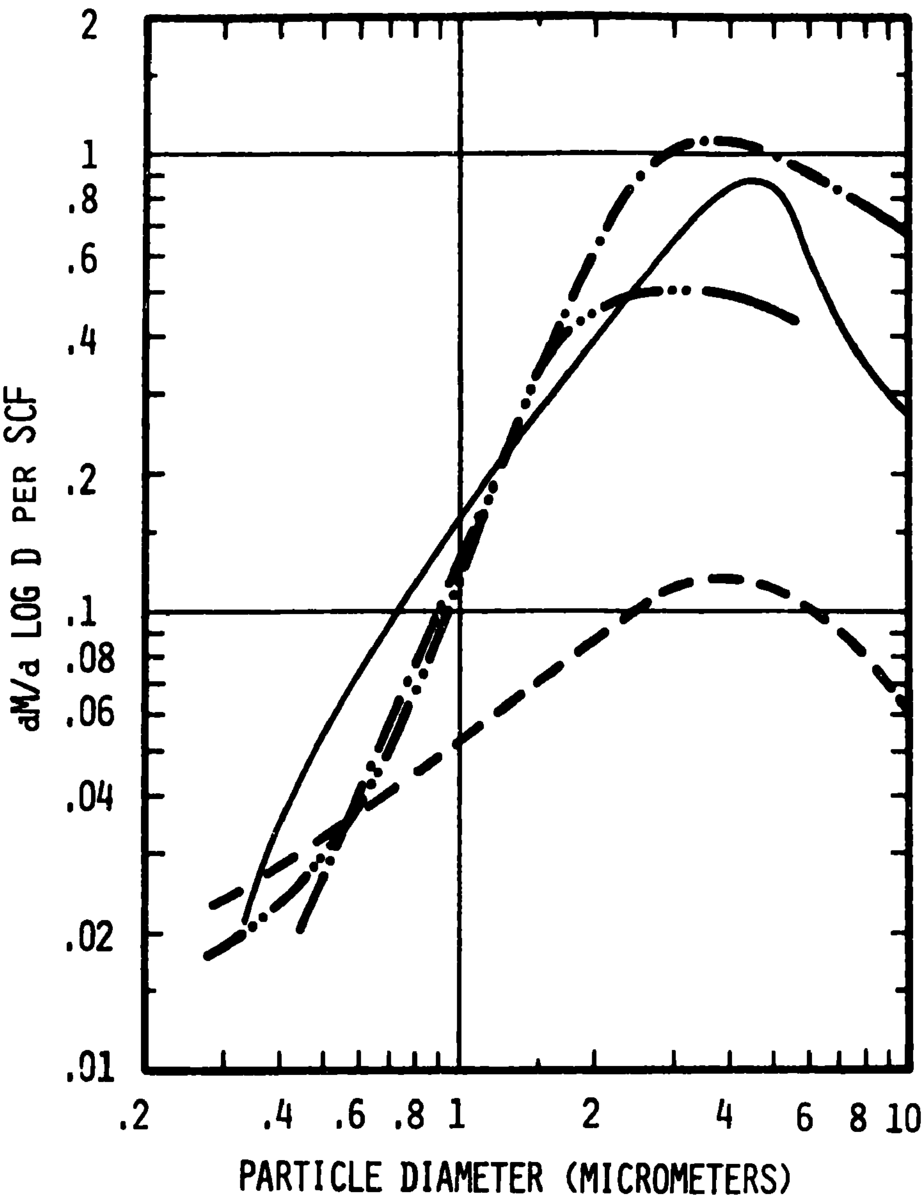

Figure 27. Inlet Size Distribution as Measured with Three Out-of-Stack Samplers. Battelle ——— ; Brink BMS 11—··—··—··; McCrone Parallel Cyclone—·—·—·—; Solid Line is the Distribution Obtained with the V.W. Mark III In-Stack Sampler for Comparison.

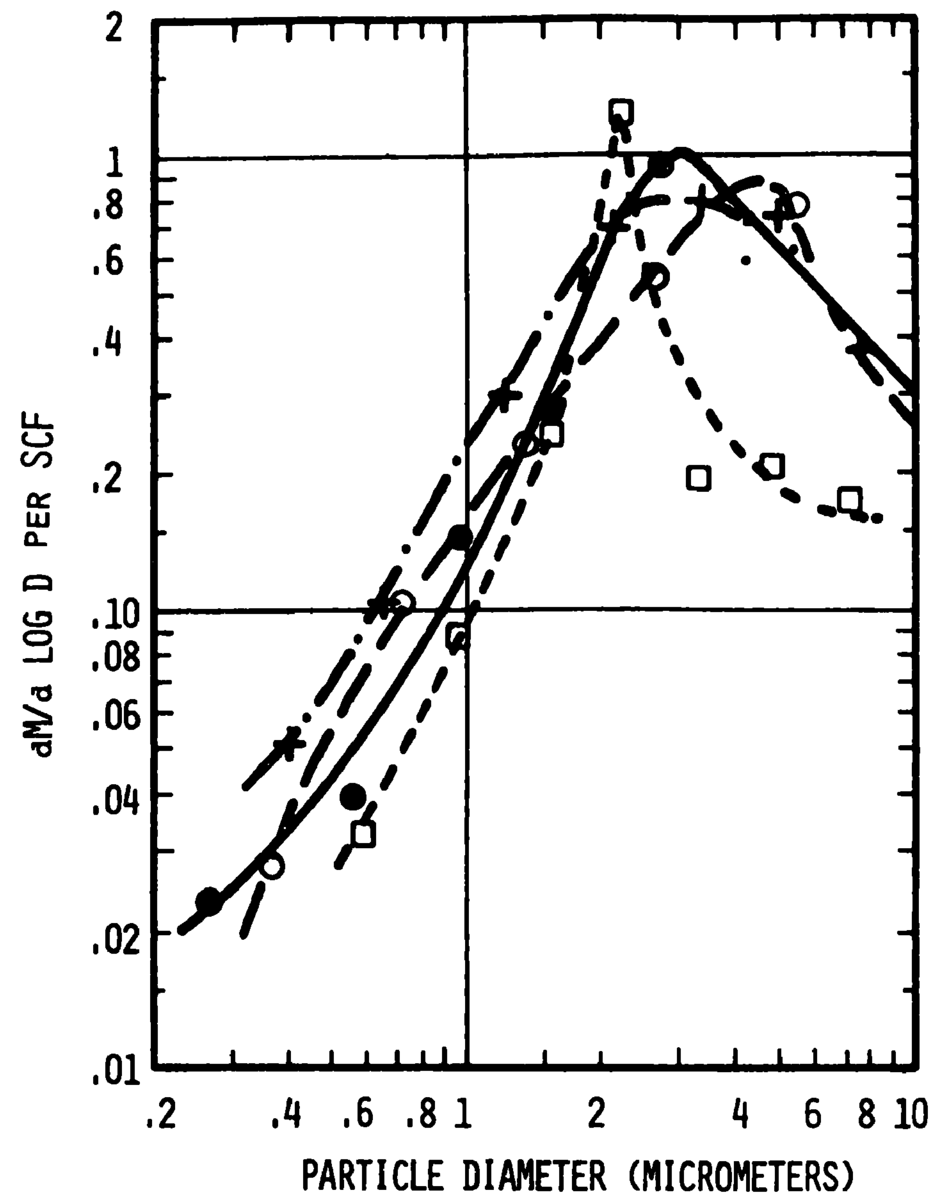

Figure 28. Inlet Size Distribution as Measured with Four In-Stack Samplers. E.R.C. Tag, □; Brink, ●; Andersen, +; Mark III, ○. (Each Point Represents the Average of Several Measurements.)

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3. A. N. Bird, J. D. McCain, D. B. Harris, "Particulate Sizing Techniques for Control Device Evaluation", presented at the 66th Annual Meeting of the Air Pollution Control Association, Paper Number 73-282, (June, 1973).

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16. Abstracts

The report describes a comprehensive particle size measurement program conducted at a coal-fired electric generating plant early in 1973. It also includes information obtained from other field tests and laboratory work. The primary particle size range of interest is from 0.2 to 2.0 μm diameter, but techniques are also evaluated for measuring larger particles. Inertial classification is the basic sizing technique considered. Among the 11 different commercial and modified sizing devices evaluated are: Andersen Models II, III, and IV; Battelle CIS-6; Brink BMS-11: McCrone; TAG; and University of Washington Mark III. The program is part of a project to devise and evaluate various techniques for field measurements of the fractional efficiency of particulate control devices.

17. Key Words and Document Analysis. 17a. Descriptors

Air Pollution
Measurement
Measuring Instruments
Fines
Particle Size
Particle Size Distribution
Size Determination
Impactors
Cyclone Separators
Electrostatic Precipitators

17b. Identifiers/Open-Ended Terms

Air Pollution Control
Stationary Sources
Fractional Efficiency
Particulate Control Devices
Inertial Classification
Cascade Impactors
Mass Concentration
Grain Loading
Battelle CIS-6 Impactor
McCrone Parallel-Cyclone Sizing Device
Anderson Models II, III and IV Stak Samplers
University of Washington Mark III Cascade Impactor
Brink BMS-11 Sampling Kit
TAG Sampler

17c. COSATI Field/Group 14B, 14D, 13B

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