2003

Performance Verification of Personal Aerosol Sampling Devices

Steven T. Luecke
University of South Florida

Scholar Commons Citation

Luecke, Steven T., "Performance Verification of Personal Aerosol Sampling Devices" (2003). *USF Tampa Graduate Theses and Dissertations.*
https://digitalcommons.usf.edu/etd/2951

Performance Verification of Personal Aerosol Sampling Devices

by

Steven T. Luecke

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Public Health
Department of Environmental and Occupational Health
College of Public Health
University of South Florida

Major Professor: Yehia Y. Hammad, Ph.D.
Thomas E. Bernard, Ph.D.
Eugene L. Szonntagh, Ph.D.
Steve P. Mlynarek, Ph.D.

Date of Approval:
August 27, 2003

Keywords: cyclone, respicon, inhalable dust, respirable dust, impactor

Table of Contents

List of Tables

List of Figures

Performance Verification of Personal Aerosol Sampling Devices

Steven T. Luecke

ABSTRACT

International standards establish criteria for size-selective aerosol sampling for industrial hygiene. Commercially available aerosol samplers are designed to conform to these criteria. This study uses semi-monodispersed aerosols generated in a vertically aligned test chamber to compare the performance of three commercially available respirable dust samplers, one of which can simultaneously sample for thoracic and inhalable dust fractions. Comparison methods are used to calculate a theoretical fractional value based on the appropriate sampling conventions of the total dust concentration and size distribution of test materials. Performance of actual samplers can be conducted by comparing observed results to the theoretical value. Results show the design of the test chamber and use of fused aluminum oxide is appropriate to conduct simplified performance verification tests for inhalable and respirable dust samplers. This study showed the TSI RespiCon followed the inhalable and respirable conventions closely, but results for the thoracic fraction required the use of a correction factor. The SKC aluminum cyclone tended to undersample the respirable fraction, while the BGI CAS4 cyclone and the TSI RespiCon appear to most closely follow the convention. Improved selection of test material and characterization of particle sizes are recommended to further develop this method of performance verification.

1. Introduction

Aerosol sampling is a common method of measuring occupational concentrations of airborne particles. Particle size fraction definitions for health-related sampling follow definitions proposed by the American Conference of Governmental Industrial Hygienists (Soderholm 1989, ACGIH, 1996) and are accepted internationally by such organizations as the European Standards Organization (CEN, 1993) and the International Organization for Standardization (ISO, 1995). Industrial hygienists and inhalation toxicologists have found use in distinguishing the inhalable, thoracic, and respirable fractions of airborne particulate matter. Although deposition throughout the intricate geometrical structure of the respiratory system is a complex phenomenon, relation of disease to anatomical location of deposition is critical to properly evaluate the health hazards and exposure limits of the inhaled particles.

This study examined the performance of three types of personal aerosol monitors used in evaluating hazardous exposures in the respirable fraction of airborne particulates. The BGI CAS4 cyclone (BGI Inc., Waltham MA) and the 37-mm SKC aluminum cyclone (SKC Inc., Eighty Four PA) are routinely used for sampling the respirable fraction of airborne particulates. In addition to these instruments, the TSI® RespiCon™ (TSI Inc., St. Paul, MN) is a virtual impaction sampler designed to differentiate three size fractions (respirable, thoracic, and inhalable) in one sampling instrument. The 37-mm cassette is the industry standard for sampling the total dust and it was used in this study for that purpose.

The purpose of this investigation was to compare the performance of the three monitors under laboratory conditions. Fused aluminum oxide is inexpensive, non-hazardous, stable, and can be found in small sizes with relatively uniform size distribution. Commercially available materials in the respirable size ranges are readily available, and some of these have been shown to have fairly low geometric standard deviations of about 1.3 (Mark, 1985). A Wright dust feeder and baffle system throughout the vertical chamber provided uniform dust concentration to the sampling area. A comparison method utilized expected size fractions based on particle size distribution and total dust collected in the test chamber, after which the expected and the observed results were analyzed.

Comparisons of observed performance and expected values were made between respirable fractions of aluminum oxide collected with the cyclones and RespiCon sampler. Comparisons were also made between total dust collected with 37-mm cassettes, the respirable fractions of the two cyclones, and the inhalable, thoracic, and respirable fractions of the multistage virtual impactor (RespiCon).

2. Literature Review

The RespiCon™ Model 8522 Particle Sampler is a personal aerosol measuring instrument which utilizes a two-stage virtual impactor with a three-stage gravimetric filter design to provide particle size resolved measurements for inhalable, thoracic, and respirable fractions (TSI Inc., 2001). The size separation is based on the currently established CEN-ISO-ACGIH size-selective conventions (50% aerodynamic diameter cut sizes for the appropriate fractions) and the instrument is designed as follows: Inlet (100 µm), Stage 1 (4 µm), Stage 2 (10 µm), while Stage 3 captures all remaining particles. The sampler requires a personal sampling pump with a flow rate capable of operating up to 3.5 LPM, a pressure drop rating of 18 in. H_2O (4.5 kPa), and sufficient power to allow the unit to operate at the specified flow rate of 3.11 LPM for 8 hours.

The two separation stages allow acceleration of aerosolized particles within a virtual space of slow moving air (Tatum, 2002). The virtual impactor design uses major and minor air flows to concentrate particle size fractions. An aerosol flows through an accelerator towards a collection probe. The major portion of the air flow is directed away from the collection probe, and the minor portion of the air flow is directed towards the collection probe. Smaller particles with low inertia follow the major air flow, while larger particle with high inertia follow the minor air flow. The ratio of the major/minor air flow results in a concentration factor for collected particles (Tatum, 2002).

The inhalable aerosol fraction of the RespiCon sampler was evaluated by Li et al (2000) and compared with results obtained in the evaluation of five other personal sampler designs. The effects of wind speed were evaluated and collection efficiencies were compared to the inhalable convention levels. At wind speeds of 0.55 m/s (representative of indoor workplaces) measured differences were less than 10%, while at higher wind speeds oversampling was observed at larger (68μm) particle sizes. The 360˚ circular inlet head of the RespiCon allows aspiration from all wind directions, which results in a sampler design that eliminates inlet wind orientation bias as observed in the other devices. Respirable and thoracic fractions were found to fit conventional efficiency levels well. While the manufacturer originally recommended a 1.5 correction factor to particles larger than thoracic, the authors found its use to be unnecessary to fit current conventions. The manufacturer concurred and there is currently no correction factor recommended for the RespiCon sampler. The authors recommended closely monitoring particle losses inside the sampler, and to maintain cleanliness in order to prevent plugging of the first collection probe.

Another RespiCon unit design incorporates a three stage photometry design in conjunction with the gravitmetric/virtual impaction technology in order to better assess real time static levels of aerosolized particulates in personal or area monitoring. Koch (1999) evaluated the unit with photometric detection under laboratory conditions and found close conformity to conventional size-selective criteria with wind speeds of up to 2 m/s and particle sizes up to 68 μm.

Most recently the precision of the RespiCon was assessed by Tatum et al (2002) in an experimental design that provided six RespiCon units sampling side by side in various forest industry facilities (wood dust), in addition comparing the samplers' performance to standard respirable cyclone and inhalable dust samplers, as well as to results obtained through scanning electron microscopy. Results indicate acceptable precision at most sampling locations. Inhalable and thoracic fractions exhibited the highest degree of precision, while an increased amount of variation was observed in the respirable fraction. This observation is consistent with Koch (1999) and Li (2001) who reported particle losses associated with the first stage collection probe.

General Performance Verification Review of Size Selective Samplers

Size selective samplers are required in many industrial hygiene applications as total mass sampling ignores the fact that toxicants captured in the upper respiratory tract or tracheobronchial part of the respiratory system can limit the extent of hazardous exposure (ACGIH, 1985). Limitations in size selective techniques are the availability of reproducible, reliable, and accurate samplers (ACGIIH, 1985). Sampler collection efficiencies are affected by sampler aspiration, penetration of particles through size selectors, and losses within samplers (Lidén, 1993). Fractional mass of collected aerosols is dependent on mass median aerodynamic diameter, flow-rate, and size distribution (Soderholm, 1989).

In conducting optimization of performance of existing respirable dust samplers, Lidén and Kenny (1993) conducted laboratory tests with small changes in sample flow rates (0.1 – 0.2 LPM) and the use of correction factors. The designated flow rate of the RespiCon unit (3.11 LPM) is not a characteristic that can be optimized as the major/minor flow rates directly effect concentrations in each stage of the virtual impactor. In this investigation, flow rates will not be modified in order to keep the appropriate size-selective fractions within the established CEN-ISO-ACGIH conventions (Lidén, 1993). However, the use of the manufacturer's recommended correction factors (disputed by Li, 2000) was examined, and results are reported both corrected and uncorrected. The respirable fraction collected by an acceptable standard 10-mm nylon cyclone should exhibit a 50% cut at d_{ae}=4.0 um and follow the current collection efficiency proposed by ACGIH (1996).

An evaluation of the SKC aluminum cyclone was conducted by Lidén (1993) in which all three generations of the SKC device were compared directly to the British SIMPEDS cyclone. The SIMPEDS (Safety in Mines Personal Equipment for Dust Sampling) was considered a validated sampler for many years prior to the establishment of the CEN-ISO-ACGIH convention and was used as a reference sampler for this side-by-side comparison. Results showed that SKC cyclones oversampled (80-120%) relative to the SIMPEDS, especially for coarser particles. Precision varied for the SKC sampler, while it was lower than the value obtained for the SIMPEDS for small particles it showed poor precision for larger particles.

Other studies have been recently published which examine aerosol samplers and target sampler criteria. Görner *et al* (2001) published results of fifteen respirable aerosol samplers used worldwide for occupational exposure assessment. That study used polydisperse coal dust as the test aerosol and examined sampler efficiency in a low-velocity wind tunnel using an aerodynamic particle sizer. Based on accuracy and bias maps, the study concluded that most of the samplers, including the SKC aluminum cyclone examined in this evaluation, were suitable for sampling the CEN-ISO-ACGIH respirable fraction of aerosols. One additional observation documented in this evaluation was that although the aerodynamic particle sizer reported some unreasonably high dynamic shape factor (K_{rv}) values, comparisons of the Andersen impactor (Andersen Inc., Atlanta, GA) and Coulter Multisizer (Coulter Electronics, Luton, UK) size distributions were very close to each other. Other studies have been published which use the aerodynamic particle sizer method for evaluating the performance of respirable dust samplers (Maynard, 1995).

Many methods have been published in which a wide variety of test designs have been incorporated. The use of mannequins has been inconsistent in evaluating aerosol sampler performance. While some believe that sampler performance is influenced by the human body on which it is mounted (Vincent, 1989), others believe that the wind tunnels used for those evaluations make such assessments difficult to perform (Kenny, 1995). Complicated system designs can use mannequins, wind tunnels, electronic counting devices and sizers (Görner 2001, Witschger 1997, Kenny 1995). Other recommendations for test systems follow a more simplified approach, such as the use of an implied standard sampler within the test scheme, and sedimentation of dust with minimal turbulence and local exhaust (Vincent, 1999). In his chapter on *Considerations for Workplace Aerosol Samplers* (Vincent, 1999), Lidén stated "the ideal performance test should be simple, quick, cheap, and valid with respect to all possible workplaces".

3. Methods

The experimental design used in this performance verification utilized a glass test chamber that had dimensions of 50" high by 18" wide by 12" deep. Fused aluminum oxide was selected as a test material as previous studies had shown it to be inexpensive, readily available in small sizes, and most importantly exhibiting a low geometric standard deviation (1.17-1.38) in terms of size distribution (Mark, 1984). A BGI WDF-II Wright Dust Feeder aerosol generator equipped with the small dust reservoir was used to provide a uniform dust supply to the chamber. An electric diaphragm pump was used to deliver air to the Wright dust feeder for dispersion of the fused aluminum oxide dust. This allowed between one and two hours of constant dust generation before refilling the reservoir. Dust was fed into the top of the chamber, and the resulting aerosol became homogenous by traveling through a series of four baffles. At the bottom of the chamber a total of 12 samplers were operated to collect the aerosol. The types of samplers examined were 2-piece total dust filter cassettes operated in the open face mode, SKC aluminum cyclones, BGI CAS4 conducting plastic cyclones, and TSI RespiCon virtual impactors. Triplicate samplers of each type inside the chamber were provided appropriate flow rates through the use of critical orifices and high flow vacuum pumps.

Gravimetric analysis was performed on the filters from each 45-60 minute sample run. Six sample runs were conducted for each of the three particle sizes obtained for this evaluation. In addition, density of the dust was determined using pycnometry on four replicates for each sample size. The size distribution of the aluminum oxide particles was determined by Andersen impactors (Vincent, 1989).

Test Materials

Fused aluminum oxide was found commercially, but only small grit sizes were of interest in this study due to the focus on respirable dust sampling efficiencies. The data on Table 1 was provided by Mark (1985) and used as a guideline in obtaining test material.

Table 1 – Physical Properties of Fused Aluminum Oxide

Grade (grit)	Mass Median $d_{ae}^{(1)}$	Mass Median $d_{ae}^{(2)}$	Geometric Standard Deviation
1200	6.0	7.0	1.36
1000	9.0	9.3	1.38
800	13.0	n/a	1.30

(1) Supplied by Electromineral Company (U.K.)
(2) Determined by Aerodynamic Particle Sizer (APS33, TSI, Inc.)

Fused aluminum oxides from three different suppliers were used for aerosolized particles in this study: Alum 1200 (Universal Photonics, Hicksville NY), AL-601 (Atlantic Equipment Engineers, Bergenfield NJ), and 1000 Uniblast (United Abrasives, Vulcan MI)). Alum 1200 and 1000 Uniblast were used as they corresponded to the 1200 and 1000 grit sizes respectively. AL-601 was included as another test material due to the manufacturer claim of size between 1-2 microns, however the actual grit size, aerodynamic diameter, and geometric standard deviation were not available.

Density determinations for the three fused aluminum oxide test powders were conducted using 10-ml and 25-ml pycnometers. This process was completed a minimum of two times for each sample and results are included in Appendix E: Particle Density. The density for all test material exhibited a range of 3.54 to 3.68 g/ml.

Particle size distributions were critical to analyze fractional collection of the sampler types. Andersen impactors were used to analyze the three particle types obtained for this performance verification. Particle size distributions were obtained for Alum 1200 and 1000 Uniblast materials from the respective manufacturers.

Instruments

Four different commercially available samplers for aerosolized dust were used in this performance evaluation. A 37-mm total dust cassette equipped with low ash PVC filter was the reference for dust concentrations in the test chamber. SKC aluminum cyclone and BGI cyclone samplers were used to collect respirable fractions, and the TSI RespiCon unit was used to collect respirable, thoracic, and inhalable fractions from the aerosolized dust within the test chamber.

Critical orifices were selected over the use of multiple personal air pumps for this system as twelve samplers were required for each sample run. Two high flow pumps were connected to two six-position manifolds to allow for the twelve samplers. Tygon tubing was connected to each port and a modified syringe needle was used as a critical orifice. From the critical orifice, additional tubing was connected to the sampler vacuum inlet, which normally is attached to a personal sampling pump.

Performance of the actual sampling devices with fused aluminum oxide dusts was evaluated gravimetrically. Initially the system itself was evaluated using open face dust filter holders to ensure that a homogenous dust concentration was created through the baffle system to all sampler locations. Once verified, the different samplers were used to observe the performance of each type. The size distribution was determined with

Andersen impactors. Density was determined by pycnometry. Comparisons of samplers were performed by examination of accuracy and precision. *System Evaluation*

Once critical orifices were assembled and the appropriate flow was verified, a system evaluation was conducted. This evaluation was designed to ensure critical flow was achieved with the manifold system, and dust provided from the feeder through the baffle system was uniformly distributed in the sampling compartment.

Four evaluations were conducted using total dust cassettes attached to all manifold positions, with results included in Table 2. Feeder rates for supplied dust were varied to evaluate manifold consistency throughout a wide range of concentrations. Although ports had different flow rates for the sampler types, it was easy to determine concentrations (mg/m^3) based on the total volume of air sampled.

Table 2 – Sample Location Verification

Sample Location	**Actual Flow**	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Mean**	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Mean**	**Rank**
	LPM	**mg/m3**	**mg/m3**	**mg/m3**	**mg/m3**	**mg/m3**	**Norm.**	**Norm.**	**Norm**	**Norm**		
1	2.617	32.5	1.8	6.4	7.6	12.1	93.5	93.1	100.7	97.6	96.2	**4**
2	3.133	33.4	1.9	7.2	8.7	12.8	96.1	98.3	113.2	111.8	104.9	**9**
3	2.461	32.6	1.4	5.9	6.5	11.6	93.8	72.4	92.8	83.5	85.6	**1**
4	2.243	33.0	1.8	6.1	8.6	12.4	95.0	93.1	95.9	110.5	98.6	**5**
5	2.228	30.0	2.2	6.6	8	11.7	86.3	113.8	103.8	102.8	101.7	**8**
6	2.224	41.4	2.0	6.6	7.8	14.4	119.1	103.4	103.8	100.2	106.6	**11**
7	3.127	35.5	2.1	6.3	8.2	13.0	102.2	108.6	99.1	105.4	103.8	**8**
8	2.207	34.2	2.1	6.7	8.7	12.9	98.4	108.6	105.4	111.8	106.0	**10**
9	2.203	34.3	1.7	6.0	8.0	12.5	98.7	87.9	94.4	102.8	95.9	**4**
10	3.137	40.8	2.3	6.3	7.4	14.2	117.4	119.0	99.1	95.1	107.6	**12**
11	2.541	37.1	2.0	5.9	7.2	13.1	106.8	103.4	92.8	92.5	98.9	**6**
12	2.103	32.2	1.9	6.3	6.7	11.8	92.7	98.3	99.1	86.1	94.0	**2**
Mean		**34.8**	**1.9**	**6.4**	**7.8**	**12.7**	**100**	**100**	**100**	**100**	**100**	
SD		**3.4**	**0.2**	**0.4**	**0.7**	**0.9**	**9.93**	**12.54**	**5.94**	**9.45**	**6.44**	
%RDS		**9.90%**	**12.20%**	**6.30%**	**9.60%**	**7.20%**						

Figure 1 – Sample Location Diagram

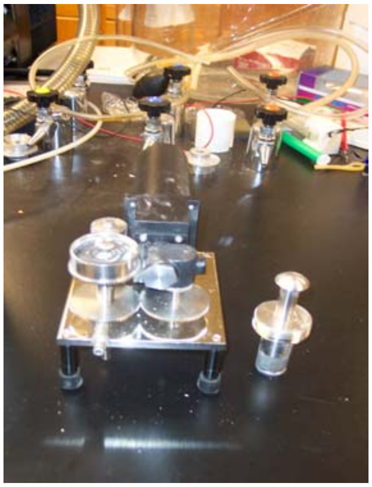
7 RespiCon (103.8%)	8 Total Dust (106.0%)	9 BGI (95.9%)	10 RespiCon (107.6%)	11 SKC (98.9%)	12 Total Dust (94.0%)
1 SKC (96.2%)	2 RespiCon (104.9%)	3 SKC (85.6%)	4 BGI (98.6%)	5 Total Dust (101.7%)	6 BGI (106.6%)

Mean dust concentrations ranged from 1.9 to 34.8 mg/m3, with relative standard deviations between 6.3 to 12.2% for the twelve sampler locations. Results were normalized and a standard deviation of 6.4% was calculated for overall normalized results. Normalization of results was used because of different concentrations over the four trial runs. Results show relatively uniform distribution and no position-specific trends based on rank over the four trials, indicating the test chamber provided an even dust concentration to each sampler location.

Calibration of the air flow-rate of critical orifices was conducted using a Minibuck M-30 calibrator while all samplers were connected with appropriate filters. Acceptance criteria for critical orifice calibration for the cyclones were obtained from the NIOSH 0600 method for respirable dust sampling (NIOSH, 1998) which matched SKC (2002) and BGI (19930 manufacturers specifications, while acceptance criteria for the RespiCon was taken from the TSI manual (TSI Inc., 2001). No formal range was required for the total dust cassettes, and a flow rate of approximately 2.2 LPM was selected to keep flow rates relatively uniform in comparison to the other sampler types. The overall flow rate into all samplers was approximately 30.4 LPM. Calibration of the critical orifices was conducted on a weekly basis, six times overall, during sampler runs for this performance verification.

As stated before, the experimental design incorporated a BGI WDF-II Wright Dust Feeder (BGI Inc., Waltham, MA) that supplied aerosolized particles at the top of the chamber (see Figure 2). According to the manufacturer, a pressure supply of 10-15 psi would result in 20-25 LPM flow rate from the dust feeder (BGI Inc., 1996). The dust feeder flow in addition to make up air from a vent opened near the top of the chamber provided air supply into the chamber. The samplers and an exhaust pump with an in-line cartridge filter provided 24 LPM air exhaust from the chamber. The dust feeder required electrical and pneumatic energy for operation. During the initial system evaluation a gas cylinder with UHP-Zero grade compressed air was used to supply air to the dust feeder. It was observed during the troubleshooting phase that three 60-minute runs at levels between 10-15 psi would drain an entire "A" cylinder. An electrically powered diaphragm pump was then used to provide consistent flow to the dust feeder at 10-11 psi.

Figure 2 – Wright Dust Feeder



Measurements and Procedures

Calibration of critical orifices was carried out on a weekly basis when samplers were used (See Appendix A, Calibration). Three sample readings were taken using a Minibuck primary flow calibrator, with standard deviations documented and mean flow rate used for air volume calculations. Calibration of high flow pumps used for Andersen impaction sampling was conducted with a Hastings mass flow meter.

A system evaluation was conducted in order to verify that the dust feeder, test chamber baffle system, and air supply/exhaust flow would provide a homogenous aerosolized particle distribution to the twelve sample locations at the bottom of the chamber. Unalum 1200 (Universal Photonics, Hicksville, NY) material was used as aerosolized dust for the system evaluation. The evaluation consisted of five test runs along with the appropriate calibrations.

Gravimetric analysis was used throughout this performance verification. Filters were pre-weighed, loaded into the samplers, and post-weighed upon completion. A Mettler AE240 (Mettler Toledo Inc., Columbus OH) balance, with sensitivity to 0.00001 gram, was used for all analysis. Since the dust feeder provided consistent aerosol supply to the test chamber, average concentration (mg/m^3) collected by each sampler type was easily calculated based on the net weight on the filter and the total volume of air passing through each sampler. Mean dust concentration, standard deviation, and relative standard deviation were calculated for the sample set of twelve samplers in each run. Modifications to the chamber and generator flow rate were completed after the first run. A summary of the next four runs showed an average coefficient of variation of 6.4% among the sample sites. This indicated acceptable performance for the test chamber.

To calculate the dust concentration, the net weight of the test filter was divided by the volume of air sampled. RespiCon results were entered on an Excel spreadsheet supplied by the manufacturer and calculated as follows:

(1) Respirable m1*1000/(Q1*ts)

(2) Thoracic (m1+m2)*1000/[(Q1+Q2)*ts]

(3) Inhalable (m1+m2+m3)*1000/[(Q1+Q2+Q3)*ts]

m1,m2,m3 refer to mg mass collected in each stage
Q1,Q2,Q3 refer to LPM flow rate at each stage
ts refers to time sampled in minutes

Table 3 – RespiCon Internal Flow Rates

Stage	Rate(Lpm)
1 (Q1)	2.667
2 (Q2)	0.333
3 (Q3)	0.111

With the test chamber successfully evaluated, data collection of actual runs with samplers in the chamber was performed. The test scheme consisted of a minimum of six test runs for each of the three particle types obtained for analysis. RespiCon samplers used filter material supplied by TSI Inc, while all other sampling devices used low-ash PVC filters (MSA #625413). Sample runs of sufficient length and concentration were required in order to evaluate through gravimetric methods. Based on experience gained in the system evaluation, runs of 45-60 minutes were conducted with 10-11 psi air supply and 1.5-2.2 RPM grinding speed on the dust feeder. Top and bottom portions of the chamber were cleaned between each run.

After sampler runs were completed particle size distributions of the three types of dust were determined using Andersen impactors. Two impactors were placed in the test chamber along with three total dust filters. Andersen impactors were run using high flow pumps calibrated to 28 LPM with the use of a Hastings mass flow meter. Fused aluminum oxides AL-601 and Unalum 1200 were initially examined. Based on results total dust filters were not included with Andersen samplers for the 1000 Uniblast material (see Results). Andersen impactors used nine fiber filters, which have shown significant errors due to bounce and blow-off when examining particles of mass-median diameter larger than 3 micrometers (Esmen *et al.*, 1980).

Figure 3 – Andersen Impactors in Chamber

Density of particles was of interest, as dust feed in the chamber to the samplers was enhanced by the settling of the aerosol. Pycnometers were used to determine density as follows: 10-ml and 25-ml glass pycnometers were cleaned and dried in an oven then weighed. The pycnometers were then filled with distilled water at room temperature to give total volume. Material (0.39 to 1.52 g) was measured and added to the pycnometer, which was then filled less then halfway with distilled water and put in a sonicator to ensure that all air bubbles were removed from between the small alumina particles in the suspension. The pycnometer was then completely filled and weighed. The volume of the solid was determined by calculating the difference between the entire volume of the pycnometer and the volume of the water (equal to the total weight minus the mass of material minus the mass of the clean dry pycnometer). The density was then calculated as the mass of the solid divided by the volume of the solid.

Analysis of Data

Trials of each material were run a minimum of six times with triplicate total and fractional samplers in the test chamber. This resulted in a concentration reported as mg dust on filter per cubic meter of air sampled. Mean, standard deviation, relative standard deviation values are reported for each reportable fraction. In this study respirable fractions are reported for the RespiCon, BGI cyclone, and SKC cyclone. Thoracic and inhalable fractions are reported for the RespiCon. Normalized results are reported for each fraction, reported as the appropriate percent of the open face cassette value. Summary data are presented for the overall mean, standard deviation, relative standard deviation, and normalized values.

Aerodynamic diameter size distributions of test materials were performed with nine-stage Andersen impactors. Two test runs were conducted for each particle type with two impactors in each sample. Mean points of the four runs were plotted for the appropriate sizes of the Andersen impaction stages (0.4, 0.7, 1.1, 2.1, 3.3, 4.7, 5.8, 9.0, and 10.0 microns). Points were joined to determine sizes at cumulative weights of 50% and 84%. Mass median diameter (MMD) is determined by the value of the size at 50%, while geometric standard deviation (GSD) is determined by dividing the value of the size at 84% by the MMD. Finally, a straight line was constructed using the points at 50% and 84%, which is the straight line that describes the particle size distribution.

Using the summary data of mean concentration from the total dust cassette and size distribution for each particle type, it was possible to calculate the idealized expected respirable, thoracic, and inhalable fractions. The expected fractions could then be used to gauge observed results of the size fractions collected by each sampler type. Collection efficiencies for particles by their aerodynamic diameter size were used for the appropriate size fractions. Collection efficiency for each size fraction was based on the corresponding value described in the ACGIH Appendix D Table 1 (ACGIH, 2003, pg 76). The collection efficiencies of the three fractions-are based on the following equations:

(4) $\mathrm{IPM}\ (d_{ae}) = 0.5[1+\exp(-0.06\ d_{ae})]$ for $0 < d_{ae} < 100\mu\mathrm{m}$

(5) $\mathrm{TPM}\ (d_{ae}) = \mathrm{IPM}\ (d_{ae})[1-F(x)]$ where $x = [\ln(d_{ae}/11.64\ \mu\mathrm{m})] / [\ln(1.5)]$

(6) $\mathrm{RPM}\ (d_{ae}) = \mathrm{IPM}\ (d_{ae})[1-F(x)]$ where $x = [\ln(d_{ae}/4.25\ \mu\mathrm{m})] / [\ln(1.5)]$

IPM = Inhalable Particulate Mass
TPM = Thoracic Particulate Mass
RPM = Respirable Particulate Mass
d_{ae} = aerodynamic diameter

4. Results

Size Distributions

The determination of size distributions of the particles used in the study in terms of their aerodynamic diameter is crucial in conducting this type of performance test. Size distribution curves are included below in Figures 4-6. These graphs display the cumulative percent mass on the x-axis and aerodynamic diameter in microns on the y-axis. In calculating the theoretical collection efficiency of each particle type, fractional mass values are taken from these size distributions. Mean aerodynamic diameter and geometric standard deviations are presented in Table 4.

Table 4 – Particle Size Distribution Summary

Aluminum Oxide	**Mean d_{ae} (µm)**	**Geo. Std. Dev.**
Unalum 1200	6.1	1.48
AL-601	6.5	1.38
1000 Uniblast	7.2	1.25

Figure 4 – Unalum 1200 Size Distribution

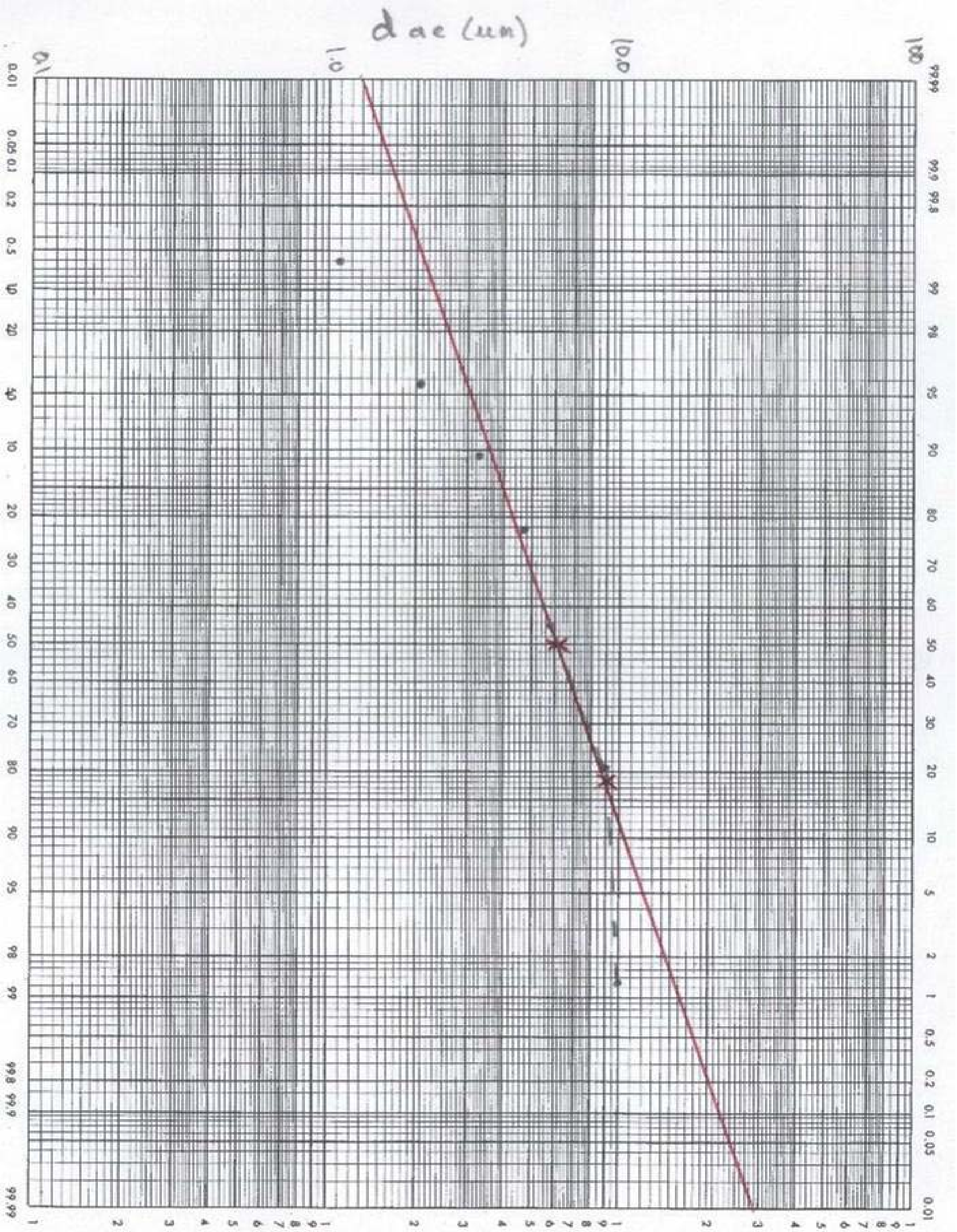


Figure 5 – AL-601 Size Distribution

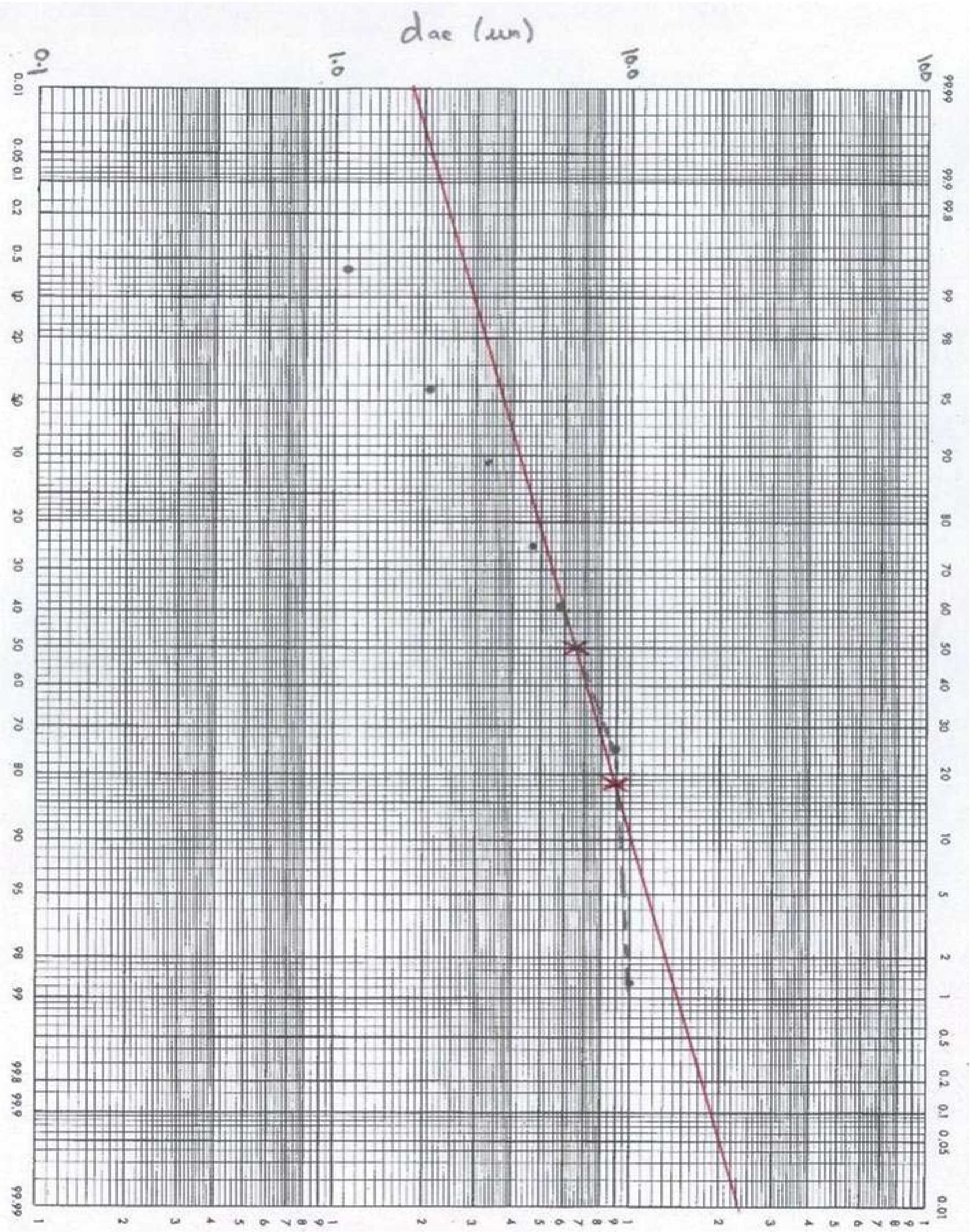
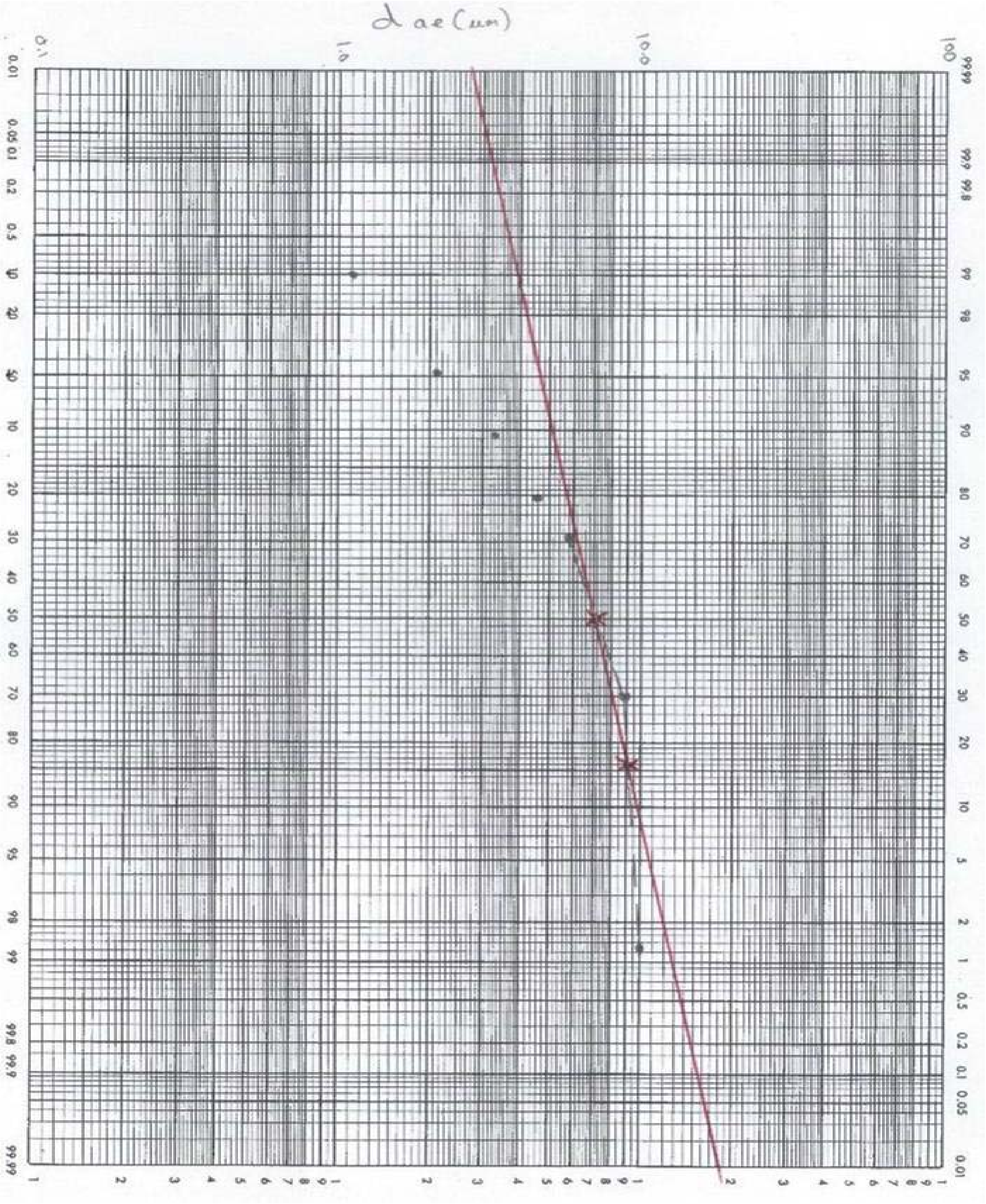


Figure 6 – 1000 Uniblast Size Distribution



While sophisticated analysis tools such as the Coulter counter are available to determine actual size, it is the aerodynamic diameter that is of interest to determine theoretical collection efficiencies. The nine-stage Andersen impactors used in this study report the particle size in terms of its aerodynamic diameter and it is designed for the smaller size range. When attempting to calculate theoretical collection efficiency for thoracic and inhalable values, there are no specific values to plot above 10 microns. It has been shown by Görner (2001) that the use of Coulter counter volume equivalent size results (d_v) and dynamic particle shape factor (K_{rv}) would result in unreasonably large differences between raw Coulter and Andersen size distributions. Görner (2001) and Ogden (1983) both reported unrealistically high dynamic shape factors in terms of efficiency measurement due to the instability of K_{rv}=f(d_v), and revealed for mineral dusts d_{ae} was not appreciably different than d_v. Therefore, Coulter results could be evaluated for aerodynamic size distribution use in future trials of this performance test without the use of dynamic shape factor corrections.

The average of four Andersen impactor trial results was lognormal plotted for each collection stage of each particle type. Straight lines were used to connect each plotted point, which were then used to determine values for 50% and 84% MMD values. The actual size distribution was then determined generating a straight line through the 50% MMD and 84% MMD values. Geometric standard deviations reported in Table 4 (above) were calculated for the size distribution by dividing the diameter at 84% by the diameter at 50%. Numbers correlate reasonably well with those obtained by Mark for particles with grit size 1200 and 1000, with the Unalum 1200 showing a slightly higher

GSD (compared to 1.36) and the 1000 Uniblast exhibiting a lower MMD (compared to 9.0 microns) than the values reported by Mark (1985).

Sampler Data

Three different fused aluminum oxide powders in the respirable size range were evaluated in the test chamber with the twelve-sampler design. Triplicate samplers of each type used gravimetric analysis to report each fraction's time-weighted average concentration. A minimum of six successful trials was conducted for each size, reporting concentration, along with standard deviation and relative standard deviation between triplicate devices. Normalized values are reported to examine the relationship between the fractions collected by the different samplers, using the total dust cassette as the normalization standard. While individual test results are detailed in Appendix B, Table 5, below, summarizes the overall sampler results. Values for one RespiCon run appear in boldface type in Appendix B, Table 12 as a result of the sampler being mishandled. Dust came off the filters and was observed on the surface of internal components. This resulted in low gravimetric numbers that were included on the table but excluded from overall reported numbers. As a result an additional run was conducted for Unalum 1200 test material.

A minimum of six acceptable sampler runs for each particle size were conducted and the results of all runs are presented as the overall values reported on Table 5 below. The overall mean value was used as the observed sampler values when compared to the theoretical expected collection values. The other critical data taken from Table 5 used in developing the theoretical collection value is the total dust collected by the open face dust cassette.

Table 5 – Sampler Data Summary

Aluminum Oxide	**Sampler Fraction**	**Overall Mean (mg/m^3)**	**Overall Std. Dev.**	**Overall Normalization**
Unalum 1200	SKC Cyclone	12.3	4.3	13.4%
	BGI Cyclone	21.5	5.1	23.3%
	TSI Respirable	29.6	9.6	32.1%
	TSI Thoracic	48.3	14.0	52.3%
	TSI Inhalable	74.1	19.1	80.4%
	Dust Cassette	92.2	24.6	100.0%
AL-601	SKC Cyclone	16.1	3.3	28.4%
	BGI Cyclone	23.4	3.0	41.3%
	TSI Respirable	22.1	2.6	39.1%
	TSI Thoracic	35.8	4.2	63.1%
	TSI Inhalable	50.8	8.6	89.6%
	Dust Cassette	56.7	10.0	100.0%
1000 Uniblast	SKC Cyclone	6.9	2.1	7.2%
	BGI Cyclone	10.5	3.1	11.1%
	TSI Respirable	6.0	1.7	6.3%
	TSI Thoracic	40.2	9.7	42.2%
	TSI Inhalable	81.3	13.7	85.3%
	Dust Cassette	95.3	16.9	100.0%

Theoretical Collection Values

Several variables had to be obtained in constructing the theoretical value that actual sampler results would be compared. The total dust in the chamber was reported with the dust cassette results. The collection efficiency of particle sizes within the three fractions was obtained from ACGIH (2003). The fractional mass of each size was taken from the particle size distribution chart. The theoretical value in mg/m^3 is then the sum of the mass of each size range multiplied by the collection efficiency multiplied by the dust concentration.

Observed values from the sampler trials and expected values based on the calculations above are included in Table 6. Data are separated by particle type used in these trial runs. Calculated expected data are reported as respirable, thoracic, and inhalable fractions. Size ranges are listed separately for inhalable, thoracic, and respirable size fractions. Size ranges are taken from those included in ACGIH Appendix D Table 1 (ACGIH, 2003, pg 76). Collection efficiencies are taken from the same referenced table and represent the ideal collection amount for each size range. The overall dust concentration (mg/m^3) multiplied by the collection efficiency multiplied by the observed particle mass (%) within that size range is that size range's contribution to the expected value (mg/m^3). Observed sampler results are included in Table 6 to compare the expected versus observed values.

Sample Calculation: ex) Determination of EXPECTED inhalable fraction of 1000 Uniblast test material

Step 1: Determine size ranges to include from ACGIH Appendix D Table 1; use values presented in that table as midpoints for size ranges.

Step 2: Include collection efficiencies as presented in same reference. If, for example, a collection efficiency of 0.94 is presented for a size range, the contribution to the overall expected inhalable fraction would be 94% of the mass within that size range from the size distribution graph.

Step 3: Determine expected mg/m^3 contribution from each size range by multiplying overall dust concentration (mg/m^3) multiplied by the collection efficiency multiplied by the observed particle mass (%) within that size range is that size range's contribution to the expected value (mg/m^3). For example, 95.3 mg/m^3 x 0.94 collection efficiency x 0.4% mass = 0.3583 mg/m^3 contributed from the 1.5 to 3.5 micron size range.

Step 4: Add up contributions from all size ranges for expected inhalable fraction.

Table 6 – Expected and Observed Collection Efficiencies

Dust	Inhalable	Size Range Collection	0-0.5	0.5-1.5	1.5-3.5	3.5-7.5	7.5-15	15-25	25-35	Fraction	mg/m3
	Fraction	Efficiency	1.00	0.97	0.94	0.87	0.77	0.65	0.58	Sum	
1000	Total		0.0000	0.0000	0.0040	0.5960	0.3990	0.0010	0.0000	1.0000	**95.3**
	Expected		0.0000	0.0000	0.3583	49.4150	29.2790	0.0619	0.0000		**79.1**
	Respicon										81.3
	Res w/CF										101.9
1200	Total		0.0000	0.0004	0.0946	0.5850	0.3050	0.0146	0.0004	1.0000	**92.2**
	Expected		0.0000	0.0358	8.1988	46.9252	21.6532	0.8750	0.0214		**77.7**
	Respicon										74.1
	Res w/CF										87.0
601	Total		0.0000	0.0000	0.0350	0.6150	0.3420	0.0080	0.0000	1.0000	**56.7**
	Expected		0.0000	0.0000	1.8654	30.3373	14.9314	0.2948	0.0000		**47.4**
	Respicon										50.8
	Res w/CF										58.3

Dust	Thoracic	Size Range Collection	0-1	1-3	3-5	5-7	7-9	9-11	11-25	25+	Fraction	mg/m3
	Fraction	Efficiency	1.00	0.94	0.89	0.81	0.67	0.50	0.18	0.02	Sum	
1000	Total		0.0000	0.0005	0.0995	0.3900	0.3500	0.1310	0.0290	0.0000	1.0000	**95.3**
	Expected		0.0000	0.0448	8.4393	29.9194	22.3479	6.2422	0.4975	0.0000		**67.5**
	Respicon											40.2
	Res w/CF											60.3
1200	Total		0.0000	0.0450	0.2750	0.3100	0.2100	0.0300	0.1297	0.0003	1.0000	**92.2**
	Expected		0.0000	3.9001	22.5660	23.0085	12.9725	1.3830	2.1525	0.0006		**66.0**
	Respicon											48.3
	Res w/CF											72.5
601	Total		0.0000	0.0120	0.2080	0.3800	0.2400	0.0600	0.1000	0.0000	1.0000	**56.7**
	Expected		0.0000	0.6396	10.4963	17.3445	16.0000	1.7010	1.0206	0.0000		**47.2**
	Respicon											35.8
	Res w/CF											53.7

Dust	Respirable	Size Range Collection	0-.5	.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-9.0	9-11	Fraction	mg/m3
	Fraction	Efficiency	1	0.97	0.91	0.74	0.5	0.3	0.17	0.09	0.05	0.01	Sum	
1000	Total		0.0000	0.0000	0.0000	0.0040	0.0410	0.1290	0.1960	0.2300	0.2800	0.0600	0.9400	**95.3**
	Expected		0.0000	0.0000	0.0000	0.2821	1.9537	3.6881	3.1754	1.9727	1.3342	0.0572		**12.5**
	Respicon													6.0
	SKC													6.9
	BGI													10.5
1200	Total		0.0000	0.0004	0.0176	0.0770	0.1550	0.1500	0.1600	0.1200	0.1600	0.0400	0.8800	**92.2**
	Expected		0.0000	0.0358	1.4767	5.2536	7.1455	4.1490	2.5078	0.9958	0.7376	0.0369		**22.3**
	Respicon													29.6
	SKC													12.3
	BGI													21.5
601	Total		0.0000	0.0000	0.0030	0.0300	0.1020	0.1650	0.2000	0.1600	0.2400	0.0350	0.9350	**56.7**
	Expected		0.0000	0.0000	0.1548	1.2587	2.8917	2.8067	1.9278	0.8165	0.6804	0.0198		**10.6**
	Respicon													22.1
	SKC													16.1
	BGI													23.4

Note: Size Range units (µm)

RespiCon inhalable results are listed both as calculated and with a correction factor. The correction factor was disputed by Li (2001) and taken off the TSI supplied analysis spreadsheet. This correction factor consisted of a weighting of particles collected in the inhalable stage of the sampler by a factor of 1.5. A more thorough discussion is included in the Comparison Analysis section.

Comparison Analysis

The comparison method in this study uses an observed sampler collected value as the numerator and an expected collection value as the denominator. The expected collection value is limited by the accuracy and precision of the particle size distributions. This particle size distribution is the basis of the comparison method, as results of sampler trials will be compared to theoretical collection values developed from data taken from the distributions. The use of triplicate sampler analysis allowed for observation of variations between sampler and test position within the chamber. This was the concept behind including the system evaluation in this study. Accuracy and precision of sampler results are reported in Table 7 and 8 below.

Table 7 – Accuracy Results

Fraction	Fused Alumina	Ideal Results	(%) TSI RespiCon	Pass / Fail *	(%) SKC Cyclone	Pass / Fail *	(%) BGI Cyclone	Pass / Fail *
Inhalable	1000	100%	102.8	P				
	1200	100%	95.4	P				
	601	100%	107.2	P				
Thoracic	1000	100%	59.6	F				
	1200	100%	73.2	F				
	601	100%	71.3	F				
Respirable	1000	100%	48.0	F	55.2	F	81.6	F
	1200	100%	132.7	F	55.2	F	96.4	P
	601	100%	208.5	F	151.9	F	220.8	F

* Pass or fail based on ±15% acceptance criteria

Table 8 – Precision Results

Fraction	**Fused Alumina**	**Ideal Results**	**(%) TSI RespiCon**	**(%) SKC Cyclone**	**(%) BGI Cyclone**
Inhalable	1000	0%	8.6		
	1200	0%	9.5		
	601	0%	4.7		
Thoracic	1000	0%	6.9		
	1200	0%	9.5		
	601	0%	8.9		
Respirable	1000	0%	8.7	9.3	9.9
	1200	0%	12.0	18.5	7.6
	601	0%	8.0	10.0	7.9
Mean			**8.5**	**12.6**	**8.5**

Accuracy of the sampler results in this study is determined by directly comparing observed values to the expected collection values generated for each sampler run for all particle types. The observed values in this study are the summary overall means calculated for all the test runs conducted for each particle type as found in Table 5. Accuracy of the samplers illustrates how close the sampler value is to the true value of the appropriate inhalable, thoracic, or respirable fraction, however in this performance based study the calculated expected value is used as the true value. Accuracy values are displayed for each sampler as percentages of the expected values and are the result of eighteen test results conducted in triplicate.

In determining a pass/fail criterion for sampler accuracy the NIOSH 0600 method for respirable particle sampling was reviewed. This method describes an acceptable bias in results of 10-20% based on geometric standard deviation of the sampled particles. If an acceptance criterion of 15% is selected based on the particles used in this study, the performance verification can be used to provide pass or fail results based on NIOSH criteria. By applying this criterion, the RespiCon unit passed all three inhalable tests, failed all three thoracic tests and respirable tests. The BGI cyclone passed one of three respirable tests. The SKC cyclone results were not within 15% of theoretical collection values. The accuracy results of the SKC aluminum cyclone did not show the over sampling characterized by Lidén (1993) in his direct comparisons to the British SIMPEDS cyclone.

The size distributions for each particle type are critical in the determination of the expected value for the sampling devices. In this study respirable fractions collected of the 1000 Uniblast material were low for all samplers. Mark (1985) published a MMD of 9.0 microns for 1000 grit fused aluminum oxide, as opposed to 7.2 microns found in this study. This shift in size distribution would result in a lower calculated expected value as less mass would have been accumulated in the respirable range (0-10 microns), which would be closer to the observed values. Similarly, all respirable fractions collected of the AL-601 material were high for all samplers. Following the same logic, if the actual size distribution of this material was smaller than what was presented in this study, a larger portion of the overall particle mass would have been accumulated in the respirable range resulting in a larger calculated expected value which would be closer to the observed values.

Precision of results is based on how well results can be repeated. In this study all samples were taken three times in the same sample run. Regardless of how efforts would be made to control time and dust feeder settings, no two chamber runs could have the identical dust concentration. Therefore precision was evaluated and reported based on relative standard deviation that would show differences between samplers within each test run. The obtained relative standard deviations were then averaged for all the runs included in this study and reported. Relative standard deviation was used to evaluate results as this type of data is not dependent upon the mean value. For example, respirable fractions cannot be greater than inhalable fractions, and if precision was based upon the mean then differences in values of the respirable range they would show lower precision than the same differences in comparison to values of the inhalable range. This study indicates the RespiCon and BGI cyclone exhibit better precision than the SKC cyclone.

Correction factors had previously been used to adjust the inhalable dust fraction of the RespiCon. More recently this has been disputed and TSI no longer recommends the use of correction factors for inhalable dust, and has never recommended them for thoracic or respirable dust. Results of this study show high accuracy of RespiCon inhalable results without the use of correction factors. As the thoracic values were lower than expected, a 1.5 overall correction factor was used in this study simply to attempt to use a single correction to adjust observed numbers. This factor of 1.5 was the value previously used for correction of inhalable losses, and was found to be effective in increasing the accuracy of the thoracic fractions as determined in this test. As indicated in Table 9, accuracy results for thoracic fractions improved from 59.6, 73.2, and 71.3 percent to 89.3, 109.8, and 107.0 percent respectively. Although all values utilizing the correction factor pass the accuracy criteria, no corroborative research can be found that indicates the need for any correction factor for the thoracic fraction sampled by the RespiCon.

Table 9 - RespiCon Thoracic Results with Correction Factor

Particle Type	Raw TPM Accuracy (%)	TPM Accuracy with Correction Factor (%)
1000	59.6	89.3
1200	73.2	109.8
601	71.3	107.0

A trend observed throughout all sample runs was that the SKC aluminum cyclone always exhibited a lower respirable fraction than the BGI aluminum cyclone. The concentrations of the RespiCon respirable fraction were lower than either cyclone for the 1000 Uniblast material and greater than either cyclone for the Unalum 1200 material.

This study design is economical to perform and allows for simple gravimetric analysis of results. Large amounts of data may be generated with relative ease in comparison to other published test methods. Results of this study indicate this performance test may be suitable for use in evaluating inhalable dust samplers. Examination of additional inhalable dust samplers, such as the SKC IOM sampler, should be conducted in order to verify these findings.

This type of study requires a more suitable method for generating particle size distributions than the use of Andersen impactors. Particle size is critical in determining expected collection values, which in turn are used to evaluate sampler performance. Smaller particles for respirable dust testing could be examined, and test material other than fused aluminum oxide should be considered. In addition, a more sophisticated approach to determine acceptable accuracy and precision of sampler results is needed.

5. Conclusions

A novel method of assessing the performance of particle size-selective sampling devices was conducted using a simplified test chamber, inexpensive test materials, and routine gravimetric analysis. This method was conducted on three sampler types tested in triplicate without use of expensive wind tunnel equipment, mannequin designs, or specialty grade particles. The use of fused aluminum oxide was based on the use of semi-monodispersed particles, but a variety of particles of interest could be used in this design, making it valuable in determining particle-specific sampler performance. This design shows promise for use as an accurate and economical approach to conduct evaluations of inhalable aerosol sampling devices for a variety of applications. Further method development of this design is necessary to conduct performance verification of respirable and thoracic aerosol sampling devices.

Evaluation of the samplers in this study showed the TSI RespiCon accurately matches the inhalable sampling convention. The thoracic fraction appeared to underestimate the expected value. Observed thoracic values showed improved results with the use of a correction factor. It is unknown whether the use of a correction factor for thoracic values is based on sampler performance or problems associated with this study. The respirable fraction was inconsistent and showed poor accuracy. While the SKC cyclones showed excellent precision, they did not show highly accurate results compared with the theoretical collection value. The BGI cyclone also showed excellent precision with the highest observed accuracy compared to the other respirable samplers.

In this type of comparison evaluation the accuracy results of samplers are directly dependent on the accuracy of the generated particle size distributions.

Future use of performance verifications of this type that rely on size distributions would benefit from either improved size distribution capabilities or better monodispersement of particles than observed in this study. The development of this method was in part based on size distribution data on fused aluminum oxide reported by Mark (1985). The numbers reported in this study show the test material may not have been as appropriate as initially theorized, as a wider size range mass median diameter size would have been beneficial. Inconsistencies between results in the respirable range indicate more control needs to be placed in the test chamber, such as including a smaller sized multi-stage impactor inside the chamber during each run. An additional consideration not examined in this study is the orientation of the open face total dust cassettes, as these values affect the theoretical fraction, and therefore interpretation of sample results. Further side-by-side testing of these three sampler types is necessary to better understand their performance characteristics.

References

ACGIH, Particle Size-Selective Sampling in the Workplace, ACGIH Report (1985)

ACGIH, Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices, Appendix D: Particle size-selective sampling criteria for airborne particulate matter (2003)

BGI Incorporated, Instructions Casella CAS-4 Respirable Dust Cyclone (1993)

BGI Incorporated, Wright Dust Feeder WDF-II Operating Instructions, Third Edition, (1995)

CEN EN 481(Comité Européen de Normalisation), Workplaces atmospheres: size fraction definitions for measurements of airborne particles in the workplace, CEN Brussels (1993)

Esmen NA, Lee TC, Distortion of cascade impactor measured size distribution due to bounce and blow-off, AIHA Journal 41: 410-19 (1980)

Görner P, Wrobel R, Mička V, Skoda V, Denis J, Fabriès JF, Study of fifteen respirable aerosol samplers used in occupational hygiene, Ann. Occ. Hyg. 45: 43-54 (2001)

ISO IS 7708, Air quality – particle size fractions definitions for the health-related sampling, International Standards Organization, Geneva (1995)

Kenny LC, Aitken RJ, Baldwin PEJ, Beaumont GC, Maynard AD, The sampling efficiency of personal inhalable aerosol samplers in low air movement environments, J. Aerosol Sci 30: 627-638 (1999)

Koch W, Dunkhorst D, Lodding H, Design and Performance of a New Personal Aerosol Monitor, Aerosol Sci & Tech. 31: 231-246 (1999)

Li SN, Lundgren DA, Rovell-Rixx D, Evaluation of Six Inhalable Aerosol Samplers, AIHA Journal 61: 506-516 (2000)

Li SN, Lundgren DA, Rovell-Rixx D, Ray AE, Effect of impactor inlet efficiency on the measurement of wood dust size distributions, AIHA Journal 62: 19-27 (2001)

Lidén G, Kenny LC, The performance of respirable dust samplers: sampler bias, precision, and inaccuracy. Ann. Occ. Hyg. 36: 1-22 (1992)

Lidén G, Evaluation of the SKC personal respirable dust sampling cyclone, App. Occ. Env. Hyg. 8: 178-190 (1993)

Lidén G, Kenny LC, Optimization of the Performance of Existing Respirable Dust Samplers, Appl. Occ. Env. Hyg. 8: 386-391 (1993)

Mark D, Vincent JH, Gibson H, Witherspoon WA, Applications of closely graded powders of fused alumina as test dusts for aerosol studies, J. Aerosol Sci 16: 125-131 (1985)

Maynard AD, Kenny LC, Performance assessment of three personal cyclone methods using an aerodynamic particle sizer, J. Aerosol Sci. 26: 671-684 (1995)

NIOSH Method 0500, Issue 2, Particulates Not Otherwise Regulated, Total, NIOSH Manual of Analytical Methods (NMAM), Fourth Edition (1994)

NIOSH Method 0600, Issue 3, Particulates Not Otherwise Regulated, Respirable, NIOSH (1998)

Ogden TL, Barker D, and Clayton MP, Flow-dependence of the Casella respirable-dust cyclone, Ann. Occ. Hyg. 27: 261-271 (1983)

O'Shaughnessy PT, Slagley JM, Photometric response determination based on aerosol physical characteristics, AIHA Journal 63:578-85 (2002)

SKC Technical Note: The Use of SKC Aluminum Cyclones, Publication 1519, Revision May 2002

Soderholm SC, Proposed International Conventions for Particle Size-Selective Sampling, Ann. Occ. Hyg. (33):301-320 (1989)

Tatum V, Ray AE, Rovell-Rixx D, Performance of RespiCon Personal Aerosol Sampler in Forest Products Industry Workplaces, AIHA Journal 63: 311-316 (2002)

TSI Model 8522 RespiCon Particle Sampler, Operation and Service Manual, TSI Inc., January 2001

Vincent JH, Aerosol Sampling: Science and Practice, Wiley and Sons, Chichester, U.K. (1989)

Vincent JH, Particle Size-Selective Sampling for Particulate Air Contaminants, ACGIH (1999)

Witchger O, Willeke K, Grinshpun SA, Aizenberg V, Smith J, Baron PA, Simplified method for testing personal inhalable aerosol samplers, J. Aerosol Sci, 29: 855-874 (1998)

Appendices

Appendix A: Calibration

The following table summarizes the calibration data taken in this performance verification. Calibrations were performed on a weekly basis during test runs. Three values were obtained for each of twelve (12) critical orifices. Table 10 reports mean flow rate (LPM), standard deviation, and relative standard deviation of three values obtained for each calibration. Table 11 reports acceptance criteria for the sampler types.

Table 10 – Calibration Summary

Date	**Value**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
2/13/03	Mean	2.609	3.128	2.458	2.220	2.207	2.222	3.151	2.232	2.223	3.134	2.597	2.204
	SD	0.002	0.003	0.002	0.003	0.002	0.001	0.004	0.002	0.001	0.005	0.002	0.007
	% RDS	0.059	0.085	0.070	0.103	0.094	0.026	0.138	0.090	0.045	0.144	0.067	0.328
3/30/03	Mean	2.617	3.133	2.461	2.243	2.228	2.224	3.127	2.207	2.203	3.133	2.541	2.103
	SD	0.005	0.006	0.002	0.006	0.006	0.001	0.008	0.001	0.011	0.002	0.006	0.003
	% RDS	0.191	0.178	0.062	0.261	0.274	0.052	0.260	0.045	0.500	0.066	0.237	0.145
4/15/03	Mean	2.623	3.152	2.481	2.237	2.222	2.231	3.086	2.239	2.224	3.083	2.556	2.119
	SD	0.001	0.001	0.004	0.013	0.003	0.004	0.005	0.003	0.006	0.002	0.003	0.000
	% RDS	0.022	0.018	0.142	0.566	0.130	0.187	0.148	0.112	0.248	0.050	0.120	0.000
4/28/03	Mean	2.613	3.146	2.442	2.230	2.222	2.219	3.120	2.250	2.233	3.090	2.592	2.135
	SD	0.003	0.003	0.002	0.005	0.002	0.003	0.003	0.006	0.003	0.000	0.004	0.001
	% RDS	0.123	0.092	0.085	0.226	0.094	0.138	0.085	0.245	0.118	0.000	0.135	0.047
5/21/03	Mean	2.600	3.138	2.454	2.224	2.223	2.220	3.121	2.246	2.234	3.092	2.542	2.151
	SD	0.006	0.003	0.003	0.004	0.001	0.000	0.001	0.001	0.002	0.001	0.002	0.003
	% RDS	0.231	0.102	0.125	0.162	0.045	0.000	0.032	0.026	0.090	0.037	0.068	0.142
6/17/03	Mean	2.572	3.093	2.401	2.186	2.187	2.180	3.149	2.238	2.219	3.098	2.580	2.142
	SD	0.001	0.002	0.001	0.001	0.003	0.001	0.002	0.003	0.003	0.003	0.002	0.001
	% RDS	0.022	0.065	0.048	0.026	0.140	0.026	0.073	0.144	0.145	0.099	0.081	0.047
	Sampler Type	*SKC*	*TSI*	*SKC*	*BGI*	*Dust*	*BGI*	*TSI*	*Dust*	*BGI*	*TSI*	*SKC*	*Dust*

Table 11 – Acceptance Criteria for Critical Orifice Flow

Sampler Type	**Criteria**	**Range (LPM)**	**Reference**
Total Dust	N/A	Reference Value	N/A
TSI Respicon	3.11 ± 2%	3.04 – 3.17	TSI RespiCon Manual
SKC Cyclone	2.5 ± 5%	2.38 – 2.63	NIOSH 0600
BGI Cyclone	2.2 ± 5%	2.09 – 2.31	NIOSH 0600

Appendix B: Sampler Data

Table 12 – Sampler Results for Fused Aluminum Oxide Unalum 1200

Trial	Sampler Type	Sampler 1	Sampler 2	Sampler 3	Ave (3)	Stand. Dev.	%RSD	Norm.
1	Aluminum Cyclone	10.9	12.7	9.8	11.1	1.5	13.1%	10.84%
	BGI Cyclone	26.4	22.3	20.8	23.2	2.9	12.5%	22.56%
	Respicon Respirable	31.7	25.6	22.1	26.4	4.9	18.4%	25.75%
	Respicon Thoracic	49.9	42.6	40.8	44.4	4.8	10.8%	43.29%
	Respicon Inhalable	70.0	89.3	81.8	80.3	9.7	12.1%	78.26%
	Open Face Cassette	101.6	106.7	99.7	102.7	3.6	3.5%	100.00%
2	Aluminum Cyclone	11.6	21.0	14.5	15.7	4.8	30.7%	13.41%
	BGI Cyclone	27.3	26.5	27.7	27.2	0.6	2.2%	23.21%
	Respicon Respirable	40.9	48.6	30.4	39.9	9.1	22.9%	34.12%
	Respicon Thoracic	65.8	71.6	48.4	61.9	12.1	19.5%	52.90%
	Respicon Inhalable	81.7	90.3	89.8	87.3	4.8	5.6%	74.56%
	Open Face Cassette	120.7	115.7	114.8	117.1	3.2	2.7%	100.00%
3	Aluminum Cyclone	17.9	10.9	11.1	13.3	4.0	30.0%	18.78%
	BGI Cyclone	21.5	20.0	18.4	20.0	1.6	7.8%	28.19%
	Respicon Respirable	32.9	***11.6***	28.5	30.7	3.1	10.2%	43.36%
	Respicon Thoracic	48.6	***31.7***	48.9	48.8	0.2	0.5%	68.85%
	Respicon Inhalable	81.6	***58.3***	73.9	77.8	5.4	7.0%	109.77%
	Open Face Cassette	73.9	70.0	68.6	70.8	2.7	3.9%	100.00%
4	Aluminum Cyclone	4.2	7.1	6.8	6.0	1.6	26.4%	10.75%
	BGI Cyclone	12.4	15.0	12.0	13.1	1.6	12.4%	23.41%
	Respicon Respirable	16.3	15.4	16.0	15.9	0.4	2.8%	28.32%
	Respicon Thoracic	26.1	27.7	24.2	26.0	1.8	6.9%	46.32%
	Respicon Inhalable	35.7	47.6	30.8	38.0	8.6	22.7%	67.79%
	Open Face Cassette	56.1	52.5	59.7	56.1	3.6	6.4%	100.00%
5	Aluminum Cyclone	10.9	10.2	13.3	11.5	1.6	14.2%	10.45%
	BGI Cyclone	20.9	21.0	21.8	21.2	0.5	2.3%	19.34%
	Respicon Respirable	40.1	33.4	43.4	39.0	5.1	13.0%	35.51%
	Respicon Thoracic	60.0	55.8	60.2	58.7	2.5	4.2%	53.45%
	Respicon Inhalable	75.1	83.6	86.1	81.6	5.8	7.1%	74.31%
	Open Face Cassette	112.8	98.5	118.0	109.8	10.1	9.2%	100.00%
6	Aluminum Cyclone	10.0	11.1	10.2	10.4	0.6	5.6%	14.62%
	BGI Cyclone	17.9	16.7	19.3	18.0	1.3	7.2%	25.18%
	Respicon Respirable	21.5	22.1	21.2	21.6	0.5	2.1%	30.30%
	Respicon Thoracic	39.0	37.4	35.3	37.2	1.9	5.0%	52.16%
	Respicon Inhalable	64.0	61.0	57.9	61.0	3.1	5.0%	85.46%
	Open Face Cassette	74.3	68.0	71.8	71.4	3.2	4.4%	100.00%
7	Aluminum Cyclone	17.8	16.6	20.1	18.2	1.8	9.8%	15.44%
	BGI Cyclone	30.6	27.5	25.7	27.9	2.5	8.9%	23.75%
	Respicon Respirable	38.5	29.6	34.3	34.1	4.4	13.0%	28.99%
	Respicon Thoracic	68.2	59.2	55.4	60.9	6.6	10.8%	51.80%
	Respicon Inhalable	98.6	93.1	89.7	93.8	4.5	4.8%	79.77%
	Open Face Cassette	107.7	121.9	123.3	117.6	8.6	7.3%	100.00%

Table 13 – Sampler Results for Fused Aluminum Oxide AL-601

Trial	Sampler Type	Sampler 1	Sampler 2	Sampler 3	Ave (3)	Stand. Dev.	%RSD	Norm.
1	Aluminum Cyclone	14.3	12.7	12.5	13.2	1.0	7.5%	27.90%
	BGI Cyclone	20.1	22.8	20.6	21.2	1.4	6.8%	44.84%
	Respicon Respirable	21.5	24.3	17.9	21.2	3.2	15.0%	44.97%
	Respicon Thoracic	36.6	37.9	31.9	35.5	3.2	8.9%	75.19%
	Respicon Inhalable	45.1	48.7	44.0	45.9	2.4	5.3%	97.29%
	Open Face Cassette	48.6	43.3	49.7	47.2	3.4	7.2%	100.00%
2	Aluminum Cyclone	18.2	13.6	16.5	16.1	2.3	14.4%	33.31%
	BGI Cyclone	18.6	21.2	21.3	20.4	1.5	7.5%	42.14%
	Respicon Respirable	20.3	21.9	20.4	20.9	0.9	4.3%	43.15%
	Respicon Thoracic	28.1	33.7	27.9	29.9	3.3	10.9%	61.88%
	Respicon Inhalable	40.3	38.4	40.6	39.8	1.2	3.0%	82.28%
	Open Face Cassette	47.8	44.4	52.8	48.3	4.2	8.7%	100.00%
3	Aluminum Cyclone	18.6	22.8	19.8	20.4	2.2	10.6%	29.71%
	BGI Cyclone	30.6	27.3	25.1	27.7	2.8	10.0%	40.29%
	Respicon Respirable	24.3	26.5	26.5	25.8	1.3	4.9%	37.54%
	Respicon Thoracic	34.7	42.3	37.5	38.2	3.8	10.0%	55.59%
	Respicon Inhalable	59.3	59.8	63.9	61.0	2.5	4.2%	88.84%
	Open Face Cassette	64.1	72.1	69.8	68.7	4.1	6.0%	100.00%
4	Aluminum Cyclone	14.7	13.6	11.8	13.4	1.5	11.0%	26.88%
	BGI Cyclone	21.2	21.8	23.5	22.2	1.2	5.4%	44.57%
	Respicon Respirable	21.6	20.4	19.4	20.5	1.1	5.3%	41.17%
	Respicon Thoracic	38.4	34.7	32.2	35.1	3.1	8.9%	70.65%
	Respicon Inhalable	43.2	48.0	46.3	45.8	2.4	5.3%	92.16%
	Open Face Cassette	52.3	50.4	46.5	49.7	3.0	5.9%	100.00%
5	Aluminum Cyclone	19.0	21.5	18.4	19.6	1.6	8.4%	28.66%
	BGI Cyclone	25.7	27.0	22.2	25.0	2.5	9.9%	36.45%
	Respicon Respirable	23.7	22.4	24.3	23.5	0.9	4.0%	34.25%
	Respicon Thoracic	37.8	39.9	42.9	40.2	2.6	6.4%	58.67%
	Respicon Inhalable	63.2	63.9	58.1	61.7	3.1	5.1%	90.10%
	Open Face Cassette	68.4	76.5	60.6	68.5	8.0	11.6%	100.00%
6	Aluminum Cyclone	14.6	12.7	14.7	14.0	1.1	8.0%	24.25%
	BGI Cyclone	22.2	24.9	25.8	24.3	1.9	7.7%	42.09%
	Respicon Respirable	18.3	20.5	24.4	21.1	3.1	14.8%	36.47%
	Respicon Thoracic	32.2	37.3	37.7	35.8	3.1	8.6%	61.93%
	Respicon Inhalable	47.6	53.1	50.4	50.4	2.8	5.5%	87.27%
	Open Face Cassette	58.3	56.8	58.1	57.7	0.8	1.4%	100.00%

Table 14 – Sampler Results for Fused Aluminum Oxide 1000 Uniblast

Trial	Sampler Type	Sampler 1	Sampler 2	Sampler 3	Ave (3)	Stand. Dev.	%RSD	Norm.
1	Aluminum Cyclone	3.5	3.2	4.3	3.7	0.6	15.5%	5.22%
	BGI Cyclone	5.0	5.0	6.5	5.5	0.9	15.7%	7.83%
	Respicon Respirable	3.8	3.7	3.1	3.5	0.4	10.4%	4.99%
	Respicon Thoracic	30.4	27.4	25.1	27.6	2.6	9.5%	39.36%
	Respicon Inhalable	73.6	65.1	60.4	66.4	6.7	10.2%	94.53%
	Open Face Cassette	76.9	63.2	70.5	70.2	6.9	9.8%	100.00%
2	Aluminum Cyclone	7.8	7.8	7.3	7.6	0.3	3.8%	6.94%
	BGI Cyclone	10.8	13.1	12.6	12.2	1.2	9.9%	11.06%
	Respicon Respirable	5.7	6.6	7.1	6.4	0.7	11.1%	5.86%
	Respicon Thoracic	44.1	36.8	35.6	38.8	4.6	11.9%	35.32%
	Respicon Inhalable	90.6	93.1	77.9	87.2	8.1	9.3%	79.31%
	Open Face Cassette	108.4	101.9	119.6	110.0	9.0	8.1%	100.00%
3	Aluminum Cyclone	7.2	6.9	6.9	7.0	0.2	2.5%	7.10%
	BGI Cyclone	10.3	12.6	9.7	10.9	1.5	14.1%	11.02%
	Respicon Respirable	6.5	6.4	5.7	6.2	0.4	7.3%	6.27%
	Respicon Thoracic	39.5	39.4	36.2	38.4	1.9	4.9%	38.95%
	Respicon Inhalable	83.7	75.5	82.7	80.6	4.5	5.6%	81.78%
	Open Face Cassette	93.9	96.4	105.5	98.6	6.1	6.2%	100.00%
4	Aluminum Cyclone	8.4	11.1	9.6	9.7	1.4	13.9%	9.26%
	BGI Cyclone	14.5	14.8	13.4	14.2	0.7	5.2%	13.59%
	Respicon Respirable	8.1	8.3	8.1	8.1	0.1	1.2%	7.77%
	Respicon Thoracic	55.6	55.6	48.4	53.2	4.1	7.7%	50.78%
	Respicon Inhalable	107.8	88.8	77.7	91.4	15.2	16.6%	87.30%
	Open Face Cassette	102.5	112.7	99.0	104.7	7.1	6.8%	100.00%
5	Aluminum Cyclone	5.2	5.6	4.8	5.2	0.4	7.7%	6.55%
	BGI Cyclone	7.8	8.4	8.3	8.2	0.3	3.9%	10.29%
	Respicon Respirable	4.7	4.6	3.7	4.3	0.6	13.3%	5.48%
	Respicon Thoracic	32.9	31.7	33.6	32.7	1.0	3.0%	41.21%
	Respicon Inhalable	69.4	66.3	63.1	66.3	3.1	4.7%	83.52%
	Open Face Cassette	71.0	80.6	86.5	79.4	7.8	9.9%	100.00%
6	Aluminum Cyclone	7.3	9.3	8.1	8.2	1.0	12.2%	7.56%
	BGI Cyclone	10.8	13.1	13.1	12.3	1.3	10.8%	11.33%
	Respicon Respirable	8.1	6.8	7.8	7.6	0.7	8.7%	6.95%
	Respicon Thoracic	49.6	53.1	49.2	50.6	2.1	4.2%	46.51%
	Respicon Inhalable	100.5	90.3	96.8	95.9	5.2	5.4%	88.06%
	Open Face Cassette	101.7	107.5	117.5	108.9	8.0	7.3%	100.00%

Appendix C: Particle Density

Table 15 – Pycnometric Density Determination

Material	**1200**	**1200**		**Mean g/ml**
Pycnometer	37 (10ml)	47 (25 ml)		
Mass of clean, dry pycnometer (g)	14.17274	15.33123		
Mass of pycnometer + water (g)	24.21825	40.32354		
Mass of water (g)	10.04551	24.99231		
Volume of pycnometer (ml)	10.04551	24.99231		
Mass of solid (g)	0.53444	0.52398		
Mass of pycnometer + solid + water (g)	24.6044	40.7032		
Mass of water = total - solid - pyc (g)	9.89722	24.84799		
Volume of water (ml)	9.89722	24.84799		
Volume of solid (ml) = V pyc - V water	0.14829	0.14432		
Density of solid = g solid / ml solid	**3.604019**	**3.630682**		**3.617**
Material	**601**	**601**	**601**	
Pycnometer	37 (10ml)	47 (25 ml)	37 (10ml)	
Mass of clean, dry pycnometer (g)	14.17293	15.33167	14.16634	
Mass of pycnometer + water (g)	24.22423	40.3207	24.21454	
Mass of water (g)	10.0513	24.98903	10.0482	
Volume of pycnometer (ml)	10.0513	24.98903	10.0482	
Mass of solid (g)	1.51287	0.7525	1.52024	
Mass of pycnometer + solid + water (g)	25.33008	40.86717	25.32224	
Mass of water = total - solid - pyc (g)	9.64428	24.783	9.63566	
Volume of water (ml)	9.64428	24.783	9.63566	
Volume of solid (ml) = V pyc - V water	0.40702	0.20603	0.41254	
Density of solid = g solid / ml solid	**3.716943**	**3.652381**	**3.685073**	**3.685**
Material	**1000**	**1000**		
Pycnometer	37 (10ml)	37 (10 ml)		
Mass of clean, dry pycnometer (g)	14.14469	14.14372		
Mass of pycnometer + water (g)	24.20134	24.19553		
Mass of water (g)	10.05665	10.05181		
Volume of pycnometer (ml)	10.05665	10.05181		
Mass of solid (g)	0.42954	0.39439		
Mass of pycnometer + solid + water (g)	24.50858	24.47839		
Mass of water = total - solid - pyc (g)	9.93435	9.94028		
Volume of water (ml)	9.93435	9.94028		
Volume of solid (ml) = V pyc - V water	0.1223	0.11153		
Density of solid = g solid / ml solid	**3.512183**	**3.536179**		**3.524**