PERFORMANCE TEST RESULTS FROM THE CASCADE IMPACTOR, THE FEDERAL REFERENCE METHOD $PM_{2.5}$ SAMPLER, AND THE IMPROVE SAMPLER

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Abstract

Performance testing was conducted on a Graseby Andersen 8-stage cascade impactor to evaluate it's accuracy. Performance testing was also conducted of a Graseby Andersen federal reference method(FRM) $PM_{2.5}$ sampler and an IMPROVE $PM_{2.5}$ sampler. These two samplers operate on very different principals; the FRM sampler uses jet impaction preseparators and the IMPROVE uses a cyclone preseparator. $PM_{2.5}$ concentrations as measured by the FRM and IMPROVE samplers as well as those determined by the Coulter Counter Multisizer from the TSP and PM_{10} samplers, were not found to be significantly different, when statistically analyzed.

Introduction

EPA promulgated new National Ambient Air Quality Standards (NAAQS) on July 16, 1997 for ozone, and particulate matter(PM) less than 2.5µm, (EPA, 1997). The new NAAQS are controversial (Shaw and Parnell, 1997). A new $PM_{2.5}$ sampler was mandated with the passing of the new PM NAAQS but concerns arose over its accuracy. One of the primary concerns was whether or not the new FRM sampler for measuring ambient concentrations of $PM_{2.5}$, does so accurately. In the initial announcement of the proposed NAAQS (EPA, 1996), EPA stated that the FRM $PM_{2.5}$ sampler is one 'by design' and that there was not sufficient time to conduct in-depth performance tests. With the limited performance data released, the implications of this statement are twofold; Firstly, it is not known whether the sampler *in fact* samples $PM_{2.5}$, or larger particles. Secondly, whatever the sampler does measure, will be used to define the concentration of $PM_{2.5}$ in the area being monitored.

PM concentrations present in ambient air to which the public is exposed are determined gravimetrically from the captured particles on the filter of a sampler. Larger particles weigh more than smaller ones, so that if larger PM is being captured, an inaccurately large concentration of $PM_{2.5}$ will be recorded. No further particle sizing of the captured PM is required by the EPA, therefore whatever is collected by the sampler will be assumed to be $PM_{2.5}$ by definition. (A cutpoint of a sampler by definition, is the mass median diameter(MMD) of the range of particles captured on the filter. i.e. 50% of the distribution should be less than the desired diameter.)

The design of the FRM sampler includes a Well-type Impactor Ninety Six(WINS) (Figure 1a) and a 10µm preseparator(Figure 1b), both of which were designed using similar engineering principles to those of the cascade impactor. This design uses the impaction of a particulate laden jet of air as a method of removing the PM out of an airstream. The authors have done preliminary performance testing of the cascade impactor and based on these results(Buch, et al, 1998), had formulated the hypothesis that the FRM $PM_{2.5}$ sampler based on its design, was in fact inaccurate.

The cascade impactor has been the only EPA reference method of obtaining a particle size distribution(PSD); i.e. a distribution of percent mass versus aerodynamic equivalent diameter(AED). Concerns over it's accuracy and problems with it's performance have been documented over the years and changes made to the original design. Despite these changes concerns over it's accuracy still exist. The results in this report reveal the problems with it's performance as verified by the Coulter Counter(CC) derived PSDs of samples taken from each stage of the impactor.

Particle Sizing Methods

There are a number of methods which can be used to perform PSDs on PM; two of which are the cascade impactor and the Coulter Counter Multisizer(CCM). Other methods have been used that utilize particle *counts* versus particle size, with size based upon microscopic measurements. These methods have some inherent inaccuracies in that only a small number of particles can be counted which may not accurately represent the distribution, and the dimension used to characterize the particle diameter most often is not the AED; If the largest diameter counted is used, the resulting mass of PM in the corresponding size range is obtained by assuming that the characteristic dimension chosen is the diameter of a spherical particle, calculating the volume of that sphere and multiplying it by the particle density (ρ_p). This procedure of obtaining the particulate mass versus AED from particle counts based upon microscopic sizing will likely result in inaccurate PSDs. (Parnell et al, 1999)

Many researchers utilize the Coulter Counter to obtain PSDs of a dust sample however, the CC method is not the EPA reference method, which poses problems with respect to the acceptability of data produced. After performance testing of the cascade impactor and comparing the subsequent PSDs produced to those obtained from the CC method, an equivalence factor was developed. With this factor, one could convert historic cascade impactor PSD data, to a more accurate PSD.

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The Cascade Impactor

The Graseby Andersen 1 ACFM Non-Viable ambient particle sizing sampler (Figure 2a & 2b), was used for our experiments. It is a multi-stage, multi-orifice cascade impactor used to obtain PSDs of ambient or other dust and to measure PM concentrations.

An impactor functions to separate particulate matter out of an airstream by jet impaction. 'Impactors that have a "sharp cutoff" curve approach the ideal step function efficiency curve, in which all particles greater than a certain aerodynamic size are collected and all particles less than that size pass through. As a practical matter, most well designed impactors can be assumed to be ideal and their efficiency curves characterized by a single number $Stk_{50,}$ the Stokes Number that gives 50% efficiency' (Hinds, 1982).

The cascade impactor is a vertical series of individual impactors or stages which correspond to different particle size ranges, as stated in the user's manual. A particulate laden air stream is pulled vertically into the impactor at the controlled flow rate of $1ft^3$/min. The air passes through the series of stages, each stage having a set of multiple orifices creating multiple jets, designed to impart a controlled velocity to the air, which is then directed at a plate below. The momentum of the particles above a pre-calculated size will impact onto the plate directly below the jets. PM smaller than this size remains in the air stream and is carried onto the next stage below. The design of the cascade impactor incorporates the assumption that all particles which strike the plate adhere to its surface, and that there is 100% capture of particles above the predetermined size. The upper limit of the particle size range on each stage will be the predetermined size of the stage above. The size range of the particles collected on each plate decreases with the cascade and the jet velocities increase as a consequence of the smaller orifices with subsequent stages. The lower limit of each plate is determined "by design" using the Ranz-Wong (1952) equation, (Equation 1).

$$\psi = \frac{C\rho_p V_o D_p^2}{18\mu D_c} \qquad \text{(Equation 1)}$$

where C = Cunningham Correction factor $\left(1 + \frac{0.16 \times 10^{-4}}{D_p}\right)$,

ρ_p = Particle density, (g/cm^3);
V_o = Aerosol velocity, (cm/s);
D_p = Particle diameter (AED), (cm);
μ = Viscosity of air, (poise);
D_c = Diameter of the round jet, (cm); and
ψ = Dimensionless inertial parameter, (typically 0.14).

Typically, a cascade impactor is placed in a location and operated for a specified period of time. After sampling is complete, the sample time is recorded and the pre-tared collection media on each plate is removed for subsequent gravimetric, and/or chemical determination. Concentration levels for each stage can be determined, as well as the distribution of particle mass versus AED (Graseby, 1985). This resulting PSD obtained by using the cascade impactor however, will be one "by design" as the particle size ranges are determined by using the Ranz-Wong equation, which may not reflect the actual *performance* of the impactor. As a result, the following are potential problems associated with the cascade impactor PSD:

1.) The user's manual provides the cutpoint for each stage, based upon equation 1 and a particle density of $1.2g/cm^{3*}$ The implication is that these limits are to be used regardless of the density of the particulate being sampled. In actuality, these numbers should change with the particle density of the particulate matter being sampled as the Ranz Wong equation is a function of particle density and is sensitive to this variable.(Marple & Willeke, 1976).
2.) The determined particle size for each stage is not accurate. Matlock (1976) reported that the particle size found on each stage by performance was much larger than the size calculated using equation 1. We have also found this to be true. (Buch et al, 1998)
3.) Particle bounce is a big concern when using a cascade impactor or logically with any other instrument which uses jet impaction, where larger particles then penetrate to lower stages. The resulting PSD of *mass* versus particle diameter (AED), will be in error. This result would suggest that a *larger* mass of fine particulates exist in the lower size groupings, which in fact would not be the case.
4.) Further particle impaction on the mounds of particulate matter created on the plates below each jet[**], can result in smaller particles being collected on a stage associated with larger particles, again resulting in an inaccurate PSD. (It would suggest that a *smaller* fraction or mass of fine particulates exist in the lower size groupings, which in fact would not the case.)
5.) High inlet PM concentrations can affect the performance of the cascade impactor. This condition can result in overwhelming the stages designed to collect larger particles, resulting in carry-over of large particles to lower stages associated with smaller particles.

* This is the density of glycerol, the aerosol media used by Ranz and Wong (1952) to determine ψ = 0.1444.

** Each plate has several small dust laden jets impacting on it, creating small mounds on the plate below each jet.

The Coulter Counter Multisizer

The Coulter Counter Multisizer is an electronic particle sizer manufactured by Coulter Electronics, Inc. which operates on the principle of electrical flow interruption by a particle. It was originally developed for use in hospitals for performing blood counts but is being increasingly used in other technical applications (Richards, 1968). In the application of particulate sizing, the CC method sizes particulate matter with the following procedure:

1.) The dust is dispersed into pre-filtered electrolyte (electrically conductive fluid). The dust and electrolyte are exposed to an ultrasonic bath to facilitate dispersion.
2.) The electrolyte containing the PM is passed through a filter to remove all PM larger than the CC aperture size. (We have been using 50µm and 30µm aperture tubes.) Hence the electrolyte containing the PM to be sized is passed through a screen with 30µm or 50µm openings.
3.) A small sample of the PM in the electrolyte is placed into a beaker containing additional pre-filtered electrolyte. The technician is careful to limit the concentration of PM in the beaker so as to limit to occurrence of coincidence (more than one particle being counted as one).
4.) Electrolyte with PM are moved through the aperture opening. Electrodes are located on both sides of the opening with a constant, controlled electric current. As a particle passes through the aperture, it interrupts the flow of current. The momentary increase in resistance between the electrodes, appears on the Multisizer screen as a pulse. The height of this voltage pulse is proportional to the *volume* of the particle being sensed. 100,000 to 300,000 particles are sized in an individual PSD. Particle sizes may range from 0.4µm to 1200µm, depending on the diameter of the orifice of the aperture tube. Aperture tubes are available with orifice diameters ranging from 15µm to 2000µm (Coulter Counter, 1992).
5.) The results of a CC PSD are PM volume versus equivalent spherical diameter (ESD). In order to obtain a PM mass versus AED, an additional assumption is made. We assume that the particle density is constant for the different size particles which is the same assumption used for the cascade impactor. We convert the ESD to AED by multiplying the ESD by the square root of the particle density. (Cooper and Alley, 1994).

The CC method also has the following inherent criticisms;

1.) One criticism of the CC method is that the process will tend *to increase the fraction of smaller particles in any sample.* There is some logic to this argument. It is likely that some PM in ambient air will enter an air sampler as a conglomerate of small particles. The process of placing the PM sample in an electrolyte and dispersing it in electrolyte utilizing an ultrasonic bath, will likely separate these conglomerates into smaller particles. Hence, the PSD will be skewed toward smaller particulate. (Our results however indicate to the contrary.)
2.) In the measurement of fine particulates, there is speculation that a fraction of $PM_{2.5}$ is as a consequence of combustion. One question we will have to address is what fraction of $PM_{2.5}$ is soluble in the electrolyte. If a significant mass of the $PM_{2.5}$ is dissolved in the electrolyte and is not counted by the CC process, a significant error in the PSD generated could result.

The CC method however, is the only reliable method that we have found to obtain accurate PSDs of PM mass versus AED. To further support of the use of the CC, there have been many criticisms of the use of the cascade impactor as will be referenced throughout this paper, the most common being due to particulate losses within the instrument as well as particle bounce and reentrainment which is known to occur. (Marple & Willeke, 1976;. Willeke, 1975; Rao, 1975; Milford & Davidson, 1987). These losses will adversely affect the PSD generated from the cascade impactor. The cascade impactor is also a very labor intensive instrument to use, requiring constant time consuming cleaning of each stage and taring of several filters for every sample run. The Coulter Counter is less time consuming and annoying to operate and the results are more reliable.

The Federal Reference Method PM2.5 Sampler

The $PM_{2.5}$ sampler used in our experiments was manufactured by Graseby Andersen. (Figure 3). The particulate laden air stream is pulled into the sampler at 0.59 ft^3/min through the PM_{10} Graseby inlet which acts as a preseparator, theoretically trapping 50% of the particulate matter which is 10µm AED or larger. This inlet does not use a collection pad on the impaction plate.

The airstream, mostly devoid of PM_{10} is then pulled through the WINS impactor which contains an oiled Borosilicate glass fiber collection pad, theoretically capturing 50% $PM_{2.5}$. EPA recommends that the pad be oiled in order to minimize substrate overloading and subsequent particle bounce-off experienced by some conventional impactors, by maintaining a continuous wetted surface (Peters & Vanderpool, 1996). The remaining particulate matter is collected on a 46.2mm Teflon filter downstream of the WINS impactor. It is the PM on this filter that is used to determine $PM_{2.5}$ concentrations in the area being monitored.

The PM_{10} preseparator and the WINS impactor both utilize the concept of jet impaction. This would imply that the

problems associated with using the cascade impactor, especially that of particle carryover, can be applied to the $PM_{2.5}$ sampler. It is likely then to find particulate matter significantly larger than by design on the Teflon filter downstream of the impactors.

Methodology

Four sets of experiments were conducted for this research. The first used a $100ft^3$ dispersion chamber with 95% PM_{10} Arizona Road Dust (ARD) (Figure 4), to evaluate the performance of the cascade impactor which was run simultaneously with a TSP sampler in the chamber. Detailed results were published in the 1998 Beltwide proceedings.

The chamber was subsequently expanded to $300ft^3$. Flyash with a higher fraction of smaller PM was then used in order to more closely evaluate the performance of the lower stages of the cascade impactor, where smaller PM is captured, without the potential influence of larger particles penetrating the higher stages. Flyash has the same particle density as Arizona Road Dust but is significantly less expensive. 98% PM_5 was obtained by using a venturi fed, barrel cyclone, the penetrate from which was dispersed in the chamber. Previous research at Texas A&M University, determined the barrel cyclone to be 95% efficient (Flannigan, 1997), (Figure 5a & 5b). The cascade impactor and the TSP were then operated in this 98% PM_5 flyash.

Collection media rather than filters were used in the cascade impactor due to the nature of its operation (no air is pulled through the collection media). Various collection media were used including oiled and unoiled aluminum, plastic and glass fiber. The oil used in all the tests was Dow Corning 704 Diffusion Pump Oil.

A swatch of collection media from each of the cascade impactor stages was then analyzed three times by the CC to produce PSDs for each stage of the impactor. PSDs were not taken of the glass fiber due to the nature of the material, which does not provide for accurate CC PSDs.

The third set up used the same dust and chamber, but a FRM $PM_{2.5}$ and a PM_{10} sampler were run with the TSP sampler (The cascade impactor was removed). The forth set-up used a venturi fed, baffle type preseparator instead of the cyclone, which produced a dust distribution of 56% PM_5, which was fed into the chamber, and an IMPROVE $PM_{2.5}$ sampler was added. The FRM sampler in it's first evaluation had been subjected to dust which was 99% PM_5 so that no dust was allowed to accumulate on the preseparator but all PM impacted onto the WINS impactor. In so doing, potential particle bounce and carryover was eliminated as was potential overloading of the preseparator. The baffle type preseparator allowed the samplers to be subjected to a broader dust distribution.

Concentration of $PM_{2.5}$ on the TSP and PM_{10} samples were determined by multiplying the mass fraction of $PM_{2.5}$ on the filter sample as determined by the CCM, by the concentration of total PM on the filter. The CC PSDs indicated that 67% and 64% of the PM sampled by the TSP and PM_{10} samplers, respectively was $PM_{2.5}$ (The fraction of PM_5 was 99% & 100)

Concentration of particulate matter on a filter was calculated using equation 2;

$$C = \frac{m}{Q \times t} \times \frac{35.31\, ft^3}{m^3} \qquad \text{(Equation 2)}$$

where C = concentration (mg/m3)
m = mass, (mg);
t = time, (mins); and
Q = flowrate, (cfm).

The airtight chamber was constructed of a PVC frame wrapped with plastic sheeting within which the samplers were run, but the dust entrainment systems and the cascade impactor pump remained outside of the chamber. All of the samplers ran for 1 hour sampling periods. The TSP (Total Suspended Particulates) PSD provided the particle size distributions for the dust in the chamber and also allowed for concentration comparisons between the samplers.

All collection media and filters were placed in petri dishes to prevent handling contamination. Prior to all weighing, the collection media and filters were conditioned in a controlled environmental chamber and allowed to equilibrate for 24 hours. The FRM $PM_{2.5}$ samples were weighed in the presence of Polonium-210 antistatic strips. In addition, foil disks were placed under the oiled Borosilicate disks in their petri dishes to control static.

Results

Cascade Impactor Performance Tests

Table 1 contains a summary of cutpoints for particle size ranges for each stage found in the user's manual, as well as for those derived by using the particle densities of ARD and flyash with the Ranz-Wong equation. The AED corresponding to the 15.9 and 84.1 percentiles of the PSDs from the CC process for each stage, with each dust are also shown. The decision was made to use the cutpoints corresponding to 15.9% and 84.1% from the cumulative PSD as the lower and upper limit of the particles size range found on each stage. The bulk of the particles on each stage should then be found between these percentiles which are needed to calculate the geometric standard deviation of the PSD(Cooper & Alley, 1994). It also reduces the volume of data needed for analysis. In comparing the cutpoints, the MMD of the performance values were used.

When the Ranz Wong equation was used so as to reflect the density of the dust used in our experiments; Arizona Road

Dust (ρ_p = 2.6g/cm^3), and flyash (ρ_p = 2.63g/cm^3), the limits were seen to differ significantly from those in the manual; Table 1, columns 2 & 3.

The CC results from the cascade impactor using the ARD/flyash, indicated a relatively wide range of PM sizes, on each stage, in some cases, the upper limit of one stage was larger than the cutpoint of the stage above. The results in Table 1 also show that performance cutpoints using ARD are larger than those specified by the user's manual as well as the Ranz Wong equation for all but stage 1, getting progressively smaller, ranging from 8.2µm on stage 1 to 3.2µm on stage 6.

When operating the cascade impactor in the first set-up with the Arizona Road Dust, the top two stages were seen to overload before the end of the 1-hour test; overloading being a 10mg accumulation of dust on any stage (Graseby, 1985). This overloading would enhance particle bounce and carryover from the top two stages and subsequent deposition onto the stages below, thereby creating an inaccurate particle size range for those stages.

In the second set-up, the finer PM allowed for only very small amounts of dust to be captured on the upper two stages. The cutpoints for these stages are within the fraction of larger PM in the dust distribution that was reduced by the cyclone. Accumulations of dust were found to consist of small particles, 1.5µm-5.7µm on the top two stages. The PSDs derived from the CC of the lower stages showed that the mass median diameter (MMD) for each stage was progressively smaller, ranging from 4.0µm to 1.8µm, from stage 3 down. These performance cutpoints still exceeded those found by the Ranz Wong equation however, indicating that on these stages, larger particles were still being deposited.

Various collection media were used in this set-up as seen in Table 1. Special care was taken with this set-up to keep the loading of each stage under 10mg even with the influence of the top two stages eliminated.

Samples of unaltered ARD and flyash were run through the Coulter Counter and PSDs were obtained. These PSDs were used to determine theoretically, what percentage of an actual impactor sample by mass, would be collected on each stage, which is the expected distribution according to the cutpoints as derived from the Ranz-Wong equation.

Figure 6 shows that for all the collection media used in the Arizona Road Dust set-up, a bimodal PSD was indicated by the cascade impactor, with the 'dip' occurring consistently at stage 3 or at 3µm(Ranz Wong). A dip at stage 3 was also found when the CC PSD of ARD was broken down in to % mass per stage according to the user's manual cutpoints, which corresponds to 4.7µm. The figure also shows that larger than ideal percent masses were collected on stages 2 through F. Comparatively, the Coulter Counter PSD of ARD (Figure 4), as well as the ideal (CCPSD) distribution in Figure 6, both show a single mode distribution peaking at 8µm, which corresponds to stage 1.

The highest percent weight of flyash both by theory and by performance was deposited on Stage 5 of the impactor for the tests conducted with flyash cyclone penetrate, again regardless of the collection media being used(Figure 7).

To compare the effectiveness of the various collection media, log-normal cumulative percent weight curves or efficiency curves were generated for ARD and flyash(Figure 8 & 9) and the mass median diameter (MMD) found as well as the diameters at 15.9% and 84.1% using Engineering Equation Solver (EES). The geometric standard deviation, σ_g which is a ratio of these percentiles gives an indication as to the sharpness of the efficiency curve i.e. how vertical the mid-section of the efficiency curve is. The closer the ratio is to 1, the more vertical or 'sharp' the curve is, and therefore the more efficient the media. (Tables 2a & 2b). Plastic with ARD and oiled plastic with flyash proved to have the sharpest efficiency curves (σ_g =1.72 & 1.59). Using the smaller ranged flyash, (Table 2b), the penetrations curves were less sharp overall.

In both set-ups, glass fiber proved to be the most variable media and provided the flattest efficiency curve, with $\sigma_{g,\,GF,\,OGF}$ ranging from 1.91 to 3.69. Plastic proved to be the most consistent media with both dust distributions given that aluminum was not used with both. Willeke and McFeters (1975) state that glass fiber as a collection medium generally increases the impaction efficiency relative to a smooth surface, but it also decreases the sharpness of the cut of the efficiency curve.

Tables 2a and 2b, show that a relationship can be derived between the Coulter Counter and the cascade impactor efficiency curves by using the ratios of the geometric mass median diameter and the ratio of the geometric standard deviation (σ_g). Oiled plastic for Arizona Road Dust was chosen from the others as it produced the sharpest efficiency curve when exposed to the broader dust distribution.

The relationships derived are:

$$\sigma_{g,\,\text{Cascade Imapctor}} = 1.21\sigma_{g,\,\text{Coulter Counter}} \quad \text{(Equation 3)}$$

$$\text{MMD}_{\text{Cascade Impactor}} = \kappa\text{MMD}_{\text{Coulter Counter}} \quad \text{(Equation 4)}$$

where κ is a range of 0.33 to 0.45;

σ_g is the geometric standard deviation, and
MMD is the mass median diameter (AED at 50%).

The assumption is made when working with the cascade impactor, that the efficiency curve of each stage is ideal; practically 100% capture of all particles greater than that

size. With the Coulter Counter analysis of each stage, the geometric standard deviation(GSD) from the cumulative PSD for each stage was determined(Table 3). The GSDs ranged from 1.39 for stage 1 to 1.22 for stage 6, using ARD and 1.45 to 1.13 from flyash. These numbers do not reflect sharp curves. The closer a GSD is to 1, the more sharp the efficiency curves.

The FRM $PM_{2.5}$ Sampler

The results of the Coulter Counter analysis of the $PM_{2.5}$ filters showed that the flyash collected on the Teflon filters was 88% $PM_{2.5}$ and 97% PM_5. The average particle sizes collected on the filter ranged from 1.7µm(15.9%) to 2.9µm(84.1%), with a MMD of 2.2µm. The actual MMDs for each sample ranged from 2.07µm to 3.82µm. The distribution of dust in the chamber is 80%$PM_{2.5}$ and 99%PM_5.

A statistical analysis of the averages from 5 determinations of $PM_{2.5}$ per sampler for the TSP, PM_{10} and FRM samplers, with a null hypothesis that there was no difference between the three methods of determining $PM_{2.5}$ was performed. The results indicated that there was in fact no significant difference between the three measures of $PM_{2.5}$ concentrations.($\alpha = 0.05$). (Table 4)

Using the baffle type preseparator, the CC analysis revealed the distribution in the chamber to be 87% PM_{10}, 56% PM_5 & 14.% $PM_{2.5}$. In this second evaluation of the FRM sampler, the statistical analysis ($\alpha = 0.05$) of the total FRM and IMPROVE concentrations with the $PM_{2.5}$ concentrations as recorded by the TSP and PM_{10}, also showed no significant difference between the concentrations from the FRM, PM_{10} and TSP, however the $PM_{2.5}$ concentration as measured by the IMPROVE was significantly different from the others. (Table 5). The analysis of the Teflon FRM filters showed the dust collected to be 97% PM_{10}, 93%PM_5 and 53%$PM_{2.5}$.

The Coulter Counter analysis of the filter samples indicate that the MMD for the IMPROVE sampler was 3.8µm, as opposed to the 2.5µm design cutpoint. That of the FRM sampler was 2.7µm.

Discussion

For years, there have been speculations over the accuracy of the cascade impactor. Some of it's operational flaws have been documented. The most significant problems include nonisokinetic sampling, wall losses or interstage losses, particle reentrainment and particle bounce-off from upper to lower stages (Marple & Willeke, 1976). Experimental studies have shown that total interstage losses in a cascade impactor are a function of particle size and are generally about 5-10% In some cases, much higher losses have been found.(Willeke, 1975; Rao, 1975). All of these problems are expected to bias the size distributions in favor of smaller particles and so affect the PSD generated (Milford & Davidson, 1987). The labor intensiveness of it's use is also a complaint. Unfortunately, the cascade impactor is the only method of obtaining a PSD, recognized by the EPA and state air pollution regulatory agencies (SAPRAs).

The Coulter Counter Multisizer method, in our opinion is more accurate and easier to use and more versatile; it can be used on a single TSP filter to obtain concentration measurements of PM_{45} to PM_{fine} including $PM_{2.5}$, from the PSDs generated once the particle density is known. One of the arguments against the use of the Coulter Counter for obtaining PSDs is that an inaccurately large fraction of smaller particles will be represented. Subsequent concentration analysis will not reflect actual conditions. This belief stems from the operational procedure of the CCM where the sample is subjected to dispersion in an ultrasonic bath, which will break up any agglomerates that would occur in ambient air. The results of our tests using flyash show exactly the opposite; The MMDs of the cascade impactor PSDs for all media used was in fact smaller than that of the Coulter Counter (Figure 7) i.e. there is a higher percentage of fine particulates indicated by the cascade impactor PSD than in the Coulter Counter PSD.

Comparison of the flyash PSDs achieved through the cascade impactor regardless of the collection media used, appeared to be the similar. The shape of the cascade impactor PSD also appeared to be similar to that of the CC, one being the translation of the other; Both methods produced a single mode PSD peaking at 60% to 70% mass. Relationships of σ_g and MMD were then developed as equations 3 and 4. These equations can be used to approximate a CI PSD to one that would be achieved by using the Coulter Counter which is more accurate. These relationships have been derived by using an 8-stage impactor, which may not necessarily apply to any other type.

All of the stages show that the corresponding CCM derived cutpoints were larger than those by design using the Ranz-Wong equation, and all but stage 1 by the user's manual. This would indicate that the performance of the cascade impactor does not conform to its design. This would also indicate that if the particle sizing procedure were performed as directed by the cascade impactor's user's manual, that the concentration of PM on the stages 2 through F would be inaccurately large (Stages 7 and F were inadequately loaded and so, the CC procedure could not yield accurate PSDs). Likewise, stage 1 has an CCMMD which is lower than design, therefore concentration calculations would be lower than actual and still unrepresentative.

The limitations of impactors due to particles bouncing off the impaction plate or being blown off the impaction plate after collection are essentially the same; in both cases, particles which should have been collected are reentrained into the airstream. For single stage impactors, this means that the concentration of particles collected on the impaction

plate will be too small. For cascade impactors, the resulting size distribution will be biased toward the fraction of smaller sizes, since reentrained particles will be collected on stages intended to collect smaller particles. (reinforced by Marple & Willeke, 1976)

These results suggested that there may be a problem with respect to the FRM $PM_{2.5}$ sampler, in that it may be sampling a larger than design fraction of larger particulates but recording them as $PM_{2.5}$

One other issue with the design of the cascade impactor is that in reality, only four 90° turns are made by the air stream around each plate in a cascade impactor. It is unlikely that a cut can be made by this change in direction, sharp enough so as to *distinctly* separate the particles out of the air stream and into their respective design cutpoints and collection plates. Some of the authors have conducted numerous tests with cyclones having as many as six turns, which indicate that the sharpness of the efficiency curve is greatly improved with multiple 360° turns.

It was expected that the concentration of $PM_{2.5}$ from the FRM sampler would be larger than that indicated by the CC derived $PM_{2.5}$ concentrations from the TSP and PM10 samplers, for one main reason; Particle carryover was anticipated as was demonstrated by the cascade impactor which would influence the calculated concentration. This was in fact the case.

The explanation for this is that by design, the FRM sampler functions so that 50% of the PM on the Teflon filter is $PM_{2.5}$, meaning that 50% of that PM is larger and 2.5µm and 50% is smaller. Looking at an efficiency curve, if the fraction of larger-than-cutpoint PM which penetrates the preseparator and is captured on the filter(A) equates the fraction of smaller-than-cutpoint PM which is captured by the preseparator and not the filter(B), then it can be assumed that the effective concentration of the PM is virtual. If A is larger than B, a greater fraction of larger PM is penetrating the preseparator onto the filter, than the mass of small PM being captured by the preseparator. The resulting efficiency curve is said to be flatter, which will have larger GSD. This fraction will thereby increase the captured PM weight and subsequent concentration of the PM. The CC analysis will also indicate that the MMD is larger than design. This is the case with the FRM sampler; average MMD =2.7µm and more so, the IMPROVE sampler; MMD = 3.8µm, σ_g =1.23.

The PM_{10} sampler has a performance based design specification that the MMD will be 10µm ± 1µm, with a GSD of 1.4 to 1.6. This range allows for the collection if PM as large as 22µm on the filter, but the MMD must be between 9µm and 11µm. This range also accounts for the fact that impaction type preseparators cannot achieve 100% capture of their design cutpoint. There are no such specifications for the FRM $PM_{2.5}$ sampler. It is assumed therefore that it is to operate at 50% capture of 2.5µm exactly, with no margin of error(the PM_{10} sampler has a 10% margin of error for the MMD). Our results of the $PM_{2.5}$ sampler indicate a performance value of 2.7µm ± 1µm; a 40% margin of error for the MMD!

The fraction of $PM_{2.5}$ on the PM captured by the TSP and PM_{10} samples was determined from the CC analysis of their respective filters, to be 64% for the PM_{10} sample and 67% for the TSP sampler. These fractions were achieved by using the dust which penetrated the 95% efficient barrel cyclone. These fractions also already exceed the necessary 50% collection required by design for a $PM_{2.5}$ sampler. It is possible then, that with a more efficient cyclone, a higher percentage of $PM_{2.5}$ could be achieved in the captured dust, especially as the barrel cyclone is not the most efficient cyclone in use. It is possible then, to scale such a cyclone to be fitted to a PM_{10} or TSP sampler. The resulting sampler could be used to monitor for $PM_{2.5}$ instead of the new FRM samplers being mandated, which would be considerably cheaper, more reliable, less fussy to use and more accurate.

There are several advantages to this. Firstly, using a cyclone preseparator, eliminates the need for an impaction surface and the problems associated with it, as referenced in this paper. Secondly, significantly less dust is captured on a FRM filter which pulls 35.4 ft^3 per hour whereas the TSP/PM_{10} pulls 2,400 ft^3 per hour. The larger resulting mass collected on the filters of the latter samplers in an equivalent time period, significantly reduces the potential for weighing errors associated with trying to *accurately* measure the weight of a small sample. A larger filter and sample also allows for easier handling. The nature of the 46.7mm filter holder for the FRM sampler is such that it is very easy to drop the filter or contaminate the sample upon removal from the holder. The sample loading is also so small that slightest touch from the operator's finger will significantly alter the measure of PM. Seemingly small contaminants will also significantly affect the gravimetric measure of concentration.

From an economical perspective, the new $PM_{2.5}$ samplers cost $5,500 to $13,000 depending on the manufacturer. Each state must buy as many samplers as have been designated as core sampling sites in that state, Texas for example has 65 core sites; 65 sites x $5500 =$357,500 at least, to be spent by the state on new samplers, not including any other costs to be incurred in the installation of these samplers. Additional samplers will also be placed in areas to identify potential "problem areas", or for background information. There are enough TSP and PM_{10} samplers in existence to be retrofitted and cyclones can be cheaply manufactured. Cyclones also produce more reliable, repeatable and accurate results.

Conclusions

1. The cascade impactor is an inaccurate method for obtaining a particle size distribution.
2. The particle size distribution obtained from a Coulter Counter Multisizer is a more accurate.
3. There exists a relationship between the PSDs obtained from the Coulter Counter and the cascade impactor:

$$\sigma_{g,\ \text{Cascade Imapctor}} = 1.21\sigma_{g,\ \text{Coulter Counter}}$$
$$MMD_{\text{Cascade Impactor}} = \kappa MMD_{\text{Coulter Counter}}$$

where κ is a range of 0.33 to 0.45;
σ_g is the geometric standard deviation, and
MMD is the mass median diameter (AED at 50%).

4. It is possible to determine $PM_{2.5}$ concentration from a TSP or PM_{10} sample.
5. There is no significant difference in $PM_{2.5}$ concentration determinations between that obtained from a TSP sample, a PM_{10} sample or from the FRM $PM_{2.5}$ sampler.
6. The size of the particulate matter captured on the Teflon filter of the FRM $PM_{2.5}$ sampler, is 2.7µm AED, when exposed to dust which is 98% $PM_{5.}$
7. A cyclone is preferable to the impaction type preseparator, for a $PM_{2.5}$ sampler.

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Table 1: Summary of the cutpoints for each stage of the impactor, using the user's manual, and the Ranz-Wong equation applied to flyash and Arizona Road Dust. Notation for the collection media: PL, plastic; AL, aluminum and O represents that the media was oiled.

	GLYCEROL	*AZ ROAD DUST-venturi*			*FLYASH-venturi/cyclone*				
			PL	*OPL*	*OPL*	*PL*	*OAL*	*AL*	
Stage	User's Manual	Ranz Wong	Performance CC	CC	Performance CC	CC	CC	CC	
	µm	µm	µm	µm	µm	µm	µm	µm	
	ρ=1.2	ρ=2.6/2.63	ρ=2.6	ρ=2.6	ρ=2.63	ρ=2.63	ρ=2.63	ρ=2.63	
			10.6	10.4	4.4	3.0	-	-	84.1%
1	**9**	**6.8**	**8.2**	**8.0**	**2.8**	**2.0**	**2.9**	**2.7**	**50.0%**
			5.8	5.4	1.9	1.5	1.9	1.4	15.9%
			9.0	9.0	5.7	3.6	-	5.5	84.1%
2	**5.8**	**4.3**	**7.1**	**7.2**	**3.8**	**2.8**	**3.2**	**3.3**	**50.0%**
			5.3	5.3	2.5	1.9	2.0	2.1	15.9%
			8.4	7.5	5.7	4.2	5.4	-	84.1%
3	**4.7**	**3**	**6.3**	**6.1**	**4.0**	**2.8**	**3.7**	-	**50.0%**
			4.7	4.6	2.7	1.6	2.5	-	15.9%
			6.3	6.3	4.8	3.6	4.1	5.2	84.1%
4	**3.3**	**2**	**5.2**	**5.0**	**3.9**	**2.9**	**3.2**	**3.2**	**50.0%**
			4.0	3.9	3.0	2.2	2.5	2.3	15.9%
			5.3	4.7	3.8	2.8	3.4	3.0	84.1%
5	**2.1**	**1.3**	**4.2**	**3.8**	**3.2**	**2.3**	**2.7**	**2.3**	**50.0%**
			3.6	3.1	2.9	1.8	2.2	1.8	15.9%
			6.3	4.3	3.3	2.3	3.1	3.3	84.1%
6	**1.1**	**0.6**	**4.0**	**3.2**	**3.2**	**1.8**	**2.8**	**2.2**	**50.0%**
			3.5	2.9	2.6	1.5	2.3	1.6	15.9%
			-	-	-	2.1	-	-	84.1%
7	**0.7**	***0.4***	-	-	-	**1.6**	**2.0**	**2.2**	**50.0%**
			-	-	-	1.4	1.5	1.6	15.9%
			-	-	-	-	-	-	84.1%
F	0.4	*0.2*	-	-	-	-	-	-	**50.0%**
			-	-	-	-	-	-	15.9%

Table 2a: Geometric standard deviations of the penetrations curves using the various filter media with ARD, from the cascade impactor and compared to those of the Coulter Counter.

ARD ρ= 2.6					
Geometric Deviations by the Ranz-Wong cutpoints					
percentiles	CC=PTI	Opl	Pl	OGF	GF
15.9	3.70	1.27	1.54	0.98	1.48
50	5.86	2.44	2.65	2.15	2.83
84.1	9.28	4.71	4.56	4.74	5.40
(1) 50/15.9	1.58	1.92	1.72	2.19	1.91
(2) 84.1/50	1.58	1.93	1.72	2.20	1.91
CI50/CC50		**0.42**	0.45	0.37	0.48
(1) CIsg/CCsg		1.21	1.09	1.39	1.21
(2) CIsg/CCsg		1.22	1.09	1.39	1.20
		1.22	1.09	1.39	1.21

Table 2b: Geometric standard deviations of the efficiency curves of the filter media using flyash, from the cascade impactor and compared to those of the Coulter Counter.

Flyash	ρ= 2.63						
percentiles	CC	OAL	Al	OPL	Pl	OGF	GF
15.9	1.71	0.86	0.36	0.43	0.37	0.38	0.34
50	2.27	0.45	0.88	0.75	0.87	1.14	0.86
84.1	3.01	1.30	1.67	1.08	1.92	4.98	1.84
50/15.9	1.33	0.52	2.42	1.74	2.35	3.01	2.51
84.1/50	1.33	2.90	1.91	1.44	2.21	4.37	2.14
CI50/CC50	*	0.20	0.39	**0.33**	0.38	0.50	0.38
CIsg/CCsg	*	0.39	1.82	1.31	1.77	2.27	1.89
CIsg/CCsg	*	2.18	1.44	1.08	1.66	3.29	1.61
Ave CI/CCsg		1.29	1.63	**1.20**	1.72	2.78	1.75

Table 3: Geometric standard deviations for each stage of the cascade impactor using 98% PM_{10} ARD and 99% PM_5 Flyash.

ARD	**Cascade Impactor; 8-stage**				
Stage 1 (Pl)	**2**	**3**	**4**	**5**	**6**
5.4	5.3	4.6	3.9	3.1	2.9
8	7.2	6.1	5	3.8	3.2
10.4	9	7.5	6.3	4.7	4.3
1.48	1.36	1.33	1.28	1.23	1.10
1.30	1.25	1.23	1.26	1.24	1.34
1.39	**1.30**	**1.28**	**1.27**	**1.23**	**1.22**
Flyash (OPl)					
1.9	2.5	2.7	3	2.9	2.6
2.8	3.8	4	3.9	3.2	3.2
4.4	5.7	5.7	4.8	3.8	3.3
1.47	1.52	1.48	1.30	1.10	1.23
1.57	1.50	1.43	1.23	1.19	1.03
1.52	1.51	**1.45**	**1.27**	**1.15**	**1.13**

Table 4: Sample average concentrations of PM_{10},, TSP & $PM_{2.5}$ from the FRM sampler.. Column 2 shows the PM2.5 concentration as recorded by the PM_{10} and TSP samplers.

Concentration	mg/m^3	
Sampler	Total Conc	%PM2.5
PM10	6.45	4.13
TSP	7.28	4.88
FRM	5.23	

Table 5: Comparison of PM2.5 concentrations as recorded by 4 different samplers and the particle size characteristics

Concentration	(mg/m^3)		Particle Sizes	(µm)	
Sampler	Total	% PM2.5	15.90%	50%	84.10%
PM10	37.09	**6.37**	-	-	-
TSP	47.1	**6.64**	-	-	-
FRM	**8.2**	-	2	**2.7**	3.6
IMPROVE	**11.43**	-	2.3	**3.8**	6.1

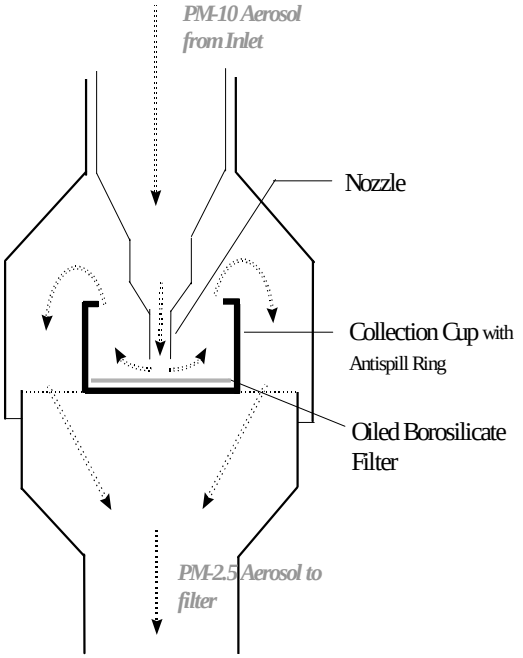

Figure 1a: Enlarged Diagram of the WINS PM2.5 impactor.

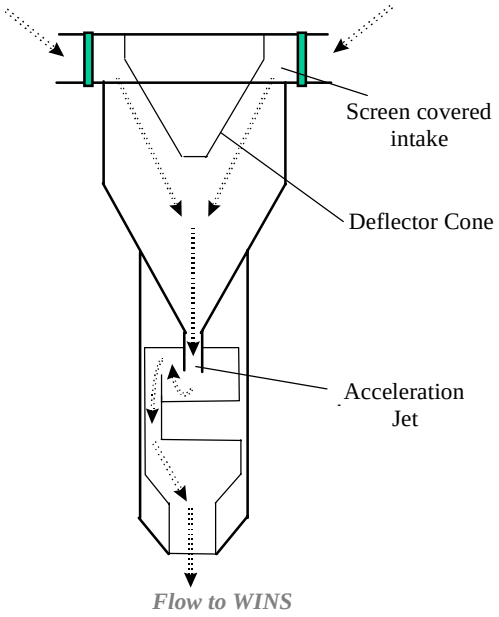

Figure 1b: Graseby Model SA246b PM_{10} "Low Flow" Inlet

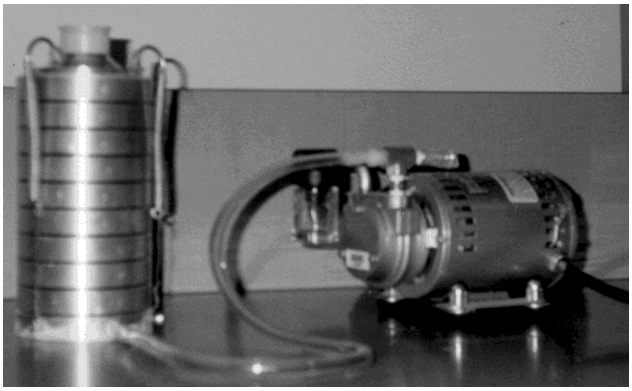

Figure 2a. The Graseby Andersen 8-stage cascade impactor and pump.

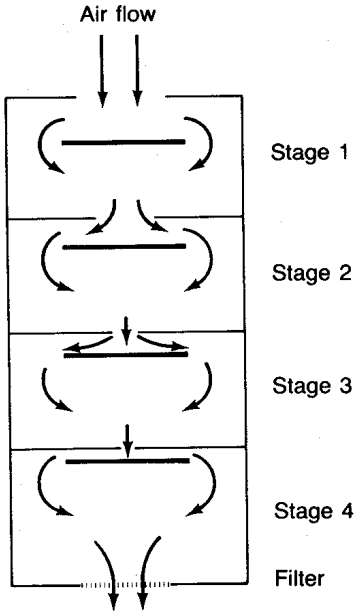

Figure 2b. A basic schematic diagram of the cascade impactor. (Cooper and Alley, 1994)

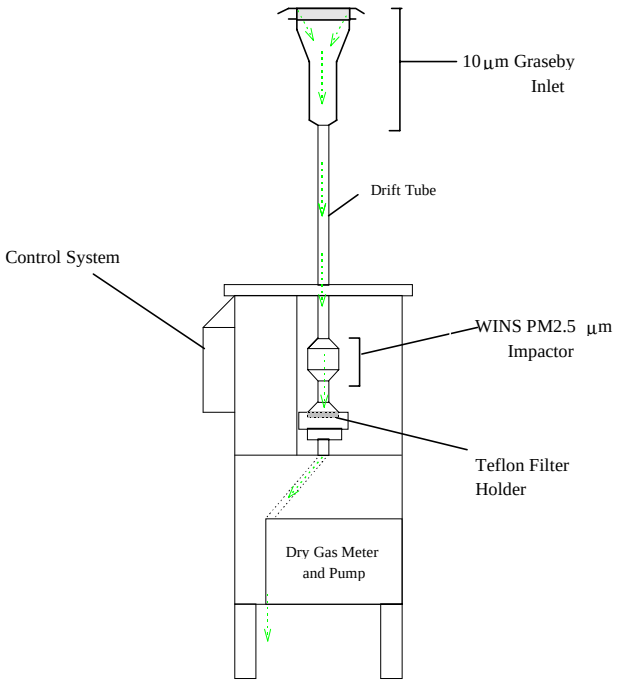

Figure 3: Diagram of the Graseby Andersen FRM PM2.5 Sampler.

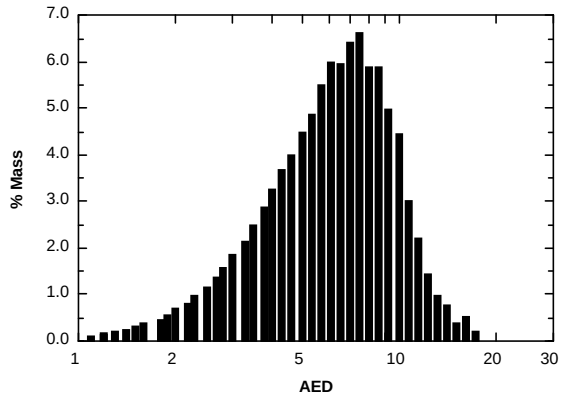

Figure 4: The Coulter Counter PSD obtained from PTI for Arizona Road Dust. Our Coulter Counter produced the same results for the TSP filter.

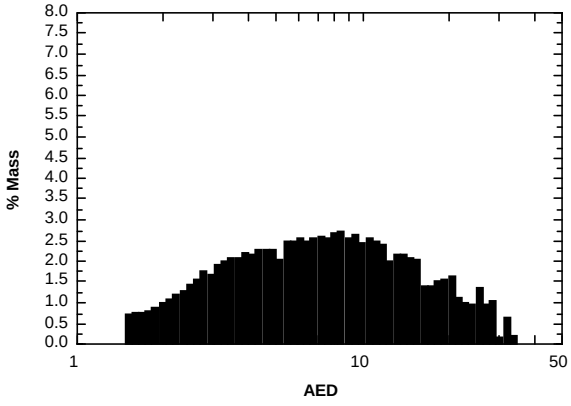

Figure 5a: CC PSD of the Flyash as it enters the barrel cyclone.

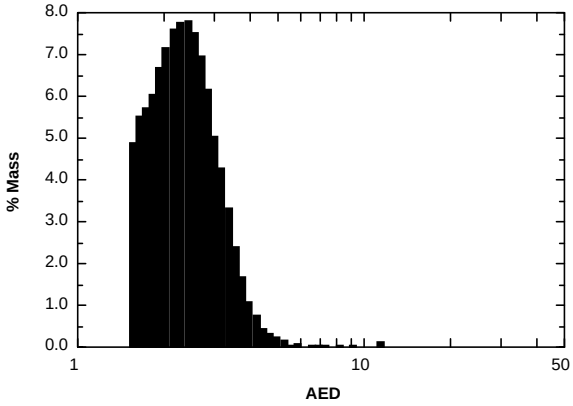

Figure 5b: CC PSD of the cyclone penetrate, entering the chamber.

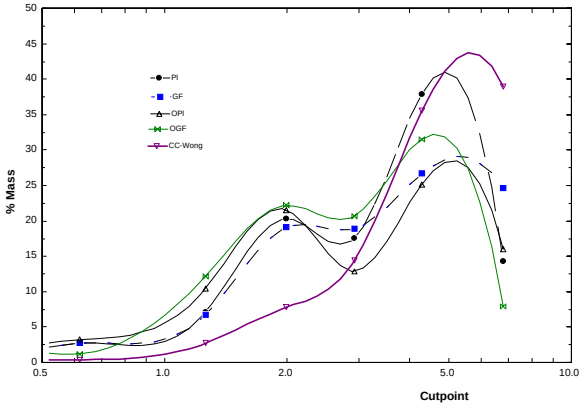

Figure 6: Particle size distribution by performance in each stage, using Arizona Road Dust against that from the Coulter Counter. Notation: GF, glass fiber; PL, plastic and O represents that the media was oiled.

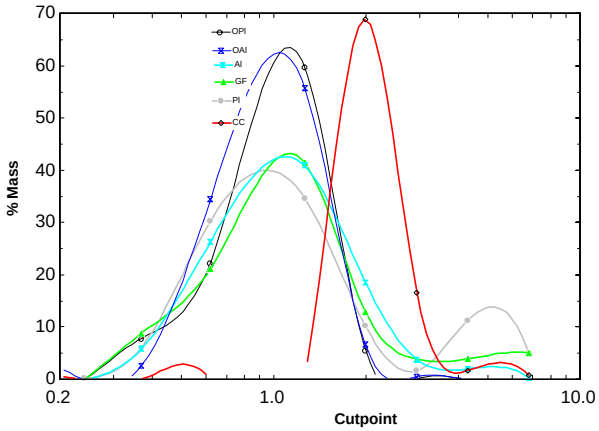

Figure 7: Particle size distribution for each stage of the cascade impactor as compared to the equivalent distribution by the Coulter Counter, using flyash. Notation: GF, glass fiber; PL, plastic, Al, aluminum and O represents that the media was oiled.

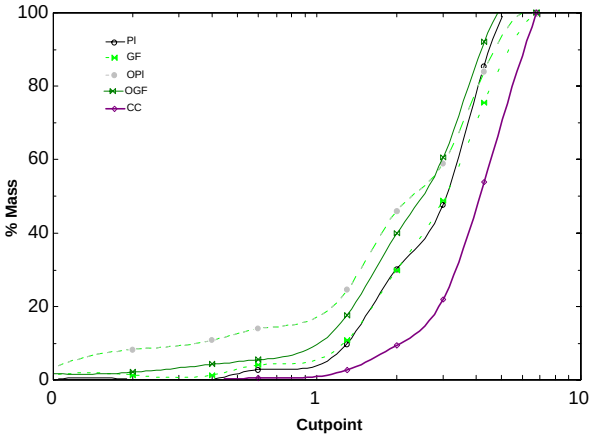

Figure 8: Efficiency curves for the collection media used with ARD. Notation: GF, glass fiber; PL, plastic and O represents that the media was oiled.

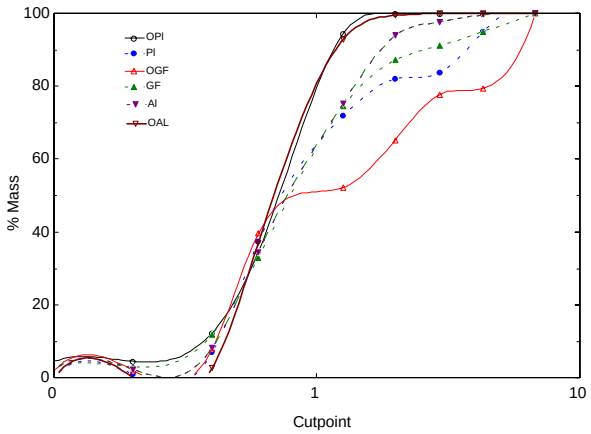

Figure 9: Efficiency curves for collection media using 99% PM5 flyash. Notation: GF, glass fiber; PL, plastic, Al, aluminum and O represents that the media was oiled.