PARTICLE SIZE DISTRIBUTION RESULTS FROM THE COULTER COUNTER MULTISIZER AND THE GRASEBY ANDERSEN CASCADE IMPACTOR.

Usha-Maria Buch, Calvin B. Parnell, Jr., Bryan W. Shaw and Brent Auvermann
Agricultural Engineering Department
Texas A&M University
College Station, Texas

Abstract

There is concern currently over the accuracy of the Federal Reference Method (FRM) PM2.5 sampler, which is used to measure ambient concentrations of particulate matter (PM) less than 2.5 micrometers. The primary concern is that EPA is mandating that the FRM PM2.5 sampler be used to measure ambient concentrations of PM2.5 and that the sampler is a PM2.5 sampler based on "design" rather than by "performance". Very little performance data has been published or released by EPA. This FRM sampler was designed using the same engineering principles as the cascade impactor, which presently, is the EPA approved method for determining particle sizing characteristics such as a particle size distribution (PSD) i.e. a distribution of particle mass versus its aerodynamic equivalent diameter (AED). The only other accessible method to obtain a PSD of PM mass versus AED is by using the Coulter Counter Multisizer (CC). The purpose of this paper is to report preliminary results of PSDs utilizing the cascade impactor and CC. In addition, inferences were made from the results as to anticipated problems relative to the performance of the FRM PM2.5 sampler and its potential inaccuracies.

Introduction

EPA promulgated new National Ambient Air Quality Standards (NAAQS) on July 16, 1997 for ozone and particulate matter less than 2.5µm, (EPA, 1997). The new NAAQS are controversial (Shaw and Parnell, 1997); one of the primary concerns is whether or not the FRM sampler for measuring ambient concentrations of PM2.5, does so accurately. In the initial announcement of the proposed NAAQS (EPA, 1996), EPA stated that the FRM 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 PM2.5 or larger particles. Secondly, whatever the sampler does measure, will be used to define the concentration of PM2.5 in the area being monitored. This measurement would then be used in determining whether an area is in compliance with the NAAQS.

Reprinted from the *Proceedings of the Beltwide Cotton Conference*
Volume 2:1687-1695 (1998)
National Cotton Council, Memphis TN

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. 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 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 a size range is obtained by assuming that the characteristic dimension is the diameter of a spherical particle, calculating the volume and multiplying it by the particle density (ρ_p). This procedure of obtaining PM mass versus AED from particle counts base upon microscopic sizing will likely result in inaccurate PSDs.

The Cascade Impactor

The Graseby Andersen 1 ACFM Non-Viable ambient particle sizing sampler (Figure 1a), is a multi-stage, multi-orfice cascade impactor. It has been used to obtain PSDs as well as to measure PM concentrations.

The impactor functions to separate the particulate matter using a series of stages corresponding to different particle size ranges. A particulate laden air stream is pulled vertically into the impactor at a controlled flow rate. The air passes through a series of orifices designed to impart a controlled velocity to the particle laden air directed at a plate. The momentum of the particles above a calculated size will impact the plate directly below the orifice. In theory, PM smaller than this size remain in the air stream to the next stage. The velocities increase as a consequence of smaller orifices (jets) for subsequent stages. The lower limit of PM impacted onto the circular plate ('cutpoints') is determined "by design". The impactor is a series of eight such stages and impaction plates with each stage consisting of 96 to 201 air jets, followed by an impaction plate. (See Figure 1b). The particle size range for each plate will decrease with the cascade. The lower limit of the particle size that should be collected on each plate is determined by the Ranz-Wong (1952) equation (Equation 1). This will be the size of the smallest particle that will impact onto each stage. For every stage however, there will be a *range* of particle sizes between the 'cutpoints' of two consecutive stages, which will impact onto the lower of the two. The first stage (Stage 1), will collect all particles larger that it's 'cutpoint'.

$$\psi = \frac{C\rho_p V_o D_p^2}{18\mu D_c} \qquad \text{(Equation1)}$$

where C = Cunningham Correction factor $\left(1 + \frac{0.16\times10^{-4}}{D_p}\right)$

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
ψ = Dimensionless inertial parameter, (typically 0.14)

The expression that was used by EPA in describing the FRM PM2.5 sampler as a PM2.5 sampler "by design" was in reality utilizing the Ranz Wong equation to design a pre-separator section that would allow PM less than 2.5 micrometers to penetrate to the filter with PM larger than 2.5 micrometers being impacted in a manner similar to the cascade impactor.

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 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). In effect, the resulting PSD from a cascade impactor is one "by design" as the particle size is determined using the Ranz-Wong equation, which may not reflect the actual performance of the impactor. As a result, there are potential problems associated with the cascade impactor PSD:

1.) The user's manual provides the lower limit particle diameter for each stage ('cutpoints'), based upon equation 1 and a particle density of $1.2 g/cm^3$* The implication is that these 'cutpoints' are to be used regardless of the density of the particulate being sampled. In actuality, these 'cutpoints' should change with the density of the particulate being sampled as the Ranz Wong equation is a function of particle density and is very sensitive to this variable.
2.) The determined particle size for each stage is not practically accurate. Matlock (1976) reported that the particle size found on each stage by performance was much larger than the size calculated using equation 1.
3.) Particle bounce is a concern when using a cascade impactor (Graseby, 1985), with larger particles penetrating to a lower stage. The resulting PSD of *mass* versus particle diameter (AED), will as a consequence be in error as it 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 $\iota = 0.1444$ was glycerol.

** 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. It 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 typically use the 100µm aperture tube. Hence the electrolyte containing the PM to be sized is passed through a screen with 100µm openings.
3.) A small sample of the PM/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 the particle passes through the aperture, it interrupts the a 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 particles within that size range 100,000 to 300,000 particles are sized in an individual PSD. Particle sizes may range from 0.4µm to 1200µm, depending on the orifice tube aperture diameters. Aperture tubes are available with aperture openings 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 in electrolyte utilizing an ultrasonic bath will likely separate these conglomerates into smaller particles. Hence, the PSD will be skewed toward smaller particulate.
2.) In the measurement of fine particulates, there is speculation that a fraction of PM2.5 is as a consequence of combustion. One question we will have to address is what fraction of PM2.5 is soluble in the electrolyte. If a significant mass of the PM2.5 is dissolved in the electrolyte and is not counted by the CC process, a significant error could result.

The CC method however, is the only reliable method that we have found to obtain accurate PSDs of PM mass versus AED.

Methodology

The set up used to investigate the cascade impactor consisted of a 100ft^3 dispersion chamber, constructed of a PVC frame and polyurethane sheeting. The cascade impactor and a Hi-Vol TSP sampler were run simultaneously in this chamber for 1 hour measurements of concentrations. A re-sealable entrance was put into one side of the chamber to allow access to the samplers, but which also allowed for any pressure equalization. Dust was fed into the chamber by means of a venturi dust feeder. The air was supplied by alternating two, 1/3 hp compressors. An orfice meter was placed in line between the compressors and the venturi to ensure the correct flowrate was maintained. (Figures 2,3,4). The dust was maintained in circulation within the chamber by the exhaust of the Hi-Vol TSP sampler which operated at 40 cubic feet per minute (CFM). Another orfice meter was placed inline with the Hi-Vol sampler to maintain this flowrate.

Concentration calculations were performed after a series of tests to ensure that the two samplers were operating in similar dust concentrations. Each piece of equipment was calibrated prior to its use.

Collection media rather than filters are used in the cascade impactor due to the nature of its operation. Initially, polyweb was used as the collection media in the impactor because it produces a lower background count than the recommended glass fiber collection media, when analyzed by the Coulter Counter. Polyweb however, is hygroscopic which creates problems during the weighing process, as any absorbed moisture counts toward the mass of the particulate matter on the media. The EPA pre-conditioning protocol for Polyweb was used, and all weighing was done in a controlled environmental chamber. Despite this, difficulties were encountered between the pre- and post- sampling weights.

Instead of Polyweb, the collection media chosen was plastic transparency film designed for use in photocopiers. These transparencies differ from regular ones in that they are coated with a clear film to help ink dust adhere to the surface of the plastic. The plastic also produced practically no background count with the CC. The plastic swatches for each impaction plate were weighed both before and after the sampling in a petri dish to reduce contamination and fly-away of particles. The sample of dust on each swatch was then analyzed three times by the CC to produce PSDs for each plate of the impactor. Arizona Road Dust (ARD) of approximately 95% PM10, was obtained from Powder Technology Incorporated (PTI) and used throughout the sampling.

Results

As previously stated, the 'cutpoints' as set by the user's manual for each stage of the cascade impactor, are derived by using a particle density of 1.2g/cm^3 and the Ranz-Wong equation. When the equation was used so as to reflect the density of the dust used, Arizona Road Dust (ρ_p = 2.6g/cm^3), the 'cutpoints' were seen to differ significantly. (Table 1.)

Table 1 contains a summary of the 'cutpoints' found in the user's manual, those derived by using Arizona Road Dust, with a density of 2.6g/cm^3 and the Ranz-Wong equation, as well as those found by using the PSDs from the CC process for each stage. The CC PSDs of the PM on each stage of the cascade impactor indicated a relatively wide range of PM sizes, on each stage. Rather than compare the entire range, we chose to use the lower limit as 15.9% and the upper limit as 84.1%. These are the two sizes, determined at the geometric standard deviations (σ_g). The bulk of the particles on each stage should be found between these deviations and can be used because the PSDs are log-normal distributions (Cooper and Alley, 1994), as seen by the bell curves in Figures 6 through 13.

The results in Table 1 also shows that there is considerable overlap between the expected particle size range between any two *design* cutpoints, and the actual range based on the PSDs. For example, on the second stage, the range "by design" is 4.3µm-6.8µm whereas by performance it is 5.3µm-9.0µm.

Some of the PSDs shown are not complete bell curves due to limitations of the Coulter Counter that was used. We do know however that 9.29% of the Arizona Road Dust (ARD) PSD supplied by PTI, is smaller than 3µm. (Also derived from a CC). The PSDs shown below, derived from the CC do show however that for each stage there exists a full range of particle sizes.

A sample of ARD was run through the CC that was used with these tests, and a PSD derived from it. It was found that this PSD was practically identical to that from PTI. The PTI PSD was then used to determine what percentage of an actual impactor sample by mass, would be collected on each *stage.* Table 2 shows the ideal percentage distribution on each stage using *design* cutpoints. This is the expected distribution according to cutpoints derived from the Ranz-Wong equation with a particle density of 2.6g/cm^3. Table 3 uses the same PSD and the *performance* cutpoints derived from the CC analysis of the impactor stages. An analysis of the particle concentration on each stage of the impactor was calculated using the mass percentages by stage, and multiplying by the concentration of dust in the chamber during sampling. Table 4 shows this distribution based on the mass actually collected in the cascade impactor.

Discussion

Table 1 shows significant discrepancies between the lower limits using the cutpoints derived from the user's manual (ρ_p = 1.2g/cm^3), the Ranz-Wong equation (ρ_p = 2.6g/cm^3), and the CC PSDs for PM captured on each stage. According to the user's manual, the lower limit of PM on the first stage should be 9µm whereas the lower limit of PM size for the first stage using the Ranz-Wong equation was 6.8µm. The lower limit found on stage one based on the CC PSD was 5.8µm. It is possible that this smaller actual value was a result of the CC method, i.e. breaking up of conglomerates of PM into smaller particle sizes due to the ultrasonic bath dispersion or it may be a result of small particles becoming trapped in the 'mounds' of the first stage. All of the following stages however, show that the corresponding CC 'cutpoints' were larger than the lower limits determined using the Ranz-Wong equation. 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, using the prescribed cutpoints without the insight provided by the CC, that the concentration of PM on the stages 2 through F would likely include particles larger than should be collected theoretically. For example, the upper limit of PM on stage 2 was 6.8µm (according to the Ranz-Wong equation) and the CC PSD indicated that upper limit was 9µm; stage 3, 4.3µm versus 8.4µm; stage 4, 3µm versus 6.3µm; stage 5, 2µm versus 5.3µm; etc.

These results suggest that we may have a relatively large problem with respect to the FRM PM2.5 sampler. If the pre-separator for the FRM PM2.5 sampler allows PM 5.3µm or larger to penetrate to the filter, the measurement of concentrations of PM2.5 may in reality be a measurement of PM 5.3 or larger.

We believe that stages 7 and F were inadequately loaded and so, the CC procedure could not yield accurate PSDs. This may account for the inconsistent particle size ranges and PSDs for these stages.

The size ranges of PM found on each stage using the CC were relatively wide: stage 1, 5.8 - 10.6µm; stage 2, 5.3 - 9.0µm; etc.. (See Table 1 and Figures 6 - 11.) This wide range of PM on each stage may be the result of a relatively flat penetration curve associated with the design of the cascade impactor. In reality, only one turn is made by the air stream around each plate in a cascade impactor. It is unlikely that a sharp cut can be made by this single change in direction and may then be insufficient so as to *distinctly* separate the particles out of the air stream and into their respective design cutpoints and collection plates. The authors have conducted numerous tests with cyclones having as many as six turns. The sharpness of the penetration curve is improved with additional turns.

The wide range of PM on each stage may also be due to small particles becoming trapped on the first stage thereby increasing the represented percent mass. In so doing, the lower stages are deprived of the smaller particles that should be there, decreasing the represented percent mass. This would also partly explain why a significant amount of small particles are seen on the upper stage CC PSDs.

Table 2 lists the results of projecting the mass of PM that should have been deposited on each stage of the cascade impactor based upon the CC PSD provided by Powder Technology Inc. (PTI) and the size ranges associated with the Ranz-Wong 'cutpoints'. (The PTI PSD was provided to us as a mass versus ESD PSD. We converted this PSD to mass versus AED prior to estimating the mass of PM that should have been deposited on each stage.) The concentrations of PM in the various size ranges are included. Similarly, the projected mass of PM on each stage based upon the lower size limits obtained from the CC PSDs performed on PM collected on each stage are listed in Table 3. These distributions can be compared with the assumption that the single turn around each plate is sufficient in separating the particles effectively. The following observations were made:

1.) A different PSD would result if the 'cutpoints' are determined from performance data (Table 3) as compared to design data (Table 2). For example, 63% of the Arizona Road Dust (ARD) PM would be collected in stage 1 using the CC

'cutpoints' versus 46% that should have theoretically been collected on stage 1.

2.) The concentration of PM in the size range represented by stage 1 would be underestimated ($40mg/m^3$ versus $54mg/m^3$) if the design 'cutpoints' are used versus the performance 'cutpoints'. Accordingly, the concentrations associated with the smaller PM ranges will be over-estimated.

These results suggest that if a user were to use the design data (Table 2) for the cascade impactor with the assumption of a sharp 'cut' at each stage, a lower than actual fraction of PM would be indicated on the first stage. This would result in higher than actual concentrations for smaller PM. (lower half of the impactor stack).

Table 4 shows the results from tests conducted in the lab with the cascade impactor in a chamber with controlled concentrations of ARD. The mass fractions (percentages) and calculated concentrations are listed. Comparing Tables 2 and 4, it can be seen that stage 1 had a significantly lower mass fraction (13.6%, Table 4) than would be expected using the projected mass with design cutpoints (46%, Table 2). It could be said that the top stage, "by performance" is underloaded and stages 2 through F, overloaded according to its design limits. The immediate explanation is that this was a consequence of particle bounce. This may not however, be the only reason. The penetration of larger PM that should impact and remain on stage 1 may also be a result of these larger particles not impacting at all but remaining entrained and eventually depositing on lower stages of the impactor as a consequence of the relatively flat penetration curve. This can again be related to the possible ineffectivity of the single turn in appropriately distributing particles by size. This would occur irrespective of particle bounce.

Bi-Modal Dust Distribution

The EPA's OAQPS (Office of Air Quality Planning and Standards) Staff Paper, 1996 refers to a bi-modal particle size distribution from which there is clear dip in the PSD at 2.5µm, producing two distinct modes of particles on either side of 2.5µm. (Figure 14). It is assumed that the cascade impactor was used to obtain this distribution, as it is the EPA approved method. This distinction in the PSD was used in the selection of 2.5µm for the new NAAQS.

From the stage weight distributions of the cascade impactor used in our tests, despite the heavy loading, a clear bi-modal distribution of the particles *was* seen in four out of five samples. The 'dip' however, occurs on the third stage of the impactor which corresponds to a 'published' cutpoint of 4.7µm, and a recalculated cutpoint of 3µm. The CC PSDs which have been performed do not show this bi-modal particle size distribution. It is thought therefore that this bi-modal distribution is a result of the performance of the cascade impactor rather than the dust itself. Furthermore, based on the performance results and the CC PSD, the second mode may be due to the natural carryover of the larger particles themselves, as stated earlier.

Conclusions

Having an accurate particle mass distribution is imperative to the determination of particulate matter concentrations. These mass distributions can also be used to test the performance of a sampler, designed to sample a *specific* particle size i.e. the FRM PM2.5 sampler. Hence, having a reliable reference method of determining a particle matter mass versus its aerodynamic equivalent diameter, will ensure that sampling procedures and measured concentrations accurately depict ambient conditions.

Based on the research presented in this paper, we believe that the EPA approved method of obtaining a distribution of PM mass versus AED, the cascade impactor, is not accurate. In addition, we have the following observations and conclusions:

1.) The 'cutpoints' as set by the user's manual for each stage of the cascade impactor, do not reflect the effect of density of the PM being sampled. The lower limits of the particle size range on each stage are however, a function of particle density as stated by the Ranz-Wong equation. The resulting PSD determined by using the user's manual 'cutpoints' will therefore not be accurate.

2.) The cascade impactor performance results including the CC PSDs of PM captured on each stage as well as the mass of PM captured on each stage in the laboratory tests were significantly different from the anticipated results, in accordance with the performance "by design". The relatively wide ranges of PM on each stage suggest that the single turn made by the jet of air directed at an impaction plate results in a relatively flat penetration curve, so allowing larger particles to penetrate to lower stages. The associated overlaps in the particulate size ranges from stage to stage are a result of the ineffective design of the cascade impactor.

3.) It is possible that the bi-modal distribution as described in the EPA Criteria Document is a result of the performance of the cascade impactor rather than the particulate matter itself, and so is not an accurate representation of the PSD of PM in ambient air.

4.) The design of the FRM PM2.5 is identical to the design of the cascade impactor. Based on the preliminary performance of the cascade impactor with respect to its design specifications, it is likely that there are potential problems with the FRM PM2.5 sampler. It is

possible that the FRM PM2.5 sampler will sample particles larger than 2.5µm, this inaccurate measure will then be used to define the concentration of PM2.5 for the area being monitored.

Future Research

Building on this research, our future work will focus on obtaining performance data of the FRM PM2.5 sampler and the "Improve" PM2.5 sampler used by the Crocker Laboratory at U.C. Davis. We will be studying the bi-modal distribution results observed from our laboratory tests of the cascade impactor, which correspond to bi-model distributions of ambient air reported by the EPA but were not observed on the Coulter PSDs. A more concentrated evaluation will also be conducted on the CC PSDs associated with the lower stages (Smaller PM) of the impactor. (New CC aperature tubes will be used to obtain the CC PSDs, below 3µm.)

References

Cooper, C.D and Alley, F.C. 1994. Air Pollution Control: A Design Approach. 2nd Edition. Waveland Press Inc. Prospect heights, Illinois.

Coulter Electronics, Inc. 1992. Coulter Sample Stand II Product Reference Manual for the Coulter Counter Multisizer. Coulter Electronics, Inc. Hialeah. Florida.

Environmental Protection Agency, 1996. 40CFR Part 50. National Ambient Air Quality Standards for Particulate Matter; Availability of Supplemental Information and Request for Comments; Final Rule, Part II. Federal Register, Vol.61, No. 241.

Environmental Protection Agency, 1997. 40CFR Part 50 National Ambient Air Quality Standards for Particulate Matter; Final Rule, Part II. Federal Register. Vol. 62, No. 138. EPA, Washington. D.C.

Graseby Andersen. 1985. Operating Manual for the Andersen 1 ACFM Non-Viable Ambient Particle Sizing Samplers. Graseby Andersen, Smyrna, Georgia.

Matlock, Stanley. 1976. Evaluation of the Modified Andersen Sampler for Determining Particle Size Distributions and Respirable Concentrations of Particulate Matter Present in the Working Environment of Cottonseed Oil Mills. Master of Science Thesis. Texas A&M University, College Station, Texas.

Office of Air Quality Planning and Standards. Environmental Protection Agency, 1996. Review of the National Ambient Air Quality Standards for Particulate Matter: Policy Assessment of Scientific and technical Information. Research Triangle Park, North Carolina.

Ranz. W.E and Wong. J.B. 1952. Jet Impactors for Determining the Particle Size Distributions of Aerosols. American Medical Association archives of Industrial Hygiene and Occupational Medicine. American Medical Association. Vol.5 No.5. Chicago, Illinois.

Richards, M. 1968. The Evaluation of Filter for the Royal Navy. Filtration & Separation 5(1):509.

Shaw, B,W and Parnell, C.B Jr. 1997. PM2.5 Emissions from Agricultural Operations. ASAE Paper No. 974097. Minneapolis, Minnesota.

Table 1. Summary of 'cutpoints' for each stage of the impactor, using the user's manual (column 2), the Ranz Wong equation (column 3), and the CC PSDs from each stage of the impactor.

Stage	User's Manual	Ranz-wong	Actual CC	
	µm	µm	µm	
	ρ=1.2	ρ=2.6		
1	**9**	**6.8**	10.6 **8.2** 5.8	84.1% 50.0% 15.9%
2	**5.8**	**4.3**	9.0 **7.1** 5.3	84.1% 50.0% 15.9%
3	**4.7**	**3**	8.4 **6.3** 4.7	84.1% 50.0% 15.9%
4	**3.3**	**2**	6.3 **5.2** 4.0	84.1% 50.0% 15.9%
5	**2.1**	**1.3**	5.3 **4.2** 3.6	84.1% 50.0% 15.9%
6	**1.1**	**0.6**	6.3 **4.0** 3.5	84.1% 50.0% 15.9%
7	*0.65*	*0.4*	*52.6* ***22.9*** *5.5*	84.1% 50.0% 15.9%
F	*0.43*	*0.2*	*49.4* ***5.6*** *3.8*	84.1% 50.0% 15.9%

Table 2. The % mass distribution through the cascade impactor using the PTI PSD applied to the Ranz Wong *design* cutpoints.

Impactor Stage	**R.Wong**	based on PTI PSD median=6.51μm	
	% in stage	% > cutpoint	Conc. mg/m^3
1	46.1	46.1	40.14
2	32.0	78.1	27.88
3	12.6	90.7	10.99
4	6.6	97.3	5.77
5	2.2	99.6	1.93
6	0.4	100.0	0.38
7	0.0	100.0	0.00
F	0.0	100.0	0.00
	100		87

Table 3. The % mass distribution through the cascade impactor using the cutpoints derived from the CC PSD analysis of samples taken from each stage of the impactor.

Impactor Stage	**CC/Impactor** based on the CC PSD		
	% in stage	% > cutpoint	Conc. mg/m^3
1	62.5	62.5	54.44
2	3.5	66.0	3.03
3	9.4	75.4	8.23
4	5.9	81.4	5.15
5	4.4	85.7	3.81
6	1.0	86.7	0.86
7,F	13.3	100.0	11.57
	100		87

Table 4. The % mass distribution through the cascade impactor using average weights obtained from a sample of 4 test runs.

Impactor *sample average*		
stage	%	conc mg/m^3
1	13.6	11.84
2	35.8	31.16
3	21.2	18.46
4	20.1	17.50
5	7.3	6.39
6	2.0	1.76
7	0.0	0.00
F	0.0	0.00
	100	87

Table 5. The % mass distribution through the cascade impactor using the PSD of the Hi-Vol TSP sampler.

TSP median = 6.39μm			
R.Wong cutpoints	% in stage	% > cutpoint	Conc. mg/m^3
6.8	35.8	35.8	31.18
4.3	47.6	83.4	41.49
3	16.6	100.0	14.45
	100		87

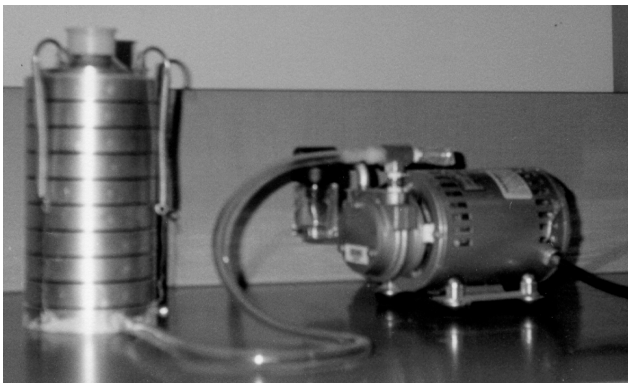

Figure 1a. The Graseby Anderson Cascade Impactor (left) and pump.

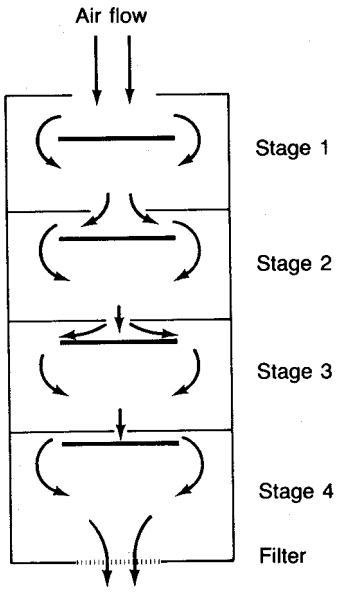

Figure 1b. A basic schematic diagram of the cascade impactor. (Cooper and Alley, 1994)

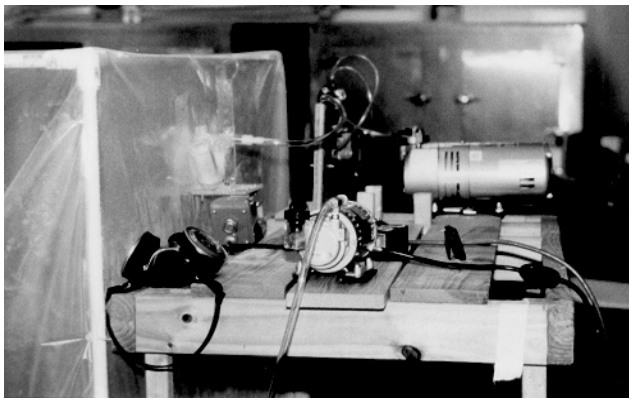

Figure 2. The 100 ft^3 dust chamber (left) and the equipment platform.

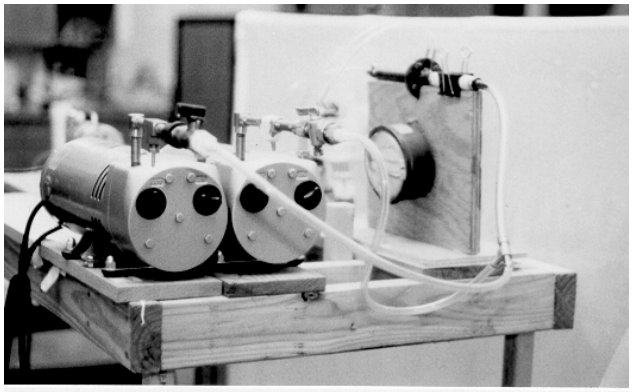

Figure 3. Air compressors and inline orifice meter attached to a pressure gauge.

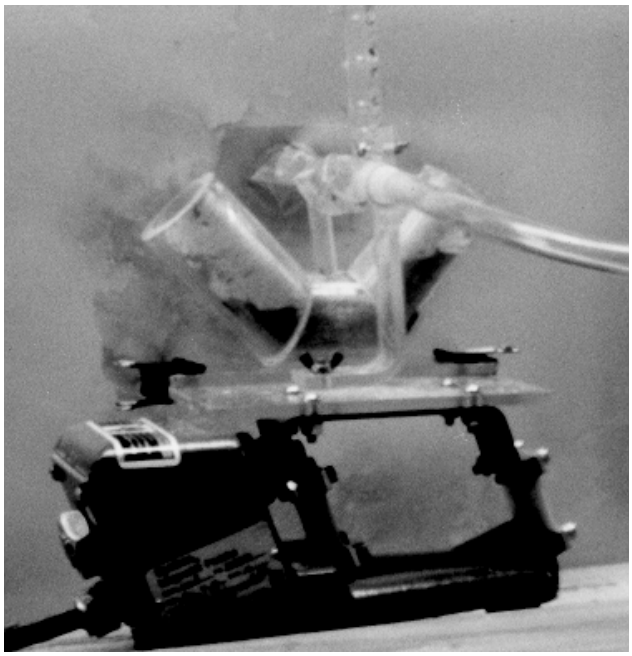

Figure 4. Venturi dust feeder attached to a vibrating platform.

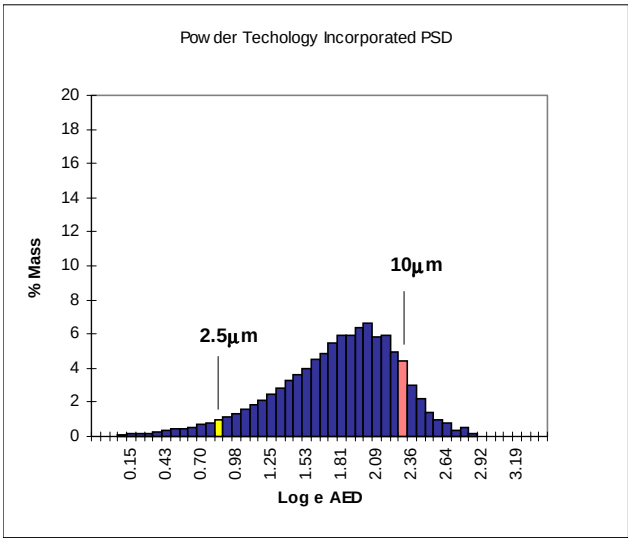

Figure 5. Coulter Counter derived PSD from Powder Technology Incorporated

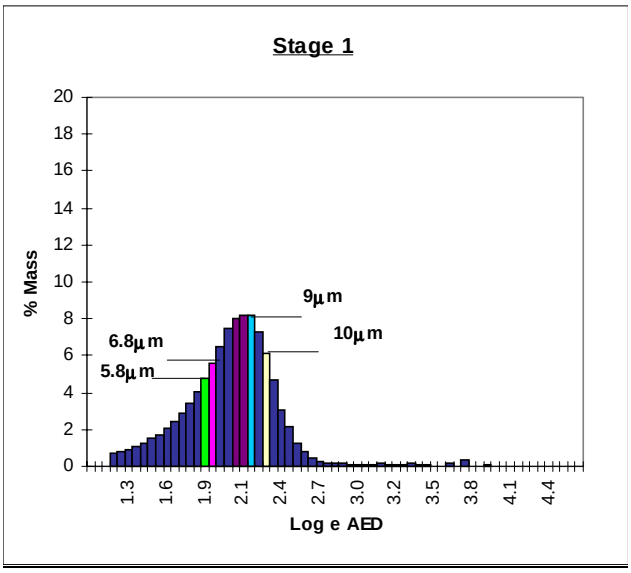

Figure 6. PSD for stage 1 of the cascade impactor

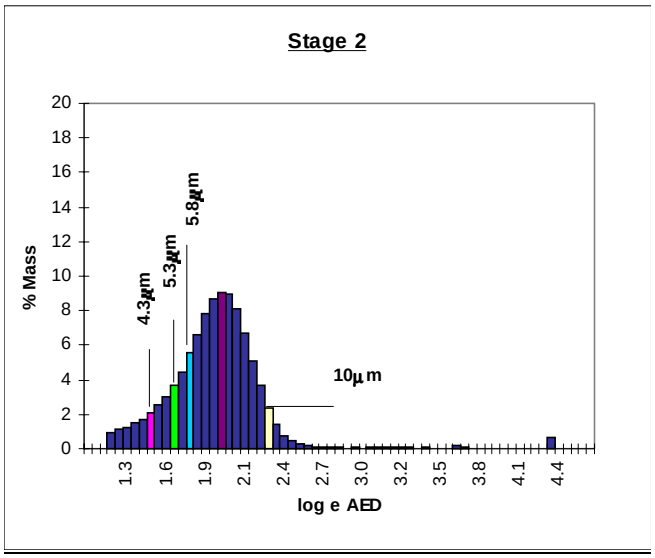

Figure 7. PSD for stage 2 of the cascade impactor

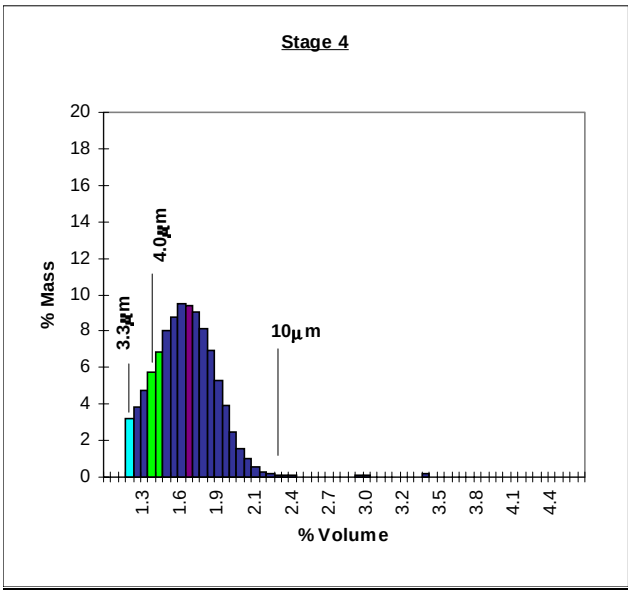

Figure 9 PSD for stage 4of the cascade impactor

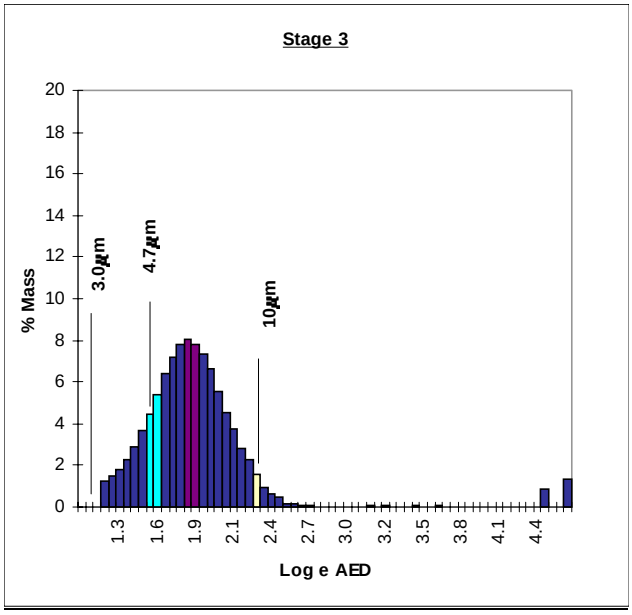

Figure 8 PSD for stage 3 of the cascade impactor

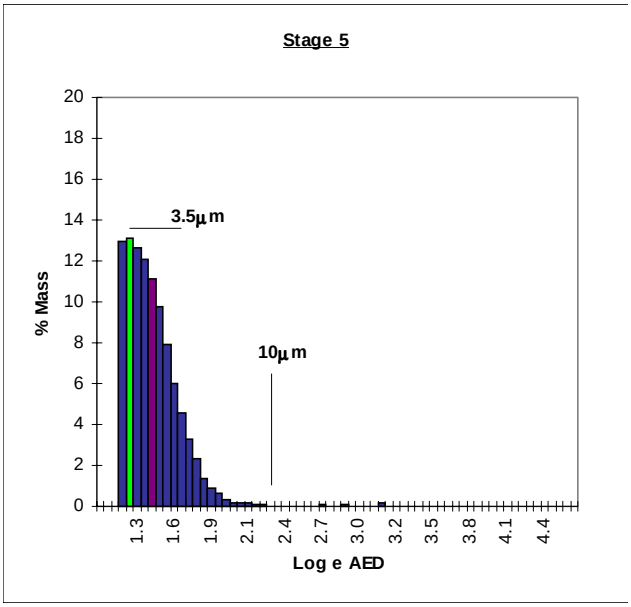

Figure 10. PSD for stage 5 of the cascade impactor

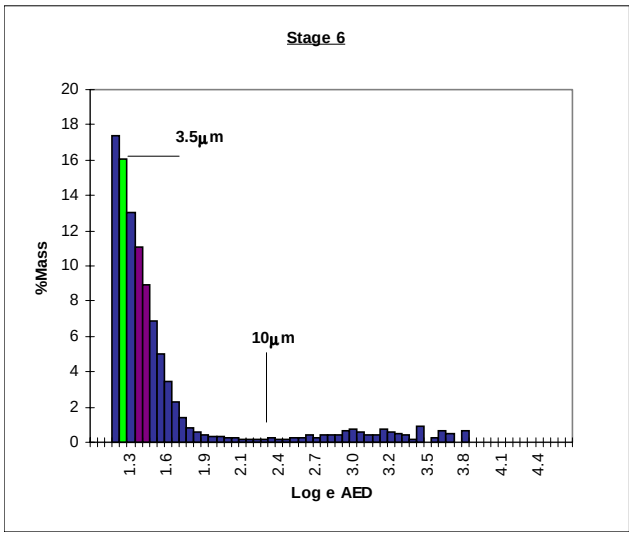

Figure 11. PSD for stage 6 of the cascade impactor

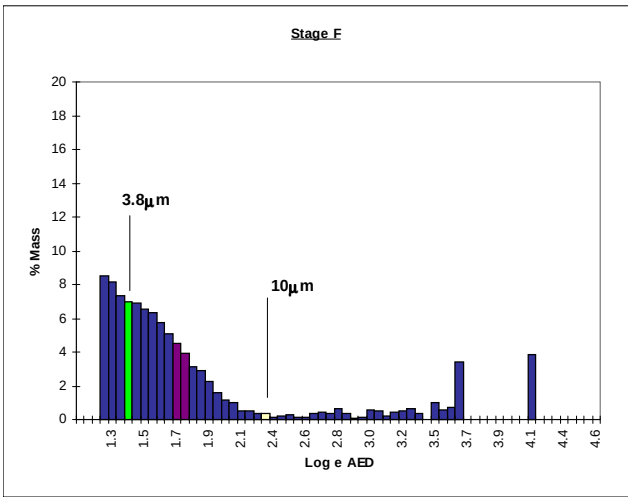

Figure 13. PSD for stage F of the cascade impactor

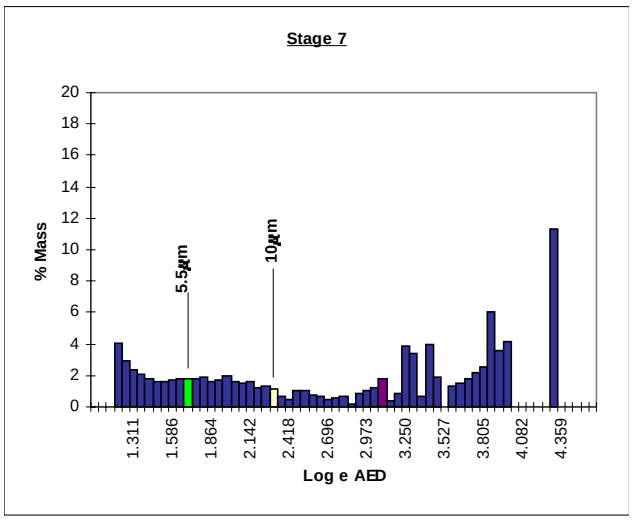

Figure 12. PSD for stage 7 of the cascade impactor

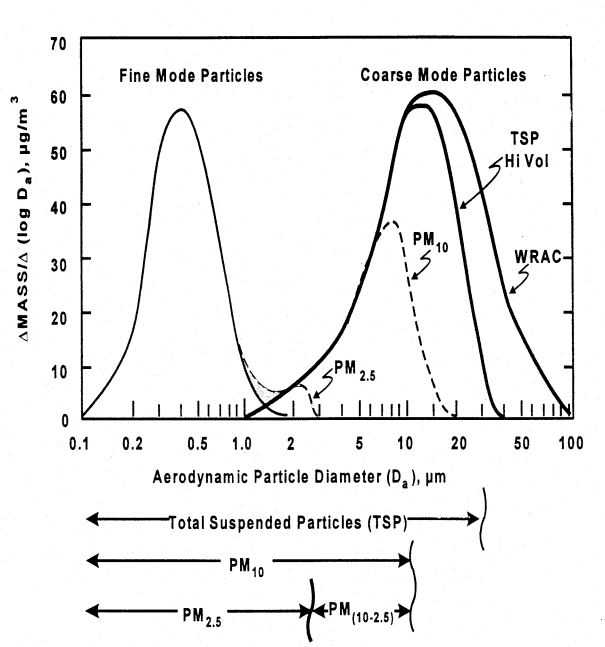

Figure IV-1. Idealized Distribution of Ambient Particulate Matter

Distribution shows fine and coarse mode particles and fractions collected by size-selective samplers such as the wide range aerosol collector (WRAC) and the TSP high volume sampler. (Adapted from Wilson and Suh (1996); CD Figure 3-3).

Figure 14. Bi-Modal PSD from EPA's "Criteria Document"