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CHARACTERIZATION OF SUSPENDED FLUE GAS PARTICLE  
SYSTEMS WITH ON-LINE LIGHT SCATTERING PARTICLE ANALYZERS

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SYSTEMS WITH ON-LINE LIGHT SCATTERING PARTICLE ANALYZERS

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ABSTRACT

Two light-scattering particle size analyzers have been tested at ANL in the process development unit (PDU) fluidized-bed combustion system. The analyzers are (1) a single-particle analyzer developed by Spectron Development Laboratory and (2) a multiparticle analyzer developed by Leeds and Northrup. Particle size distributions and mass loadings determined at different flue gas duct locations with the Spectron and the Leeds and Northrup instruments have been compared with those obtained with (1) an Andersen cascade impactor, (2) a Coulter counter, and (3) positive filters. These comparison were used to evaluate the two instruments at their present state of development.

## CHARACTERIZATION OF SUSPENDED FLUE GAS PARTICLE SYSTEMS WITH ON-LINE LIGHT SCATTERING PARTICLE ANALYZERS

### INTRODUCTION

In the development of pressurized fluidized-bed combustion (PFBC) systems, an on-line particle analyzer for the flue gas could provide continuous particle size and loading analysis without disturbing the off-gas stream. These measurements will be used (1) in measuring the efficiency of upstream particulate-removing devices (cyclones and filters), (2) establish gas turbine performance at different particulate loadings, and (3) to protect turbines or a test cascade in the event of sudden system upsets. In a pressurized FBC system, the flue gas will be at  $\sim 900^{\circ}\text{C}$  and  $\sim 1000$  kPa ( $\sim 10$  atm) between the boiler and the turbine. In the absence of an on-line particle analyzer, routine batch sampling of the hot off-gas using inertial impactors will be necessary. Batch sampling from a pressurized hot off-gas environment (described in a following section) is difficult, and the long time lag between sampling and analysis of samples by the latter technique is also a disadvantage.

Two types of optical analyzers which have not yet been proven for fluidized-bed application were evaluated. Both instruments use laser light beams. One is a single-particle analyzer (a particle morphokinometer, developed by Spectron Development Laboratory) which characterizes the scattered light from each particle (laser interferometer method), and the other is a Microtrac multiparticle analyzer developed by Leeds and Northrup, which characterizes the entire particle distribution in its optical path.

#### Single-Particle Analyzer

The single-particle analyzer measures the sizes of particles and their velocities by measuring the light scattered from each particle as it crosses

an interference pattern generated by the intersection of two laser beams. A schematic drawing of a typical single-particle analyzer is given in Fig. 1. The laser beams are directed radially into the flue-gas duct of the ANL PDU combustion system through specially designed windows. The region of measurement of this instrument, called the probe volume or sample space, is at the center of the duct where the two coherent beams intersect and generate the interference pattern. The scattered light signal from each particle in the sample space is detected and is changed to an electric signal shown in Fig. 1. The light may be detected in either a forward or backward observation mode. In the ANL evaluation, forward-scattered light was detected. Particle size has been shown to be a function of (1) the ratio of the AC to DC amplitude of this signal and (2) the shape of the particle.<sup>1</sup> (Farmer, 1972). The particle sizes that can be measured depend on the interference fringe spacing ( $\delta$ ) in the sample space. The interference fringe periods and the corresponding detectable spherical particle size ranges used in this evaluation are given in Table I. The fringe periods were set by adjusting the angle ( $\alpha$ ) at which the two laser beams intersected.

A more detailed description of the principles of the single-particle analyzer is available in the literature.<sup>1</sup> (Farmer, 1972)

#### Multiparticle Analyzer

In the more conventional light-scattering technique used in multiparticle analyzers, a single laser beam is directed into the off-gas duct. The particle size distribution is obtained by examining the Mie scattered light from particle-laser beam interaction. All of the particles in the beam's path (off-gas duct cross section) simultaneously scatter incident light. As a result, the size of an individual particle cannot be determined. The particle size distribution can be obtained by examining the total scattering intensity as a function of angle and laser beam polarization and by comparing the experimental data with theoretical calculations for assumed size distributions.<sup>2</sup> (Weiss and Frock, 1976)

The multiparticle analyzer used in this work utilizes a new measurement technique in which three measurements of the scattered light are made. These measurements are accomplished by means of a uniquely shaped spatial filter

which, when placed in the Fraunhofer diffraction plane, transmits the proper amount of light as a function of scattering angle to give the desired responses. These measurements may be used to determine the mean diameter and variance of the distribution for particles in the 1-50  $\mu\text{m}$  range. Also, one measured signal is proportional to the volume of the particles illuminated, and this can be used to calculate the concentration of particles (loading) in the fluid stream.

If the type of distribution is known (*i.e.*, normal or log-normal) and if the distribution is unimodal, the information on mean diameter and variance is sufficient to completely describe the distribution of the suspended particles. The distribution of the particles leaving the combustor is multimodal (see next section) and cannot be characterized with this instrument. The distribution of the particles leaving the cyclones is unimodal and very nearly log-normal; it is expected that a multiparticle analyzer is capable of characterizing the suspended particles in the flue gas on either side of the filter upstream from the turbines. The primary objective in this work was to evaluate these instruments for gas-particle streams that would be expected on either side of such a filter.

## SYSTEM AND PROCEDURE FOR FLUE-GAS PARTICLE MEASUREMENTS

The flue gas system of the ANL fluidized-bed combustion system (PDU) has been modified for these evaluations, as shown in Fig. 2. Windows for particle analyzers have been installed in two locations; one pair is upstream from the primary cyclone. The other windows are near the system outlet with the capability of routing the flue gas past these windows, either upstream or downstream from the sintered metal filters (S4 and S5, Fig. 2). With this arrangement, it is possible to size (1) the coarse entrained particles from the combustor, (2) the smaller particles escaping the two cyclones, and (3) the smallest particles passing through the sintered metal filters (representative of particles that might enter turbines). The coarse particles leaving the combustor were not sized with the multiparticle analyzer. Downstream from each window location, sampling ports have been installed that allow (1) particle size analysis of representative grab samples with cascade impactors and (2) measurement of particle loading with membrane filters. Also, steady state particle samples were obtained from the cyclones and test filter.

The particle size measurements were obtained (1) with on-line particle analyzers, (2) using an Andersen cascade impactor (described below), and (3) from steady state samples obtained from the cyclones and/or the test filter. The steady state samples were analyzed by sieve analysis and with a Coulter counter.

Coulter counter analyses are performed by suspending the particles in an electrolyte (2 wt % NaCl in H<sub>2</sub>O); surfactants are used to enhance dispersion. In the Coulter counter, the suspension is passed through an orifice which isolates two electrodes. As a particle passes through the orifice, it generates a resistance pulse; the size of the pulse is proportional to the volume of the particle or the electrolyte that is displaced by the particle. The measurable

size range of particles is limited by the size of the orifice ( $\approx 2-50\%$  of the orifice diameter). A distribution is calculated by assuming that the particles are all spherical. This instrument was calibrated with standard particles (Dow polystyrene latex particles, pollen, and National Bureau of Standards glass beads).

Particle size distributions on a weight basis were obtained by assuming that all observed particles were spheres of equal density and that the particles observed with the on-line instruments (single-particle and multiparticle analyzers) were identical to those that were mechanically removed from the system and later analyzed. Since density is assumed to be constant for all particle diameters, the fractional volume distribution and fractional mass distribution are equivalent.

Cascade impactors are the devices used most often for obtaining size distributions of airborne particles in process or ambient air in the size range 0.3-20  $\mu\text{m}$ . In this study, an Andersen cascade impactor was used to obtain combustor flue gas particle size distribution data for flue gas grab samples. Each stage of the impactor consists of equidiameter orifices followed by a target plate for collecting the particles. Smaller orifices are used in successive stages, and thus smaller particles are collected in successive stages. The particle size distributions are calculated from experimental data by relating the mass that is collected on each stage to the corresponding stage diameter. Impactor designs (including the design of the impactor used) are based on the theoretical development of Ranz and Wong.<sup>3</sup> (Ranz and Wong, 1952) The size measurements obtained with the cascade impactors are aerodynamic diameters (based on aerodynamic behavior of spherical unit-density particles). These particle measurements should be most appropriate in characterizing airborne particles in relation to turbine erosion, which is an aerodynamic process. Previous FBC studies have shown that measurements of combustion particles with cascade impactors, Coulter counters, and microscopes are in good agreement.<sup>4,5</sup> (Vogel *et al.*, 1974) (Hoke *et al.*, 1977) Because of previously found agreement between the different measuring techniques and of the scope of this evaluation, no direct microscopic comparisons have been made in this evaluation. However, it is planned to perform such a comparison during the on-going work on the evaluation of particulate clean-up components at ANL, which is a much more extensive task.

The total cumulative mass distributions obtained with the impactor in two consecutive measurements of suspended particles leaving the secondary cyclone (SGL-2C) are given in Fig. 3. Aerodynamic mass diameters of 2.7  $\mu\text{m}$  and 3.0  $\mu\text{m}$  were obtained, it being assumed that the apparent density of all particles was 1.0  $\text{g}/\text{cm}^3$ . The sampling conditions for the impactor samples are given in Table II. The total cumulative mass distribution obtained with the Coulter counter is also given in Fig. 3. The log-mean diameter was found to be 3.5  $\mu\text{m}$ , which compares favorably with the distribution means obtained with the cascade impactor. Because the Coulter counter was calibrated with standard particles and its measurements of combustion particles agreed well with cascade impactor measurements, it was assumed that these comparative measurements were representative of the true particle distributions. The evaluation of the multiparticle analyzer was performed only with cascade impactor comparative measurements.

The sampling system in the FBC system for the cascade impactor is illustrated in Fig. 4; for some samples, a glass fiber membrane filter was substituted for the impactor. The particle laden-flue gas flowed by the optical windows (located in the line downstream from the cyclones or metal filter), where the particles were sized with a light-scattering particle analyzer. Next, the off-gas line was expanded to reduce the velocity to that compatible to isokinetic sampling with the cascade impactor and membrane filters. The tip of the sampling probe (0.78-cm ID for single-particle analyzer evaluation and 1.33-cm ID for the multiparticle analyzer evaluation) was machined to enhance aerodynamic stability near the probe entrance. The sample line was electrically heated to maintain the temperature of the gas sample above its water dew point. The cascade impactor and the membrane filter holders was contained in a heated pressure shell to permit sampling from the pressurized (3 to 8 atm) combustion system. Gas velocities were calculated from measured gas flows and local temperatures.

## CHARACTERISTICS OF SUSPENDED PARTICLE DISTRIBUTIONS AT DIFFERENT FLUE-GAS CLEANUP STAGES

The total size distribution of particles elutriated in the combustor during a coal combustion experiment (SCL-1) was obtained by combining Coulter counter measurements with sieve analyses of samples collected in the cyclones and metal filter. The particles passing through the metal filter were justifiably assumed not to contribute significantly to the total mass size distribution. The fractional mass distribution in successive half-volume intervals of all particles between 2  $\mu\text{m}$  and 1000  $\mu\text{m}$  is given in Fig. 5. (The loading in the flue gas leaving the combustor is  $\sim 14$  grains/scf or  $\sim 20$  grains/acf which is quite high.) This distribution consists of elutriated partially sulfated limestone (apparent density;  $\rho_a = 1.9 \text{ g/cm}^3$ ), unburned coal ( $\rho_a \sim 1.0 \text{ g/cm}^3$ ), and coal ash ( $\rho_a \sim 0.6 \text{ g/cm}^3$ ). Since these materials could not be separated, the distribution could only be obtained by assuming a uniform density; thus, the smaller-diameter fractions, which contain more of the lighter ash and carbon, are probably biased high.

Since the distribution of particles leaving the combustor is multimodal, the detailed characteristics of the distribution can only be obtained with a single-particle analyzer such as was used in this work. However, because the distribution extended from 2  $\mu\text{m}$  to 1000  $\mu\text{m}$ , only that part of the distribution below  $\sim 70 \mu\text{m}$  could be sized with the single-particle analyzer.

The distribution of the particles escaping from the cyclones during a different coal combustion experiment (SGL-2C) is given in Fig. 6. The mass loading at this flue gas location is  $\sim 0.2$ - $0.5$  grain/scf, and the mass contribution by particles larger than 10  $\mu\text{m}$  is small. The largest mass fraction consisted of 3.0 to 3.8  $\mu\text{m}$  particles, which contained 22.5 wt.% of the total loading. This distribution can be characterized as a log-normal distribution and it is expected that particles escaping from the filter have the same type

of distribution. Thus, because the type of particle distribution that a gas turbine will see is expected to be log-normal, both single-particle analyzers and multiparticle analyzers can be used in the hot flue gas of a PFBC system.

Because the flue-gas particle distributions are not homogeneous (carbon, fly ash, and unburned coal), the extent to which particle shapes, apparent densities, refractive indices, *etc.* affected the differences between measurements obtained by different measuring principles (techniques) was evaluated with experiments in which only virgin limestone particles were suspended and measured in the flue gas. This was accomplished by continually feeding virgin limestone into the cold combustor, thereby maintaining a steady state fluid bed of virgin limestone. The particles that elutriated were generated by attrition and had basically homogeneous properties. The fractional mass distribution of virgin limestone leaving the cyclones of the PDU system was determined with the Coulter counter and is given in Fig. 5 (LASER-1B). It was also log-normal in nature and the log-mean diameter was approximately equal to that obtained for the combustion experiment measurement (SGL-2C). Thus, this distribution can also be characterized by use of both single-particle and multiparticle light-scattering analyzers.

## EXPERIMENTAL EVALUATION OF THE SINGLE-PARTICLE ANALYZER

Some results of particle size measurements obtained with the single-particle analyzer for several combustion experiments have been compared with size distributions determined by Coulter counter for steady state particle samples and cascade impactor measurements. In addition to size measurements, particulate loading measurements were compared. The measurements with this laser instrument were made in the PDU combustion system's off-gas duct between the combustor and the primary cyclone, where all particles elutriated in the combustor were observed. Also, particle size measurements between the secondary cyclone and the metal filters are reported.

### Measurements of Particle Size Distribution

The conditions for the combustion experiments in this evaluation are given in Table II. In the first experiment (SGL-1), the distribution of particles leaving the combustor was measured. Two fringe periods, see Table I, were used on the single-particle analyzer, 71.4  $\mu\text{m}$  and 22.3  $\mu\text{m}$ . The measured particles consisted of limestone fragments, coal ash, and unburned coal.

In the comparison, only the mass distributions in the measurable particle size ranges (1.5-23  $\mu\text{m}$  and 5-74  $\mu\text{m}$ ) of the single-particle analyzer were compared with the corresponding distributions obtained with the Coulter counter. The small (1.5-23  $\mu\text{m}$ ) and the large (5-74  $\mu\text{m}$ ) particle measurement comparisons are given in Figs. 7 and 8, respectively. For the small-particle size range (Fig. 7), the mass log-mean particle diameters obtained were 8.5  $\mu\text{m}$  with the Coulter counter and 20  $\mu\text{m}$  with the single-particle analyzer. For the large-particle size range, the mass log-means of the partial distributions were found to be 26  $\mu\text{m}$  with the Coulter counter and 70  $\mu\text{m}$  with the single-particle analyzer (Fig. 8). The difference between the two measurements is greater for larger particles.

The conditions for combustion experiments SGL-2C and SGL-1C, in which the sizes of suspended particles between the secondary cyclone and the metal filters of the PDU combustion system were measured, are given in Table II. Particles with diameters of 0.2 to 3.1  $\mu\text{m}$ , and 1.5 to 23  $\mu\text{m}$  were sized with the single-particle analyzer. The resulting partial (1.5-2.3  $\mu\text{m}$ ) mass distributions are given in Fig. 9. The mass log-means of these distributions are 3.5  $\mu\text{m}$  (Coulter counter) and 17  $\mu\text{m}$  (Curve A, single-particle analyzer). In the distribution obtained with the single-particle analyzer, the mass particule population increased sharply for particles larger than 15  $\mu\text{m}$ . Since at this point the flue gas had passed through two cyclones, most particles larger than 10  $\mu\text{m}$  should have been removed, as found with the Coulter counter measurements.

The submicron particles were measured with the single-particle analyzer in experiment SGL-1C (see Table II), using a fringe period of 2.94  $\mu\text{m}$ . To achieve the recommended velocity of  $\sim 3.0$  m/s or less (necessary due to response of electronics), the flue stream was split downstream from the cyclones and only a metered portion was allowed through the sampling system. Because the Coulter counter at ANL is not capable of measuring particles smaller than 1.5  $\mu\text{m}$ , the small particle measurements made with the single-particle analyzer were compared with the partial mass cumulative distribution obtained with the cascade impactor (Fig. 10). The mass log-means obtained were 0.72  $\mu\text{m}$  (single-particle analyzer) and 1.6  $\mu\text{m}$  (impactor). The agreement obtained is considered to be as good as might be expected for the small particle measurements.

Because of the low loadings ( $\sim 0.05$  grain/scf) downstream from the metal filter, no size measurements could be made with the single-particle analyzer. Not enough measurable (1.5-23.9  $\mu\text{m}$ ) particles passed through the sample space. However, the present state of the art on turbine technology suggests that this particle size range will be significant at loadings of  $\sim 0.05$  grain/scf in causing turbine damage.

On-line particle analyzers will be most useful downstream from FBC particle-removal devices to monitor particle distributions and loadings in the flue gas that enters gas turbines. Particles  $< 10$   $\mu\text{m}$  and  $> 1$   $\mu\text{m}$  are expected to erode the turbines. It is encouraging that the characteristics of the fractional distributions obtained by the two different methods (single-particle analyzer *vs* Coulter counter) were the same and that the discrepancy between the two

measurements became smaller for smaller particles ( $<20 \mu\text{m}$ ). However, a significant difference remained between the comparative measurements for 1.5 to 23.9  $\mu\text{m}$  particles (the mass log-means obtained with the single-particle analyzer were a factor of at least 3 larger). Possible reasons for the difference are given below:

- a. The mass loading downstream from the combustor was  $\sim 14$  grains/scf ( $\sim 20$  grains/acf), which is quite high. Thus, for the measurements upstream from the cyclone, the chance that there would be more than one particle in the sample space of the single-particle analyzer was high. Over 98% of the signals were rejected by the single-particle analyzer because of particle coincidence interference. (Signal rejection rates between 97% and 90% are considered acceptable by the manufacturer.)
- b. The original calibration for spherical particles, which was obtained with low number densities of mists and aerosols by microscopic measurements, is greatly influenced by particle shape and orientation in the sample space. The bias becomes more pronounced for larger particles via visibility function.<sup>1</sup> (Farmer, 1972).
- c. Fragile particles might have broken up as the particle samples were collected in the cascade impactor or in the cyclones and test filter or as they were prepared for Coulter counter analysis (dispersed in an electrolyte). This effect could impose a bias towards small diameters in Coulter counter and impactor measurement.

The agreement in the cold experiments between the single particle analyzer and impactor was better for the measurements with the lower loading (downstream from the cyclones). However, because the suspended virgin limestone particles were relatively homogeneous, similar in shape (not dependent on diameter), and consistent in scattering properties (refractive indices), a better than the found agreement was expected between the single-particle analyzer measurements, the measurements with the cascade impactor (seen in Fig. 11), and the Coulter counter.

Because of difficulties in evaluating the causes for discrepancies between the single-particle analyzer and comparative measurements, an empirical

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Because of difficulties in evaluating the causes for discrepancies between the single-particle analyzer and comparative measurements, an empirical

correlation of the experimental data was used to obtain a best fit for the calibration curve. In this analysis, it was assumed that the Coulter counter and inertial impaction measurements were correct. The particle distribution measurements obtained with the Coulter counter and cascade impactor were expressed as histograms, with intervals equivalent to the single-particle analyzer increments. The diameter-dependent factor necessary to force the fractional contributions of the histogram intervals from the single-particle analyzer into agreement with those from the Coulter counter and impactor measurements was obtained. The ratios of the fractional contributions obtained from the Coulter counter and impactor measurements to those obtained from the single-particle analyzer for a considerable number of measurements were correlated with the reduced diameter of the interval,  $D/\delta$ . ( $D$  is the particle diameter and  $\delta$  is the fringe period of the laser probe volume.) By use of least squares techniques, the following correlation was obtained:

$$\ln (K) = -4.91 \ln\left(\frac{D}{\delta}\right) - 2.5 \left[\ln\left(\frac{D}{\delta}\right)\right]^2 \quad (1)$$

where  $K$  is the ratio of the expected mass concentration in the diameter interval to the measured number of particles within the analyzer interval. This correlation gives a fair fit (the correlation coefficient is  $\sim 0.88$ ).

The above discussed experiments were reanalyzed using this empirical calibration and the measurements in these experiments were adjusted using the calibration function (Eq. 1). The results for SGL-2C, in which the particle measurements were performed on suspended particles downstream from the cyclones, are given in Fig. 9 (Curve B). This figure also contains the distribution which is based on the calibration function originally supplied by the manufacturer (Curve A):

$$K \propto 1/D \quad (2)$$

The mass log-mean diameters for SGL-2C (Fig. 9) were:  $3.5 \mu\text{m}$  (Coulter counter),  $8.8 \mu\text{m}$  (Eq. 1 calibration), and  $18 \mu\text{m}$  (supplied analyzer calibration). Although the adjusted (by Eq. 1) analyzer measurements still deviate from the Coulter counter measurements, agreement of the measurements improved significantly.

### Measurement of Particulate Loadings

Loading measurements cannot be made with the single-particle analyzer in its present state of development because the appropriate volume of the sample space is not readily attainable without a comparison measurement. Comparative loading measurements by gravimetric means were used to predict the probe volumes, and it was estimated that at best, the loadings could be estimated within one order of magnitude with the single-particle analyzer for high loading conditions ( $>0.1 \text{ g/m}^3$ ).<sup>6</sup> (Montagna *et al.*, 1977). No particle measurements were made with the analyzer under low loading conditions because too few particles passed through the probe volume.

## EXPERIMENTAL EVALUATION OF THE MULTIPARTICLE ANALYZER

Windows for the multiparticle analyzer were installed near the system outlet with the capability of routing the flue gas past these windows, either upstream or downstream from the metal filters. The sampling port for representative grab samples was installed upstream from the window location. Steady-state grab particle samples were obtained with: the cascade impactors, membrane filters, and a total flue gas test filter. (The test filter replaced the metal filter during sampling periods, but loadings obtained with this filter are not reported in this paper.)

### Measurement of Log-Mean Particle Size

The log-mean aerodynamic particle diameter ( $\bar{D}_{AE}$ ) measurements obtained with the impactor may be compared with the "projected" particle area mean diameter ( $\bar{D}_A$ ) obtained with the multiparticle analyzer. The volume mean diameter,  $\bar{D}_V$ , also obtained with the multiparticle analyzer, is larger by definition:

$$\ln \bar{D}_V = \ln \bar{D}_A + 0.5 \ln^2 \sigma_n \quad (3)$$

where  $\sigma_n$  is the geometric standard deviation on a number basis;<sup>7</sup> (Irani and Callis, 1963)  $\bar{D}_V$  is more sensitive to changes in the distribution.  $\bar{D}_A$  corresponds more closely than does  $\bar{D}_V$  to impactor diameter measurements,  $\bar{D}_{AE}$ , which are dependent on the particle's aerodynamic drag and inertia.<sup>8</sup> (Orr and Dalla Valle, 1960) The multiparticle analyzer also measured the arithmetic deviation of the distribution. The geometric standard deviation,  $\sigma_n$ , can be calculated from Eq. 1 and the measurements  $\bar{D}_A$  and  $\bar{D}_V$ . The calculated value of  $\sigma_n$  and  $\bar{D}_A$  were used to characterize the log-normal distribution of suspended flue gas particles.<sup>6</sup> (Montagna *et al.*, 1977) The resulting distributions from the multiparticle analyzer are slightly narrower (less variance) than the distribution from the cascade impactor.

The conditions for the combustion experiments and some cold experiments are given in Table III together with the measured diameters and loadings. Because the contribution of particles smaller than 1  $\mu\text{m}$  was less than 10%, mass basis, the impactor distributions were not truncated to accommodate the range of the multiparticle analyzer (1-20  $\mu\text{m}$ -dia). In coal combustion experiments, the aerodynamic log-mean diameter ( $\bar{D}_{AE}$ ) ranged from 2 to 3.5  $\mu\text{m}$  and the projected area mean diameter ( $\bar{D}_A$ ) ranged from 2.2 to 3.4  $\mu\text{m}$  for all suspended particle measurements when the loading (gravimetrically obtained) was relatively high ( $>0.1 \text{ g/m}^3$  or  $>0.044 \text{ grain/scf}$ ). The volume mean diameters ( $\bar{D}_V$ ) ranged from 2.9 to 5.5  $\mu\text{m}$  for the same measurements.

In "cold" experiment LN-9-5, only virgin limestone particles were measured. The loading was also relatively high ( $>0.1 \text{ g/m}^3$ );  $\bar{D}_A$  was 2.7  $\mu\text{m}$ , in comparison with 1.5  $\mu\text{m}$  for  $\bar{D}_{AE}$ . It had been expected that the measurements made on the suspended virgin limestone would have agreed better than those made on the mixture of particles during combustion experiments. However, the ( $\bar{D}_{AE}$  and  $\bar{D}_A$ ) agreement for suspended combustion particles was slightly better than for the above measurements under high loading ( $>0.1 \text{ g/m}^3$ ) conditions. In comparison with the multiparticle analyzer, the mass log-mean diameters of particles leaving the cyclones (loadings  $\geq 0.1 \text{ g/m}^3$ ) measured with the single-particle analyzer (only particles between 1.5 and 23.9  $\mu\text{m}$  were compared) were at best a factor of three greater than those obtained by the Coulter counter and impactor measurements.

The agreement of  $\bar{D}_{AE}$  with  $\bar{D}_A$  was poorer for measurements made at lower loading conditions ( $\leq 0.01 \text{ g/m}^3$ ) in experiments LN-9 and LN-11.  $\bar{D}_{AE}$  ranged from 0.63 to 1.9  $\mu\text{m}$  and  $\bar{D}_A$  ranged from 2.0 to 5.5  $\mu\text{m}$ . The loading of  $\sim 0.05 \text{ g/m}^3$  for particle diameters of 1-10  $\mu\text{m}$  is presently being proposed as the approximate maximum tolerable loading for turbines. Because the particulate loading tolerances on turbines remain uncertain, it is desirable to have optical instruments capable of measuring particle loadings  $< 0.05 \text{ g/m}^3$ . In these low loading measurements,  $\bar{D}_A$  was approximately three times larger than  $\bar{D}_{AE}$ . Considering the difficulty of obtaining accurate impactor measurements for the comparison, this agreement can be considered fair at this stage. In comparison, no particle measurements could be made with the single-particle analyzer at these low loadings because not enough particles passed through the sample space of the instrument.

## Measurement of Particulate Loadings

In these experiments, particulate loadings were measured in addition to mean particle sizes. Values for comparison were obtained by three backup methods. The amount of particulate collected on a total flue gas metal filter located downstream from the multiparticle analyzer windows and sampling port provided one backup measurement. The other backup measurements were grab samples, and each consisted of (1) the particulate collected in the impactor including a backup filter to the impactor and (2) the material collected on a membrane filter.

For the measurements during the combustion experiments in which the loadings were high ( $>0.1 \text{ g/m}^3$ , gravimetric), the gravimetric loadings were a factor of four or less smaller than the optical loading measurements made with the multiparticle analyzer, see Table III. (The loadings from the multiparticle analyzer are proportional to the particulate density assumed;  $1.0 \text{ g/cm}^3$ .) For many high loading measurements, such as LN-4-2, the gravimetric and multiparticle analyzer loadings were very close. The gravimetric loadings under low loading conditions ( $<0.01 \text{ g/m}^3$ ) were one order of magnitude less than the optical multiparticle analyzer loadings. The semicontinuous background loading signal is compared with the background plus sample loading signal in Fig. 12 for low loading ( $\leq 0.01 \text{ g/m}^3$ ) measurements. The loading measurements signal is only 4% greater than the background; this can account for the order of magnitude difference between the multiparticle analyzer measurements and the gravimetric loading measurements. These low loading measurements were made on suspended particles that had escaped through the metal filter.

In the cold experiment (LN-9), loadings determined gravimetrically were one order of magnitude smaller than those obtained in the hot experiments for the high loading measurements; they were about two orders of magnitude smaller for the low loading experiments. This large difference may be due to an increase (over the period of an hour) in the multiparticle analyzer background signal during these cold experiments (see Fig. 13). The average gas linear velocity in the flue gas duct near the optical windows was  $\sim 30 \text{ m/s}$  during the cold experiments; during the hot combustion experiments, the linear gas velocity was only  $\sim 3 \text{ m/s}$ . A higher gas velocity creates more turbulence and a greater chance for particles to build up in the free space between the windows and

and the flue gas flow stream. The background was observed to decay to normal after flow of limestone-laden air was turned off.

## CONCLUSIONS

The single-particle analyzer is capable of characterizing a suspended-particle distribution as a histogram. Thus, the actual shape of the size distribution can be obtained. The multiparticle analyzer can characterize a distribution by giving the mean and a nongeometric variance of the distribution. Unless the type of distribution is known and it is unimodal, the latter instrument cannot describe the distribution of the particles. The distribution downstream from the cyclones of a PFBC system is expected to be log-normal, based on measurements in this and other studies. Therefore, the distribution can also be obtained with multiparticle analyzer measurements. However, the single-particle analyzer has a greater capability to characterize particle distributions.

For high-loading ( $>0.1 \text{ g/m}^3$ ) measurements, the projected particle area mean diameters obtained with the multiparticle analyzer were generally  $<25\%$  smaller than the aerodynamic mass log-mean particle diameters determined with the impactor. In comparison, for the same loading conditions, the mass log-mean particle diameters obtained with the single-particle analyzer were a factor of three (or more) greater than those obtained by Coulter counter and impactor measurements. For low loading conditions ( $<0.01 \text{ g/m}^3$ ), the mean diameters obtained with the multiparticle analyzer were approximately three times larger than log-mean diameters obtained with the impactor. No particle size measurements could be made at these low loadings with the single-particle analyzer.

For high loadings, the gravimetric loadings were a factor of four or less smaller than the optical loading measurements made with the multiparticle analyzer. However, many measurements made at these relatively high loadings by

the two techniques were very close. Under low loading conditions ( $<0.01 \text{ g/m}^3$ ), the gravimetric loadings were one order of magnitude less than the optical measurements with the multiparticle analyzer. For these low loads, the loading measurement signal is only 4% greater than the background; this is a potential source of error. If the background can be reduced electronically or via cleaner windows and/or optical path, this instrument would be very promising for on-line PFBC measurements to protect the gas turbines.

For the single-particle analyzer, loading measurements cannot be made at its present state of development because the appropriate volume of sample space is not readily calculable. Based on comparative measurements by gravimetric means, it was estimated that at best, loadings could be estimated within one order of magnitude with the single-particle analyzer for high loads. No low loading ( $<0.01 \text{ g/m}^3$ ) measurements have been made with the single-particle analyzer.

The multiparticle analyzer is a state of development allowing it to be used with little operator training. Operation of the single-particle analyzer requires much more care, and data reduction is presently very time-consuming. The single-particle analyzer is a first-generation instrument and has much potential. On the other hand, the multiparticle analyzer is a more advanced instrument and with some refinement can be useful now in the development of PFBC technology.

#### ACKNOWLEDGMENTS

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TABLE I. SELECTED INTERFERENCE FRINGE SPACINGS AND THE CORRESPONDING MEASURABLE SPHERICAL PARTICLE SIZE RANGES

Fringe Period, $\mu\text{m}$	Min. Particle Diameter, $\mu\text{m}$	Max. Particle Diameter, $\mu\text{m}$
71.4	4.9	74
22.3	1.5	23
2.94	0.2	3.1

TABLE II. EXPERIMENTAL CONDITIONS FOR A COMBUSTION EXPERIMENT  
IN THE EVALUATION OF THE SINGLE-PARTICLE ANALYZER

Location of PM Windows: Between PDU combustor and  
cyclones, SGL-1.  
Between second cyclone and  
filter, SGL-2C.

Sorbent: Greer Limestone

Coal: Sewickley

System Pressure, kPa: 308 (3 atm)

Fluidizing Gas Velocity, m/s: 1.0

Exp.	Combustor Temp, °C	Conditions at PM Windows		Conditions Near Probe at Sampling Duct		
		Gas Velocity, m/s	Temp, °C	Gas Velocity $V_{fg}$ , m/s	Temp, °C	Ratio of Duct Velocity to Probe Gas Velocity $V_{fg}/V_s$
SGL-1	850	5.2	350	-	-	-
SGL-2C	855	11.8	123	3.26	110	1.16
SGL-1C	855	2.6	90	0.91	60	1.15

TABLE III. COMPARISON OF PARTICLE SIZES AND LOADINGS OBTAINED WITH THE MULTIPARTICLE ANALYZER, THE ANDERSEN IMPACTOR, AND MEMBRANE FILTER

FBC Combustor Conditions:

Pressure 308 kPa (3 atm)  
 Temperature 855°C  
 Fluidizing Velocity 1 m/sec  
 Sorbent Greer Limestone  
 Coal Sewickley

Exp.	MICROTRAC			Andersen Impactor		Membrane Filter Loading (g/m <sup>3</sup> )
	$\bar{D}_v^c$ (μm)	$\bar{D}_A^d$ (μm)	Loading <sup>g</sup> <sub>co</sub> (g/m <sup>3</sup> )	$D_{AE}^e$ (μm)	L (g/m <sup>3</sup> )	
LN-4-1-a	5.1	2.8	0.43	2.2	0.33	0.64
LN-4-1-b	2.9	2.2	0.83	3.5	1.1	1.3
LN-5-1-a	5.5	3.4	0.18	6.0 <sup>f</sup>	0.21	0.41
LN-5-2-b	3.9	2.3	1.0	3.2	0.98	0.40
LN-6-1-a	4.4	2.8	0.46	3.0	0.12	0.54
LN-6-2-b	3.6	2.2	0.64	3.5	1.1	1.0
LN-10-3-b	3.8	2.2	1.5	2.0	0.56	-
LN-10-4-b	-	-	0.37	-	-	0.63
LN-11-1-a	11.9 ±.3	5.5 ±.11	0.12 ±.01	1.9	0.01	-
LN-11-2-a	-	-	0.13 ±.01	-	-	0.009
LN-11-3-a	10.5 ±.2	4.97 ±.12	0.11 ±.02	1.8	0.01	-
LN-9-3-a <sup>g</sup>	2.24 ±.36	2.01 ±.06	0.21 ±.04	0.63	0.001	-
LN-9-2-a <sup>g</sup>	-	-	0.10 ±.02	-	-	0.003
LN-9-5-b <sup>g</sup>	3.77 ±.23	2.72 ±.07	1.20 ±.06	1.5	0.115	-
LN-9-4-b <sup>g</sup>	-	-	0.52 ±.17	-	-	0.110

<sup>a</sup> 1 g/m<sup>3</sup> = 0.437 grain/scf

<sup>a</sup> After filter.

<sup>b</sup> Between secondary cyclone and filter.

<sup>c</sup> Volume mean diameter.

<sup>d</sup> Projected area mean diameter.

<sup>e</sup> Aerodynamic mean diameter.

<sup>f</sup> Suspect, possibly due to unexpected flue gas re-entrainment.

<sup>g</sup> Cold elutriation experiments - only virgin limestone particles measured.

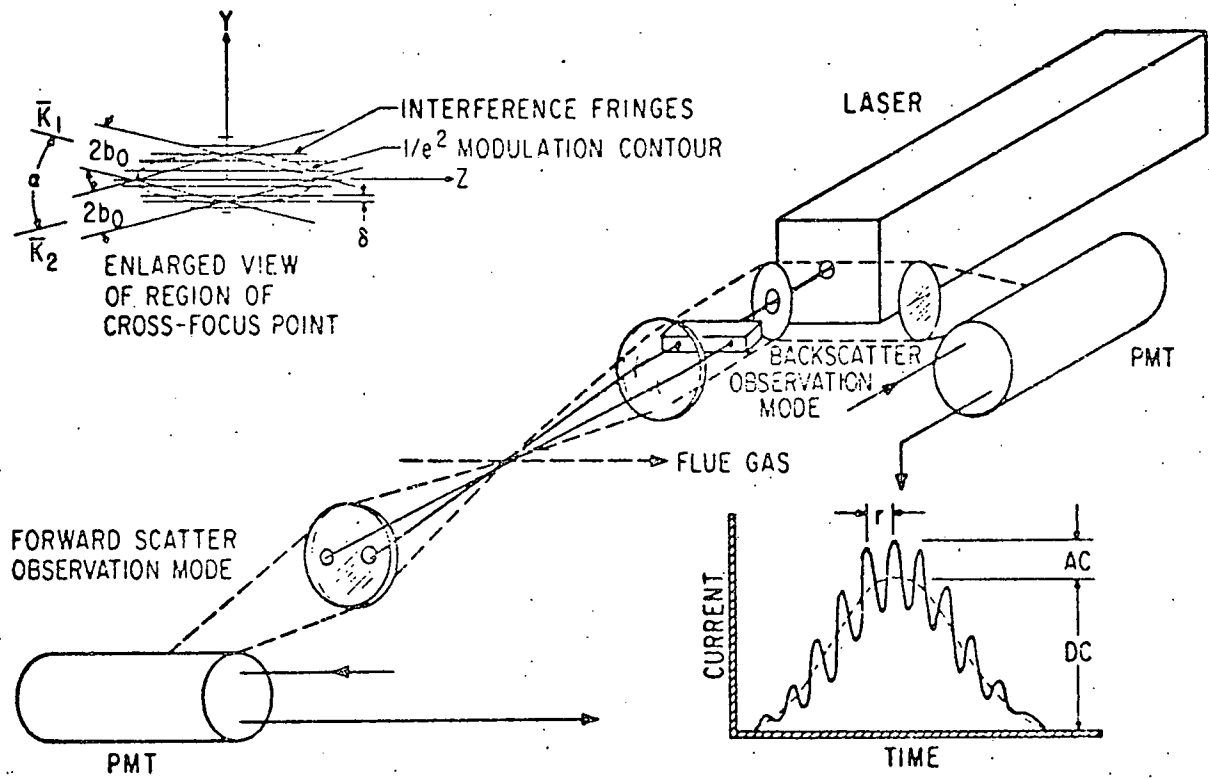


Fig. 1. Spectron Development Laboratory's PM Analyzer System for Velocity and Particle Measurement

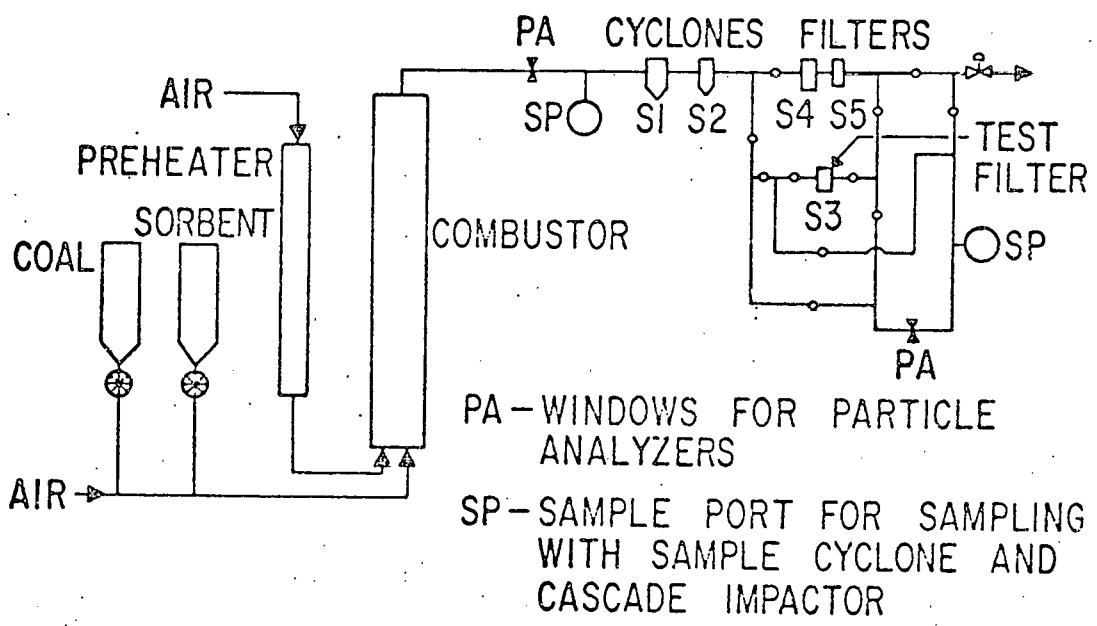


Fig. 2. Schematic of FBC System with Modified Flue-Gas System

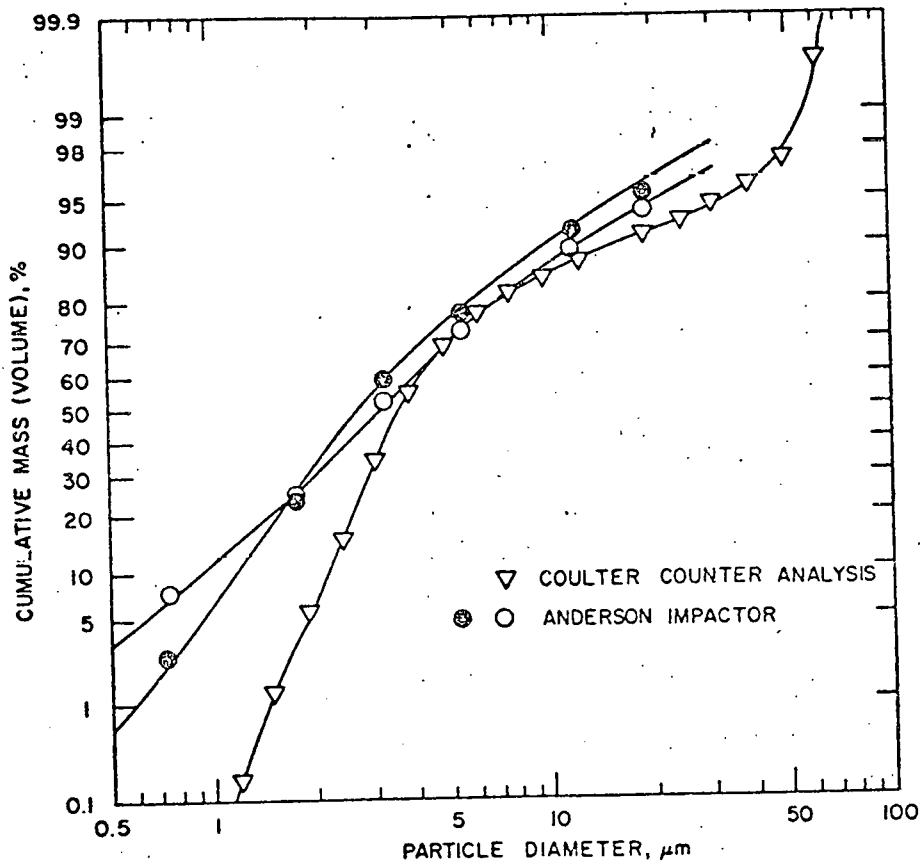


Fig. 3. Cumulative Mass Distribution of Particles in the Flue Gas Between the Secondary Cyclone and the Metal Filter (SGL-2C)

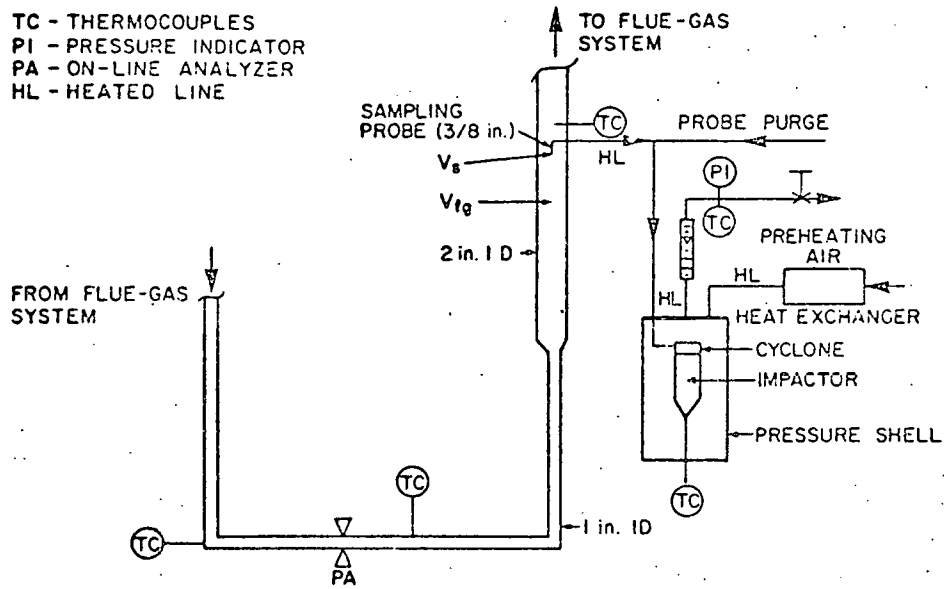


Fig. 4. Flue Gas Particle Sampling System

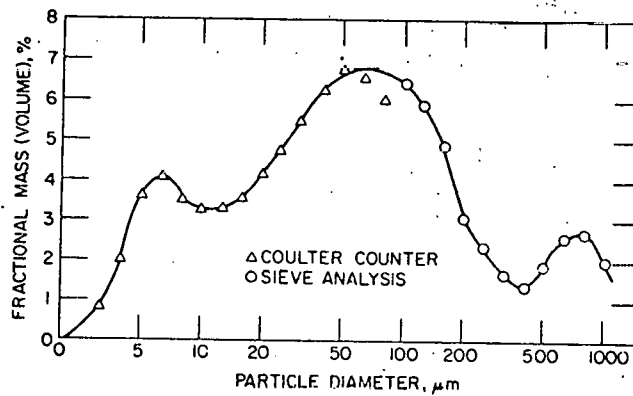


Fig. 5. Fractional Mass Distribution of All Elutriated Particles during a Combustion Experiment (SGL-1) from the ANL FBC Combustor

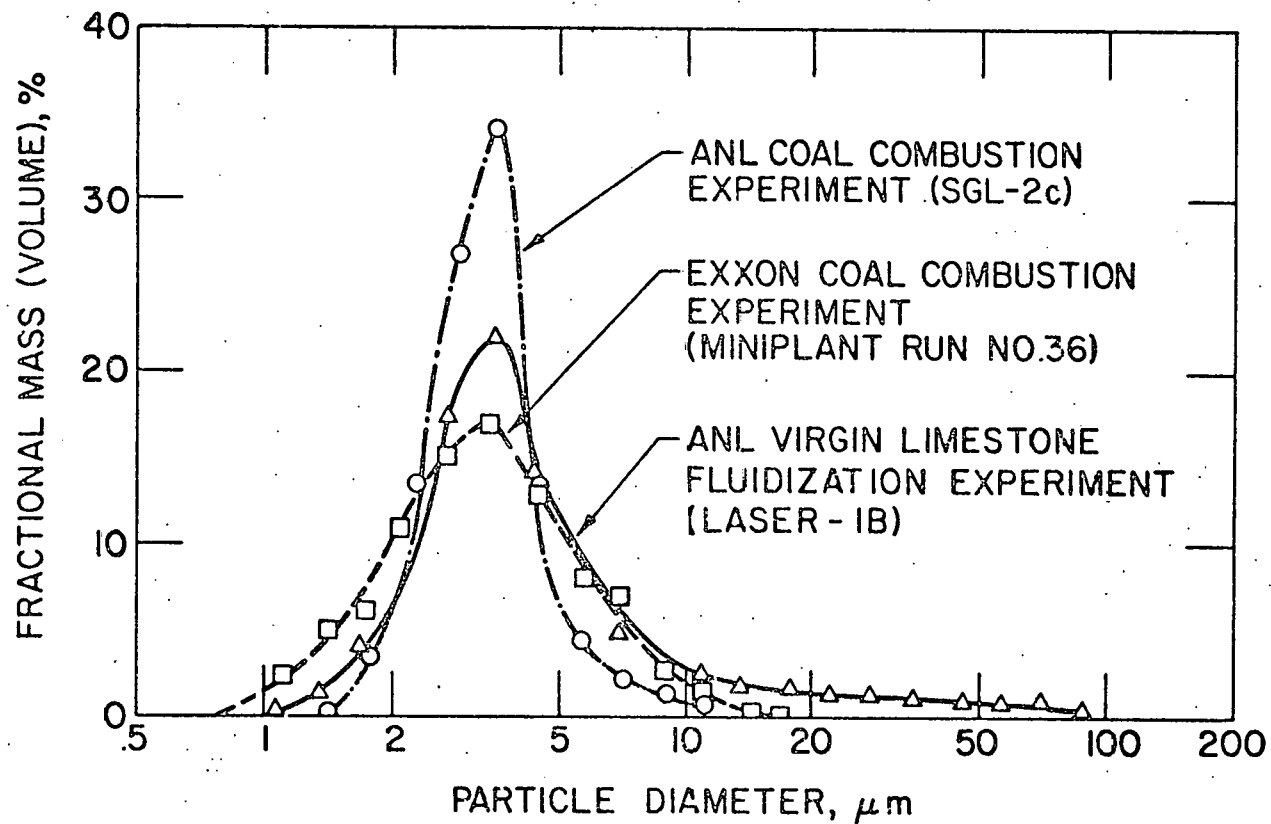


Fig. 6. Fractional Mass Distribution of Particles Escaping FBC Flue Gas System's Cyclones

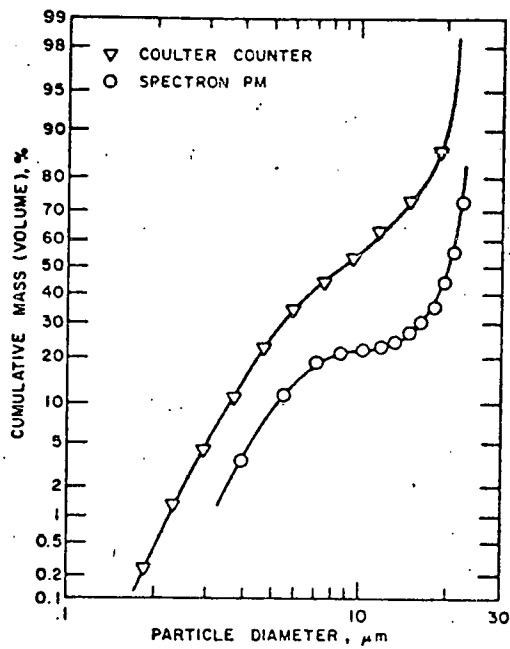


Fig. 7. Comparison of the Partial (1.5-23  $\mu\text{m}$ ) Cumulative Mass Distribution of Particles Leaving the Combustor (SGL-1)

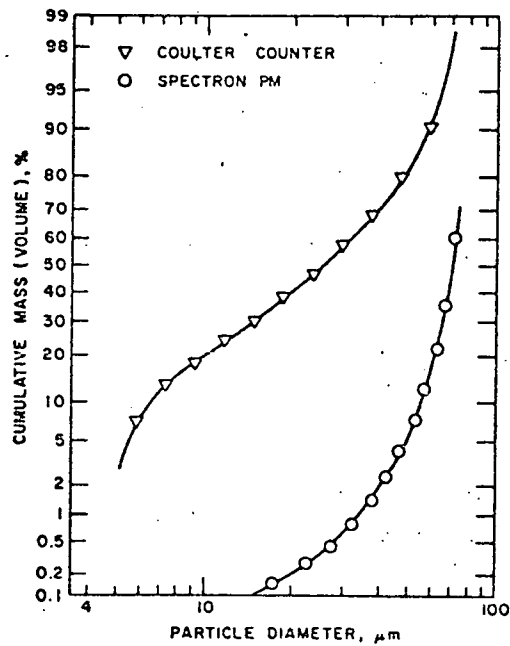


Fig. 8. Comparison of the Partial (5-74  $\mu\text{m}$ ) Cumulative Mass Distribution of Particles Leaving the Combustor (SGL-1)

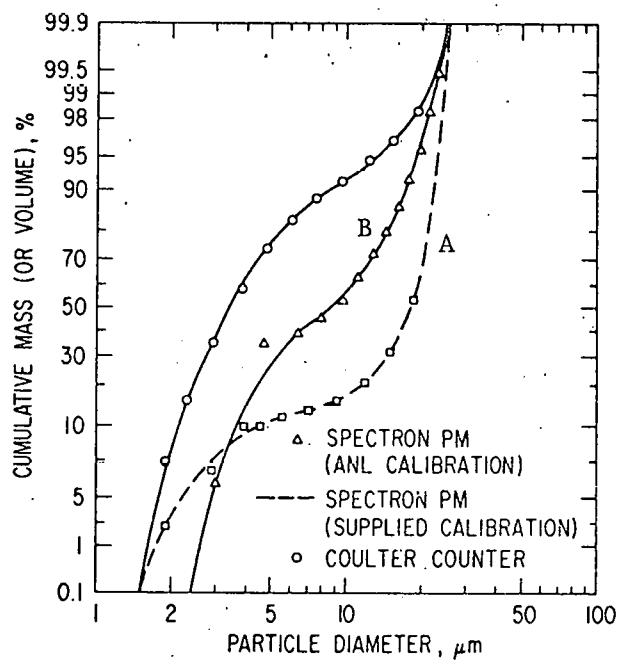


Fig. 9. Comparison of the Partial (1.5-23.8 μm) Cumulative Mass Distribution of Particles Leaving the Secondary Cyclone (SGL-2C)

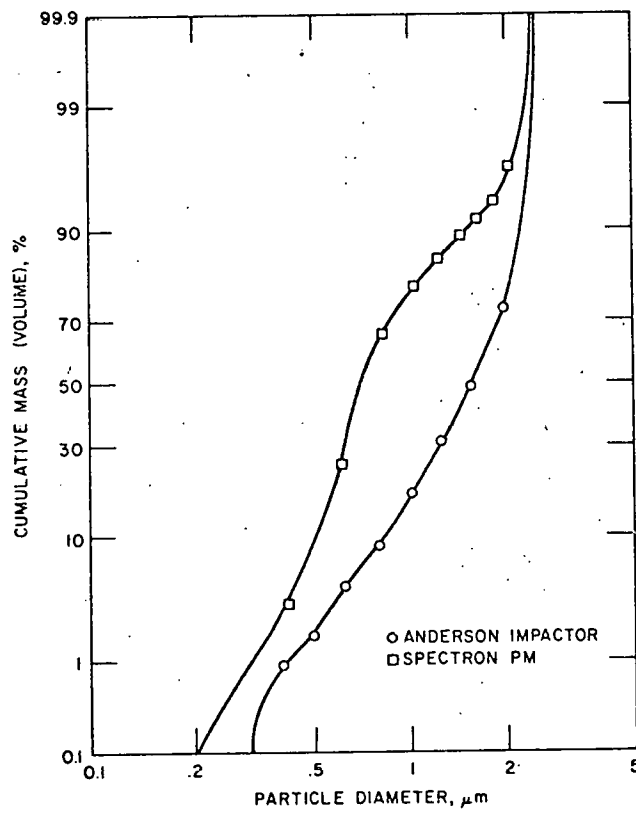


Fig. 10. Comparison of the Partial (0.2-3.1  $\mu\text{m}$ ) Cumulative Distribution of Particles Leaving the Secondary Cyclone (SGL-1C)

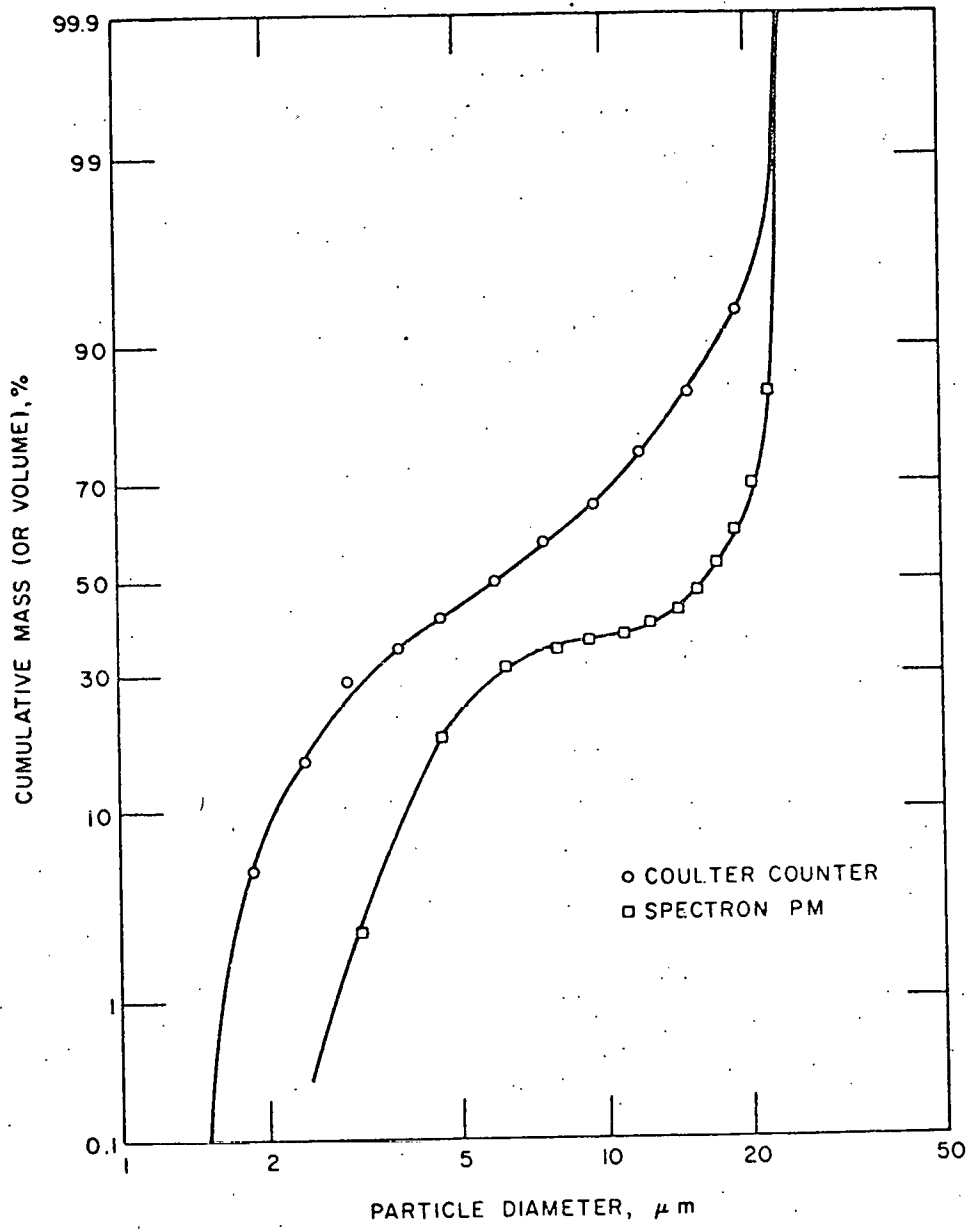


Fig. 11. Comparison of the Partial (1.5-23.4  $\mu\text{m}$ ) Cumulative Distribution of Particles Leaving the Secondary Cyclone during a Cold Fluidization Experiment (LASER-4A-2)

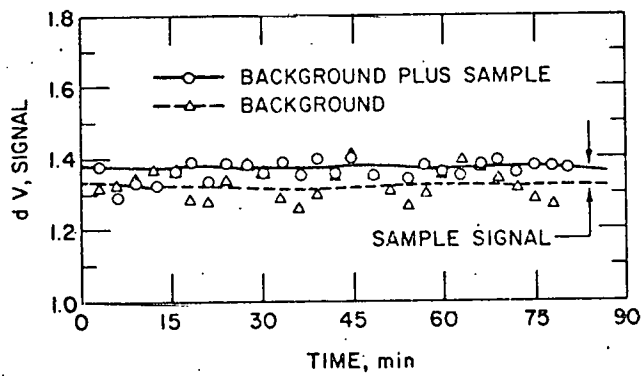


Fig. 12. A Comparison of the Semi-continuous Background Signal with the Background plus Sample Signal from MICROTRAC, Experiment LN-11

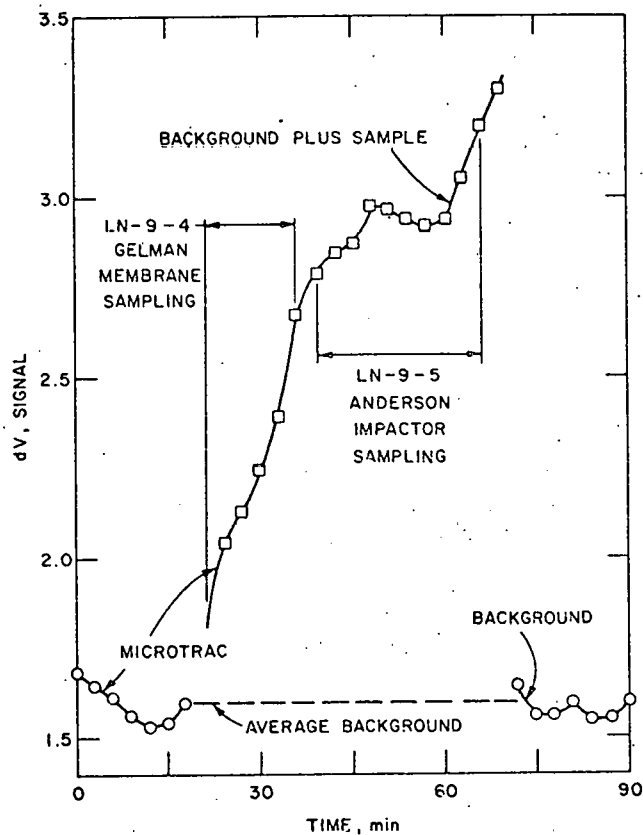


Fig. 13. The Semi-continuous Particulate Loading Signal from the MICROTRAC Particle Size Analyzer for Measurements LN-9-4 and -5