Analysis of aerodynamically respirable dust generated from quartz containing orthodontic and dental composites utilizing air rotary abrasion

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Analysis of Aerodynamically Respirable Dust Generated from Air Rotary Abrasion of Quartz Containing Orthodontic and Dental Composites

A thesis presented by Matthew Aaron Almeida

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Abstract:

Introduction: Quartz has been cited by the International Agency for Research on Cancer (IARC) as a human carcinogen. Exposure to quartz containing aerodynamically respirable aerosols (particle size of 0.5-5.0 μm) is possible during air rotary abrasion to remove the adhesive from teeth following orthodontic bracket debond. The purpose of this study was to: 1) characterize the particle size distribution of composite adhesive dust within an aerosol generated by air-rotary abrasion of quartz filled adhesives, 2) determine the potential for quartz exposure to the respiratory system, and 3) determine the effectiveness of dental masks in removing aerodynamically respirable dust (0.5 – 5.0 μm). **Methods:** Quartz-containing composites, Transbond XT (3M Unitek) and Light Bond (Reliance), were abraded into an aerosol using high speed air-rotary abrasion, and separated into size fractions using an 8-stage Cascade Impactor (Tisch, Cleves OH). In order to breakdown the distribution of dust particles, the average mass percent was calculated for each stage. The average filler percent per stage was determined by collecting the fractioned dust into porcelain crucibles and placing them in a 600°C furnace to vaporize the resin component. Separate trials using a Technol dental mask (Fisher Scientific, Hampton NH) covering the intake port were conducted using Transbond XT. The mass percent per stage, estimated number of particles per stage, and average filler percent per stage were analyzed and compared to the unfiltered Transbond trails. The data was analyzed using two-way ANOVA with Tukey's test. **Results:** The results showed that approximately 5% of the total dust generated was potentially aerodynamically respirable (particle size of 0.5 μm – 5 μm). The dust contained a decreasing percentage of quartz filler on average from 70-40% as particle sizes decreased. Calculations based on particle size and mass collected showed that billions of

dust particles were generated in the aerodynamically respirable range. Use of a dental mask removed over 99% of the dust mass that was collected, however it displayed little ability to filter dust particles in the 2-5 μm size range and offered no filtering protection from particles smaller than 2 μm. **Conclusion:** Exposure to aerodynamically respirable dust containing quartz particles appears likely during orthodontic adhesive removal with a high-speed handpiece. The results showed that use of a dental mask did not protect operators from exposure to smaller sized particles which are the greatest risk for inhalation to deeper regions of the lungs. Further studies are needed to determine the extent of this exposure in clinical settings.

Introduction:

The bonding of brackets to teeth using composite adhesives has been the standard of practice in the orthodontic profession for decades. In order in provide clinically adequate bond strength, some of the composites rely upon the use of quartz as a filler agent (Collard 1991). Of potential concern, quartz has been recognized by the International Agency for Research on Cancer (IARC) as a human carcinogen, and can be responsible for the deadly lung disease, silicosis (IARC 1997). Silicosis is characterized by a nodular pulmonary fibrosis throughout the lungs (Hunter 1955). These pathologic changes generally take years if not decades to occur following exposure.

One of the easiest and most effective means of removing composite adhesive following orthodontic bracket debonding is with air-rotary abrasion using a high-speed handpiece (Ireland 2003). This procedure generates a dust aerosol that is spread throughout the work environment (Harrel 2004). Within this aerosol, dusts particles between 0.5μm – 5μm have the ability to travel to the lung's terminal alveoli without being filter out in the upper respiratory tract. Particles in this size range have been termed aerodynamically respirable (Collard 1991, Giordano 2000). It is believed that these aerodynamically respirable dust particles are composed of resin as well as filler components. Therefore exposure to these particles may place orthodontic operators at risk to develop silicosis.

The use of universal precautions such as the dental mask is commonly thought to protect operators from this type of exposure (Brune 1980). However studies suggest that dental masks filter out only about 70% of the dust mass under ideal circumstances (Brune 1980, Korn 1989, Collard 1991, Harrel 2004). This indicates that reliance on dental masks alone may not provide protection from aerodynamically respirable exposure.

This project had four purposes. First, it sought to design a filtration and collection apparatus and develop a protocol to quantitate aerodynamically respirable orthodontic adhesive dust generated by air rotary abrasion. The second aim was to analyze the mass percent of the aerodynamically respirable dust relative to the total dust collected. The third goal was to analyze the collected dust to determine the relative amounts of quartz silica filler present within the aerodynamically respirable dust samples. The final aim was to determine the effectiveness of a dental mask at filtering aerodynamically respirable dust. The hypothesis for each purpose respectively is that 1) using an 8-stage non-viable cascade impactor air sampler, aerodynamically respirable dust can be isolated; 2) air rotary abrasion from high-speed dental handpieces will produce a significant, measurable amount of aerodynamically respirable dust in the particle size range of 0.5-5.0 μm; 3) aerodynamically respirable dust from orthodontic adhesives will contain significant amounts of crystalline quartz; and 4) dental masks provide little to no protection from aerodynamically respirable dust when filtering the particles from sampled air.

Background and Significance:

The use of composite adhesives to bond orthodontic brackets to teeth has become nearly universal throughout the world. These composites are very similar to the types of composites used in restorative dentistry. They all contain a resin component that is mainly Bis-GMA (bisphenol A diglycidylether methacrylate). They also contain a filler component which is generally a hard substance such as silica, glass, or aluminum silicate. Finally, some sort of chemical or photoactive initiator is used to promote curing of the composite. These can be benzoyl peroxide / tertiary amine for chemical activation or in the case of photoactivation, the radical generator is champhorequinone. The difference between the two classes is the formulation of the components. For instance, the necessary bond strength needed to endure orthodontic and masticatory functions is approximately 5.0-7.8 MPa (Reynolds, 1975). Therefore, orthodontic adhesives generally use larger filler particles of around 1-5 μm, and use it to the extent of 70% by mass. This is different from restorative composites which generally use smaller, submicron particles and a variety of filler levels depending on the composite's intended function (Collard 1989, Collard 1991, Ireland 2003).

During orthodontic debonding, brackets are removed using a peeling motion, inducing bond failure at the interface between the bracket and the composite adhesive. The adhesive that remains bonded to the tooth can then be removed with instruments such as hand scalers, ultrasonic scalers, or with air rotary abrasion. Air rotary abrasion is the most common and effective means of composite removal and can be accomplished using either high or slow-speed handpieces (Ireland, 2003). Although effective, the process generates aerosols that can accumulate dust on the operator's hands, patient's face, operatory equipment, and into the surrounding air. This aerosol can be spread for a

distance of at least 18 inches (Harrel 2004). The air-driven high-speed handpiece is second only to ultrasonic cleaners in generation of airborne contamination (Miller 1978). Further, from a bacterial standpoint, air abrasion generates environmental bacterial counts that nearly equal those generated by ultrasonic scalers (Harrel 2004).

Two research projects published in 1989 and 1991 by Dr. Stephen Collard introduced dentistry to what in the environmental hygiene industry is called *aerodynamically respirable* dust. He took restorative composites, ground them with high-speed air-rotary abrasion, and analyzed the dust. Aerodynamically respirable dust is the term used to describe any aerosol which contains particles that are within the 0.5-5.0 μm size range (Giordano, 2000). Dust in this size range has the potential to be biologically dangerous. Because the particles are so small, they are easily maintained in the airstream over long distances, thus bypassing the body's built-in filtering mechanisms. Larger particles are mainly deposited in the upper respiratory tract and upper bronchioles of the lung where alveolar macrophages and mucociliary elevator mechanisms can efficiently remove them from the lungs (Reiser, 1979). Particles between 0.5-5.0 μm in size, however, are likely to be deposited in the terminal, non-ciliated alveoli (Collard 1991, Harrel 2004). Here the body depends almost entirely on macrophages to consume and clear any debris. In most cases this mechanism is sufficient, but as has been shown with asbestos inhalation the processes can be ineffective. The asbestos particles induce fibrotic changes in the lungs that can lead to respiratory failure and cancer in the form of mesothelioma (Collard 1989).

As mentioned previously, some orthodontic adhesives use silica as a filler material. Silica has three crystalline forms; quartz, cristobalite, and tridymite (Donaldson 1992). All of these forms have been recognized by the International Agency for

Research on Cancer as a group I human carcinogen (IARC, 1997). It has also been recognized as a human carcinogen by the National Toxicology Program (NTP, 2000). When aerodynamically respirable crystalline silica is inhaled, it can cause damage to the pulmonary tissues. This inflammation tissue can be converted in time into collagenous scars, which can cause permanent constriction and deformities of bronchi and bronchioles (Gross 1970). Ultimately, this can lead to a debilitating and deadly form of pneumoconiosis (pulmonary fibrogenic disease associated with the inhalation of dusts) called silicosis (Hearl, 1997).

Silicosis is characterized by a nodular pulmonary fibrosis throughout the lungs (Hunter 1955). These pathologic changes generally take years if not decades to occur following exposure. The chronic nature and need for long term exposure may explain why little attention has been paid to this disease in the dental and orthodontic literature. Industrial hygiene groups have long since recognized the potential hazards of silica on the human lung (Wozniak 1979, Dufrensne 1987, Luchtel 1989, Hearl 1997, Bello 2002, Linch 2002, Yabuta 2003). It is possible that the clinical dental community has not been using these materials in dentistry for a sufficient length of time to observe widespread pathology, or they not have reached exposure levels large enough to cause disease.

Three factors that affect pathogenicity of silica are microstructure, particle size, and concentration (Collard, 1991). Silica is found in either an amorphous or a crystalline form (Dufresne 1987). The crystalline form has been found to be the more pathogenic. Tridymite is the most fibrogenic, followed by cristobalite and quartz (Reiser 1979). The exact mechanism of pathology is not known. Studies suggest that it may be due to negative surface charges on the dust particles (Horvath 1976, Wallace 1990). Others suggest that the shape of the crystal can cause physical damage to the cells they

encounter (Soutar 1999). The size of the particles also can greatly influence pathogenicity. Particles in the range of 0.5 to 5 μm can make their way into terminal alveoli where removal is solely dependent on macrophage clearance (Reiser 1979, Collard 1989, Giordano 2000). It is in these terminal alveoli that the fibrogenic changes are initiated leading to pulmonary constriction. Reiser (1976) suggests that particles between 1.0 and 2.0 μm are the most fibrogenic. Concentration and length of exposure will also act to determine if the disease will be acute or chronic.

Acute silicosis occurs when large doses of aerodynamically respirable aerosols are inhaled over a short period of time. Death in these cases usually occurs in 1-2 years due to progressive respiratory failure. There is no effective treatment in these cases (Reiser, 1976). Although this type of exposure is unlikely in a typical orthodontic setting, chronic exposure can lead to a similar disease called chronic silicosis. Chronic silicosis develops as a result of frequent, low dose exposures to silica. The threshold exposure is usually measured as a concentration ratio of silicon/sulfur in the pulmonary tissues. When the Si/S ratio exceeds 0.3, clear-cut pulmonary changes are imminent (Funahashi 1984). Until this occurs, the disease may remain entirely asymptomatic for decades. In industries were the risk of silica inhalation has been highly recognized such as mining, tunneling, and brick making, routine pulmonary radiographic tests are generally taken. Workers may go for years without any radiographic or respiratory function changes. Only when the characteristic fibrotic nodules develop within the lungs will the pulmonary changes become noticeable on chest x-rays. A slowly progressive constriction of the repiratory pathway with loss of function ensues. As in the acute case, management is directed solely at alleviating symptoms management (Reiser, 1976).

Another concern is that non-aerodynamically respirable dust may also present a health concern. Because the nose and upper respiratory tracts will likely filter out these larger mass particles they, will not contribute to lung pathology. However, Bello (2002) believes they may contribute to elevated cancers of the buccal cavity, throat, and GI tract. Further, several epidemiologic studies have implicated the ingestion of silica as a cause of esophageal cancer (Rose, 1968a,b; O'Neill et al., 1980, 1982; Newman, 1986). As the upper respiratory tract filters higher mass dust particles, they are generally cleared from the body through ingestion. As a result, a reported 2.8-fold risk increase in esophageal cancer along with a clear dose-response by length of exposure has been found in industries were silica dust inhalation is common (Pan 1999).

There is also a theory called *particle toxicity*, which states that inhaled particles can have adverse health effects irrespective of chemical composition. For example, titanium dioxide dust has a low biological toxicity and is considered inert. However, large doses of it have been shown to cause failure of lung clearance, chronic inflammation and fibrosis, and a few cancers in rats (Lee 1985). What is unclear is whether or not humans respond with equally susceptibility. What must be kept in mind is that pneumoconiosis has been documented from a wide range of occupationally exposed dusts. This is supported by, Gross (1970) who found pulmonary changes induced by "safe" material dusts such as glass, ceramic aluminum silicate, and brucite. These dusts induced the mobilization of macrophages, which consumed the dust and occupied alveolar spaces. This in turn evaginated off respiratory bronchioles and alveolar ducts. The walls of these alveoli were thickened by a combination of surface cell enlargement and arborescence of the septal argyrophilic stroma. This further led to the development of fibroblastic tissue processes. In time these areas were resolved, but it opened

questions as to the effects of repeated insults and the long term responses of the alveolar tissues.

The link between silica and pulmonary fibrosis leading to cancer appears at first to be reasonably clear-cut. However, it should be pointed out that not all research is in agreement. Soutar (2000) has eloquently compared various studies and points out the strengths and faults of each. He brings to light that the role of silica in the development of lung pathology may not be as direct as we believe it to be. Most interesting is the study done by Davis (1983) were occupational dust exposures in Vermont granite workers were examined. The study included extremely detailed records of dust and quartz measurements, as well as a series of cross-sectional surveys. He concluded that there was no relationship between silica exposure and lung cancer (1983). It should be noted that this study commenced in the 1920's and it required conversions from particle counts to gravimetric measurements. This caused large errors in exposure estimates and weakened the power of the study. A second study of British coal miners from the 1950's also found no relation between silica exposure and lung cancer (Miller 1997). It should be noted that in this study silica content in the respirable dust was less than 10%. No data was given as to whether or not this silica was free or bound to other components within the dust. Finally, Gross (1979) pointed out that rats inhaling 100 mg/m^3 of fibrous glass for more than a year did not produce any proliferative lesions.

In regard to the dental literature, the group that has received most of the concern regarding hazardous exposure to respirable dental and orthodontic materials has been on laboratory technicians (Mjor 1985). It has been generally believed that high-volume evacuation systems as well as the use of dental facemasks protect orthodontic operators from the hazards of airborne dusts. The typical high-volume system used in clinical

practices has an aperture diameter of 0.95 cm and an air displacement of 10 standard cubic feet per minute (scfm). This is equivalent to 4.72 liters per second (L/m). By definition, this does not classify as high-volume evacuation (HVE; Harrel 2004). Brune (1980) determined that an effective evacuation system should have an aperture diameter of 3.5 cm and an air displacement of 30 L/m to effectively remove respirable dust. Even at this rate research suggests that only 90% of contamination is removed (Harrel 2004). This difference suggests that orthodontic evacuation system's air displacement and dust removal is at most only 16% of what is considered adequate (Collard, 1991).

The facemask traditionally worn by dental clinicians may give a false sense of protection from respirable dusts. Brune (1980) pointed out that the three-dimensional network structure of the dental facemask constitutes a pore size ranging from 10 to 100 μm. This will reduce inhaled dust in some cases by only 70% based on weight, allowing particles in the critical size range of 0.5 to 5.0 μm to pass unimpeded through the mask (Brune, 1980). In essence, the masks that the dental industry relies on for protection are only equivalent to a coarse-dust mask used in the mining industry. Thus clinicians are poorly protected and are at significant risk from breathing respirable silica under the circumstances commonly found in most clinical settings (Korn, 1989).

To date, no published data is available which addresses the quantity and quality of dust generated when orthodontic adhesives are air-rotary abraded. This project seeks to determine if high-speed abrasion generates aerodynamically respirable dust. Secondly, this study will determine if and to what extent quartz filler is present within the aerodynamically respirable dust. It will also estimate the number of particles that is present within the aerodynamically respirable dust. Lastly, it will determine the effectiveness of a dental mask to remove dust particles within the aerodynamically

respirable size range, and characterize the size of the particles that are able to penetrate the mask.

Materials and Methods:

Composite Sample Fabrication

Two commercially available light cured orthodontic adhesive resins were examined: Transbond XT (3M Unitek, Monrovia, CA), and Light Bond (Reliance, Itasca, IL) (Table I).

Table I. Fillers in composites, as reported by manufacture

Composite	Filler Type	Weight Percent	Average Size(μm)
Transbond	Quartz	70	3
Light Bond	Quartz	78	5

A vacuum mold of a 3 mm thick x 12 mm diameter disk was made using 2 mm x 125 mm round Biocryl (Great Lakes, Tonawanda, NY) material in a Ministar (Great Lakes, Tonawanda, NY) machine. This size disk ensured that an adequate amount of dust was generated for particle size measurements. Composite disks were then made using this mold for each composite type and cured for 60 seconds using an Ortholux (3M Unitek, Monrovia, CA) LED light. A small composite projection ("handle") was formed on the top of the disk (Fig. 1.). Three disks for each of the two composites were fabricated. They were weighed on a digital balance (A&D Company, Model GR-120, Tokyo, Japan) to a tenth of a milligram. The mass recorded as M_i.

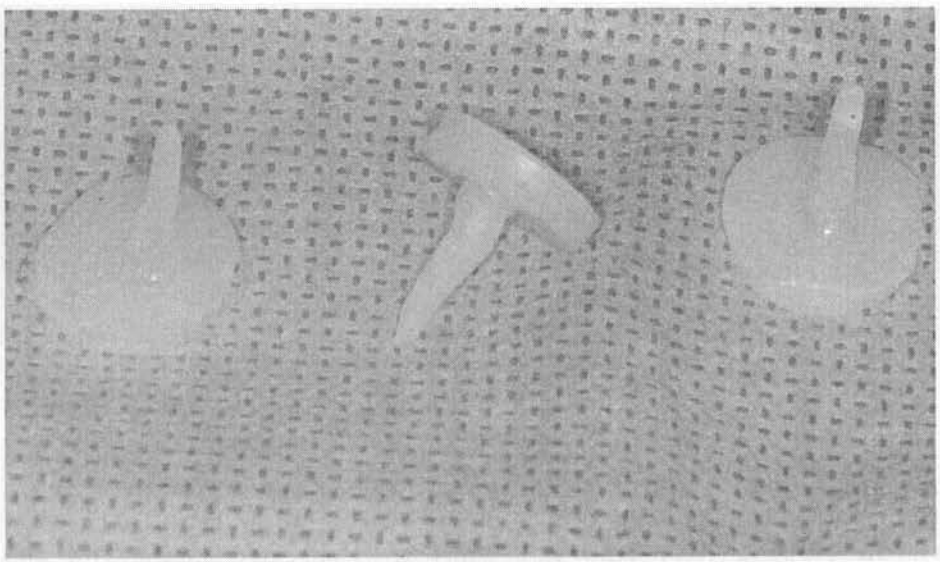


Figure 1. 3 Composite Samples showing disk that was abraded and attached handle

Dust Collection

The testing apparatus used to collect the dust generated from grinding the composite disks consisted of a 50 x 35 x 30 cm Plexiglas box connecting to a multi-stage, multi-jet, Cascade Impactor type air-sampler (Tisch Environmental, Model 20-800, Cleves, OH) (see appendix A) with attached vacuum pump (Reliance Electric, Model 1531-107B-G557X, Gallipos, OH). The air-sampler was attached to a 2.54 cm hole in the right wall of the box by way of the plastic hose. The vacuum pump, calibrated to draw 28.3LPM, was attached to the air-sampler (Fig. 2.).

Figure 2. Test chamber with handpiece (R) with cascade impactor (center) attached to vacuum pump (L)

The three composite disks from each composite type were ground into dust using a carbide finishing bur (Brassler USA, H48L, Savannah, GA), in a high-speed handpiece (Dentsply, Des Plaines, IL) without water spray. Light pressure and intermittent shaving strokes were used, which maintained a smooth, flat surface on the composite disk. The handpiece was run at 70 psi. During the grinding event, aerosol from within the box was drawn into the air-sampler. The atmospheric pressure within the box was maintained by an open 2.54 cm diameter hole in bottom of the box opposite the intake assembly. The distance from the bur to the hole leading to the air-sampler was held at approximately 33 cm (13 inches). This has been cited as the average distance an operator's head will be for the operating field (Chasteen 1978). Following each run the collected dust was analyzed as described below, and the apparatus was cleaned and reassembled for the next sample to be processed. The bur was changed after every grinding each disk.

Dust Segregation

Inside the air-sampler dust particles were separated automatically into the eight stages of the compactor based on aerodynamic diameter (see appendix A). According to the manufacture's specifications, 95% of unit density spherical particles collected in each stage will be within the particle size cutoff values listed in Figure 3. This diagram also depicts where the fractions, if inhaled, would settle out in the human respiratory tract.

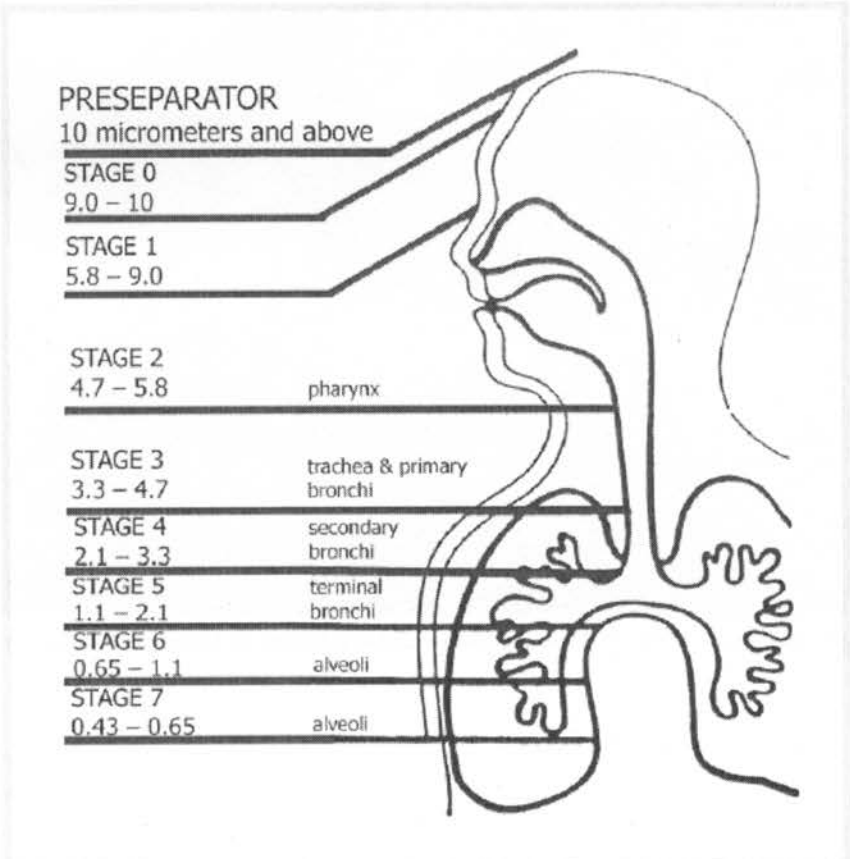


Figure 3 Cut-off diameters and estimated particle penetration by stage (modified from Tisch Cascade Impactor manual pg. 7)

The mean and median diameters of particles collected in a stage are assumed to be equal. This particle size is referred to as the mass median diameter (MMD). The distribution is also assumed to be normal (see Appendix 1). The MMD of unit density spheres (d_o) for each stage were calculated. The particle density (p_c) is normally estimated at 1.0 g/m^3.

The stage cut-off values are used to determine each particle's Equivalent Aerodynamic Diameter (AED). Based on the definition of aerodynamically respirable dust as having particles that range in size from 0.5-5.0 μm, any dust found on stages 4-8 was considered aerodynamically respirable.

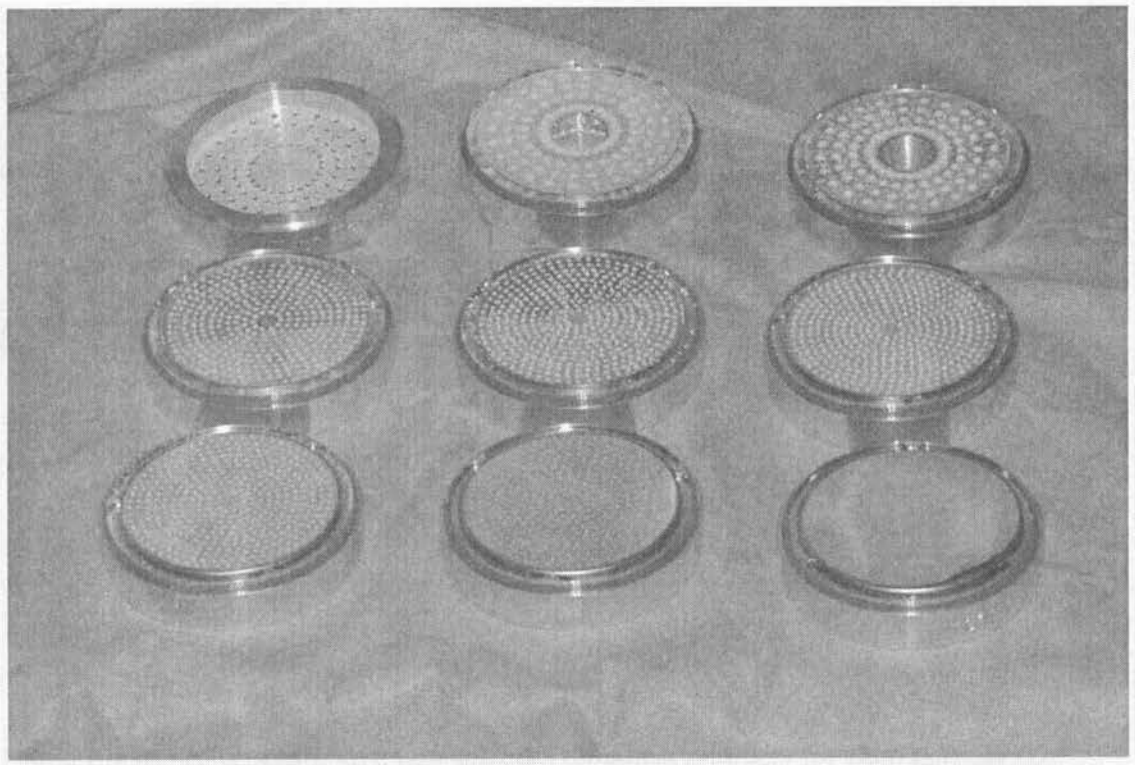


Figure 4. Composite dust collected in impactor stages. Preseparator (UL) with stages 1 through 8 (L to R and U to D)

Mass of Dust Collected

The vacuum pump remained on for 5 minutes after the three disks were ground into dust while the chamber was aerated with a dental air/water syringe to free any trapped aerodynamically respirable dust. The mass of the collected dust was analyzed using the formulation suggested by Collard (1991) and the manual provided with the

Cascade Implactor by Tisch Environmental. The composite handles were then removed from the box, collectively weighed and the mass recorded as M_H. This value was subtracted from the initial mass (M_i) to determine the mass of dust generated (M_{DG}): $M_{DG} = M_i - M_H$. The air-sampler was disassembled, the eight trays removed and individually weighed, and the net mass of dust collected in each stage (MS_n) was determined by subtracting the weight of the tray alone which was measured prior to each experiment, where n indicates the stage number (n = 0, 1,….,7). The total mass of dust collected (M_{DC}) in the eight stages was determined by:

$$M_{DC} = \Sigma\, MS_n$$

The mass percent dust collected (MPDC) out of the total generated dust mass was determined by:

$$MPDC = (M_{DC}/M_{DG},) \times 100$$

The mass percent of dust collected in each stage was determined by:

$$(MS_n/M_{DC}) \times 100$$

Using Figure 4, the lower size was selected (smallest number) for each particle size range. This number represents the Effective Cut-Off Diameter (ECD) for each Impactor Stage. This ECD can also be determined by viewing Figure 5.

Particle Diameter (microns)
≥ 9.0
5.8 - 9.0
4.7 - 5.8
3.3 - 4.7
2.1 - 3.3
1.1 - 2.1
0.7 - 1.1
0.4 - 0.7
0.0 - 0.4

Figure 5. Effective Cut-Off Diameter

The results of the particle size analysis was plotted on Log-Probability paper with the Effective Cut-Off Diameter as the ordinate and the cumulative percent less-than the particle size range by weight as the abscissa (Fig. 6). By assuming a log-normal particle size distribution, the particle size Geometric Standard Deviation (σg) is determined by:

$$\sigma_g = \frac{84.13\ \%\ \text{Diameter}}{50\%\ \text{Diameter}} = \frac{50\ 5\ \text{Diameter}}{15.87\%\ \text{Diameter}}$$

Whenever these two Standard Deviations were not equal (such as represented in a Bimodal size distribution), the Impactor measured size distribution was not represented by a straight line and therefore not truly log-normal. A preferred method of presenting the Standard Deviation was:

$$\sigma_g = \left(\frac{84.13\ \%\ \text{Diameter}}{15.87\ \%\ \text{Diameter}} \right)^{1/2}$$

It is commonly accepted that the Particulate Size Distribution should be presented in graphical form rather than reporting the Mass Mean Diameter and the Standard Geometric Deviation. By plotting the ECD vs. cumulative the particle concentration for any particle size range can be determined (Fig. 6).

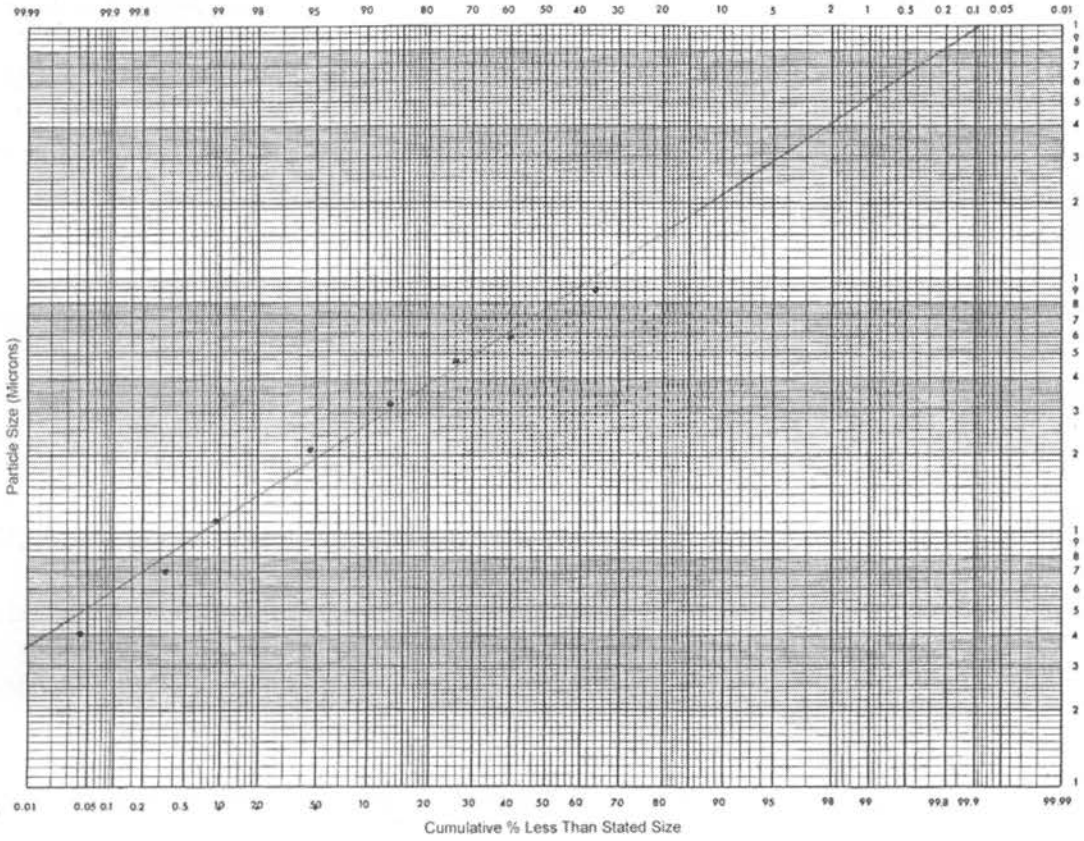


Fig. 6 Log probability graph of particle size vs. cumulative mass % less than stated size (Transbond #1)

Estimated Number of Particles Collected

The estimated number of particles was determined using the method provided by Tisch Environmental's Cascade Impactor manual. The number of dust particles collected in each stage (NS_n) is calculated by:

$$NS_n = MS_n/MP_n$$

MS_n is the mass of dust collected in stage n. MP_n is the mass of a MMD dust particle collected in the same stage, calculated by:

$$MP_n = \rho_c \times VP_n$$

VP_n is the volume of a MMD dust particle collected in the same stage. For a spherically shaped MMD dust particle $VP_n = (\pi/6 \times (d_c))^3$, so that $NS_n = (6 \times MS_n) / (\pi \times (d_c)^3 \times \rho_c)$. The total number of dust particles collected (N_{DC}) in the eight stages is determined by:

$$N_{DC} = \Sigma NS_n$$

The percent of the dust particles collected in each stage was determined by: $(NS_n/N_{DC}) \times 100$. The cumulative percent of dust particles collected for the stages below was plotted against d_c for each stage on a log-probability graph. A first order regression was plotted on the same graph. The corresponding mass percent and number particle size distribution means were compared for significant differences by one-way analysis of variance (ANOVA) and Tukey's multiple comparison test ($p < 0.05$).

Percent Filler in the Dust

The collected dust was then placed into pre-weighed porcelain crucibles. The leftover composite handle was also placed into a pre-weighed porcelain crucible. The air-sampler was ultrasonically cleaned for 10 minutes in mild soap, rinsed with deionized water, ultrasonically cleaned for 10 minutes in deionized water and air dried. The stainless steel collection trays were weighed and the air-sampler reassembled. The Plexiglas box and plastic tube was washed with mild soap, rinsed with deionized water and air-dried. The dust collection apparatus was reassembled and the procedure repeated for each composite. The porcelain crucibles were then reweighed to determine the mass of the contents and then placed into a furnace (Fisher Scientific, Isotemp 10-650-14A, Hamptom, NH) to vaporize the resin component of the collected dust. The furnace temperature was held at 600°C without vacuum (Fig 7).

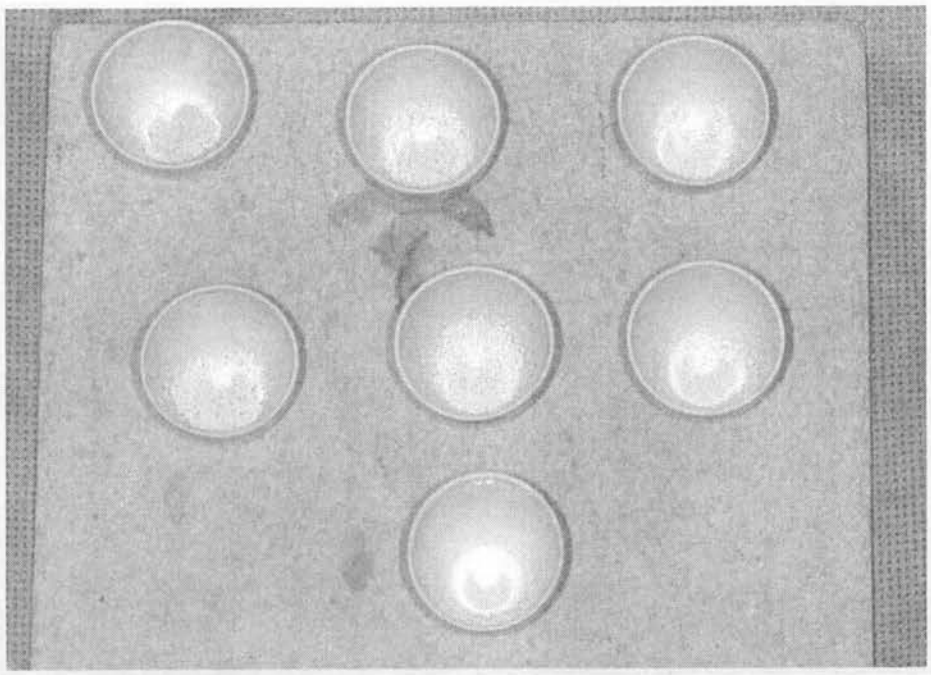


Figure 7. Collected dust samples from stage 1 to 7 in porcelain crucibles (L to R)

The samples were heated to constant mass to ensure the entire resin component was vaporized. This left only filler material in the crucibles. Using this mass, the percent filler in the composite dust was determined. The percent filler in the samples on each stage (Sn) was then compared using one-way ANOVA and Tukeys test ($p < 0.05$), and qualitatively compared to the percent filler in the cured composite handles (CC). Comparisons were made between CC vs. Sn and Sn vs. Sn one-way ANOVA and Tukeys test ($p < 0.05$). The procedure was repeated for each composite type.

Dental Mask as Filter Collection

As a related pilot study in this project, three composite disks were fabricated from Transbond[a] in the same manner as described in the "Density of Composites" section. The collection apparatus was modified to include a dental mask (Kimberly Clark, Tecnol

Procedure Mask, Roswell, GA) placed over the intake orifice of the air sampler (Fig. 8 & 9).

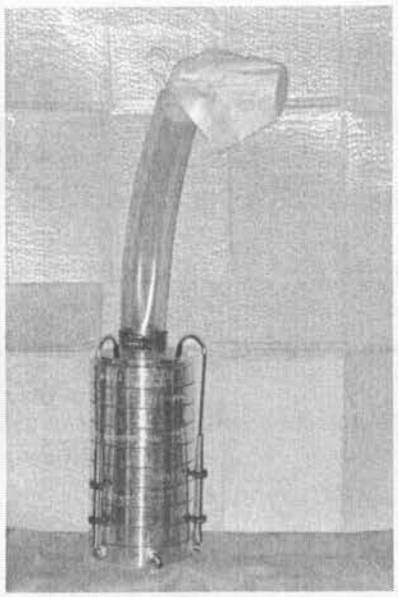


Figure 8. Impactor w/mask attached to intake

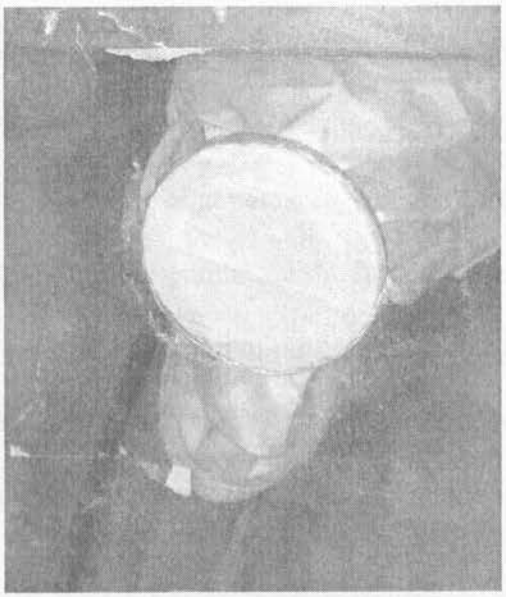


Figure 9. Mask viewed from inside collection chamber

The collected samples were abraded and analyzed as described in prior sections. The dental mask was weighed before (Mi) and after the experiment (Mf) to determine the mass of dust collected (DMc) in the mask using: Mf – Mi = DMc. The percent filler isolated from the samples was averaged over each stage and compared statistically against the Transbond[a] sample generated without filtration by using two-way ANOVA and Tukeys test ($p \leq 0.05$).

Results:

Log Probability Graphs:

Log probability graphs for each trial conducted were generated (Appendix B). The plots were generated by placing the Effective Cutoff Diameter as the ordinate and the cumulative percent less-than the stated particle size range by weight as the abscissa (see Fig. 5). This means a given point on the graph describes what percentage of the dust is equal to and smaller than the size stated. Log probability graphs are the standard means to display air sampling results, and allow for easy visualization of particle distribution. A first order linear regression plot has been included for each graph. This allows one to quickly reference where the particles of any given percentage are distributed and what particle size fraction it belongs to.

Mass Percent / Stage:

Results of the Transbond and Light Bond mass percents vs. stage number are shown in Appendix C, Table I. The mass percent of dust generated from the two adhesives distributed differently over the eight stages, however there was no difference between the composite types. This is because when the mass percentages are summed together by the statistical package each composite data set adds up to 100. For this reason there will be no difference when comparing these groups and the statistical software will report that the data sets are equivalent. There was a difference between the individual stages. Results of Tukey's test showed that the mass percent on each stage was statistically equivalent for the two adhesives, except Light Bond had more on stage 1 and Transbond had more on stage 4.

In the Transbond trials, there was a decrease in mass percent collected in the smaller particle size ranges (Table II, Fig. 10). The average ranged from 32% in the upper stages (larger particles) to only a fraction of a percent in the smaller stages. Stages 4-8 represent the aerodynamically respirable fraction. These stages represent 29.76% of the collected dust mass percent. Tukey's multiple comparison tests showed that stages 1 and 2 collected significantly different mass percentages. Stages 3, 4, and 5 were equivalent and less than 1 and 2. Stages 5 and 6, as well as 6, 7, and 8 were also found to not be significantly different. Horizontal bars found in figures 10 – 17 connect stages found to be equivalent by Tukey's test.

Table II. Mass Percent of Transbond by Stage

				Impactor Stage				
Trial	1	2	3	4	5	6	7	8
2	35.83	23.56	14.04	13.55	8.40	3.71	0.58	0.29
3	32.45	22.55	14.85	15.41	9.56	4.22	0.79	0.17
4	28.54	25.79	13.05	15.55	10.04	5.56	1.12	0.36
AVG	32.28	23.97	13.98	14.84	9.33	4.49	0.83	0.27
SD	3.65	1.66	0.90	1.12	0.84	0.95	0.27	0.10

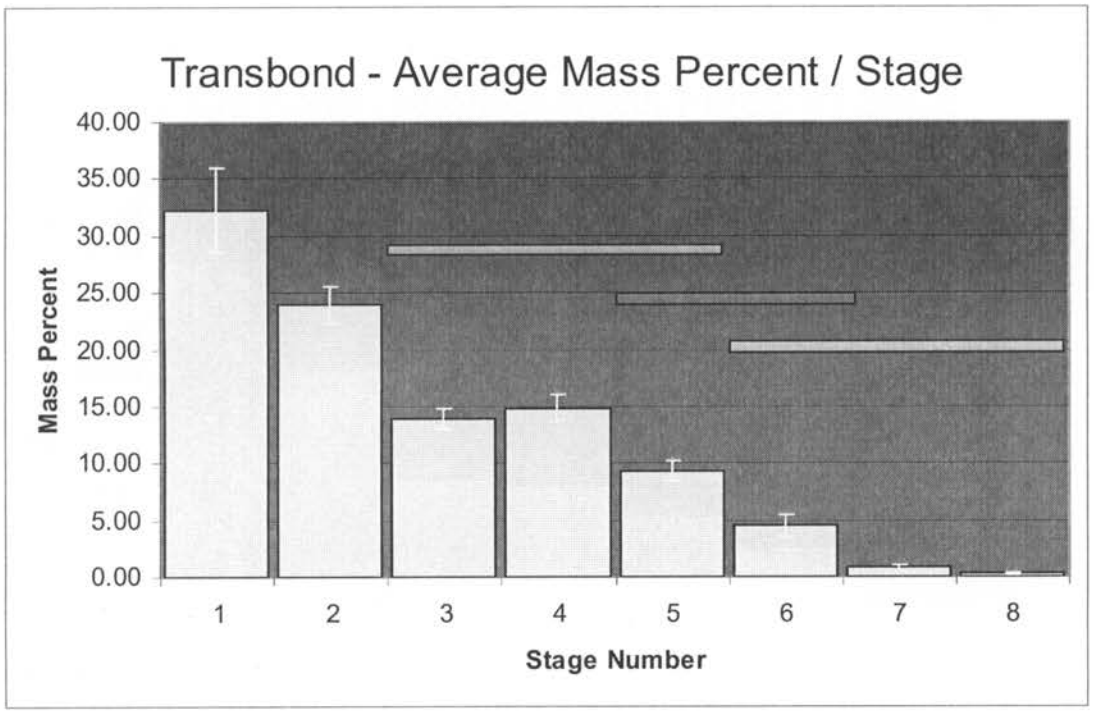


Figure 10. Transbond – Average Mass Percent by Stage showing decreasing mass percent with increasing stage number. *horz. bars indicates sig. equivalent groups

The Light Bond trials showed similar trends in mass percent decrease with particle size decrease (Table III, Fig. 11). Light bond displayed slightly higher initial mass percents with values ranging from 39% in upper stages to 0.4% in the lowest stage. Aerodynamically respirable dust accounted for 23.32% of the collected dust mass. Stages 1 and 2 collected statistically different percentages, there was no difference between stages 3, 4 and 5, also 5 and 6 were equal.

Table III. Mass Percent of Light Bond by Stage

				Impactor Stage				
Trial	1	2	3	4	5	6	7	8
2	33.04	25.50	13.64	13.49	9.09	4.24	0.80	0.19
3	43.20	24.48	10.76	10.55	7.07	3.26	0.52	0.15
4	40.85	26.69	11.86	9.87	6.68	3.27	0.70	0.07
AVG	39.03	25.56	12.09	11.30	7.62	3.59	0.67	0.14
SD	5.32	1.11	1.45	1.92	1.30	0.57	0.14	0.06

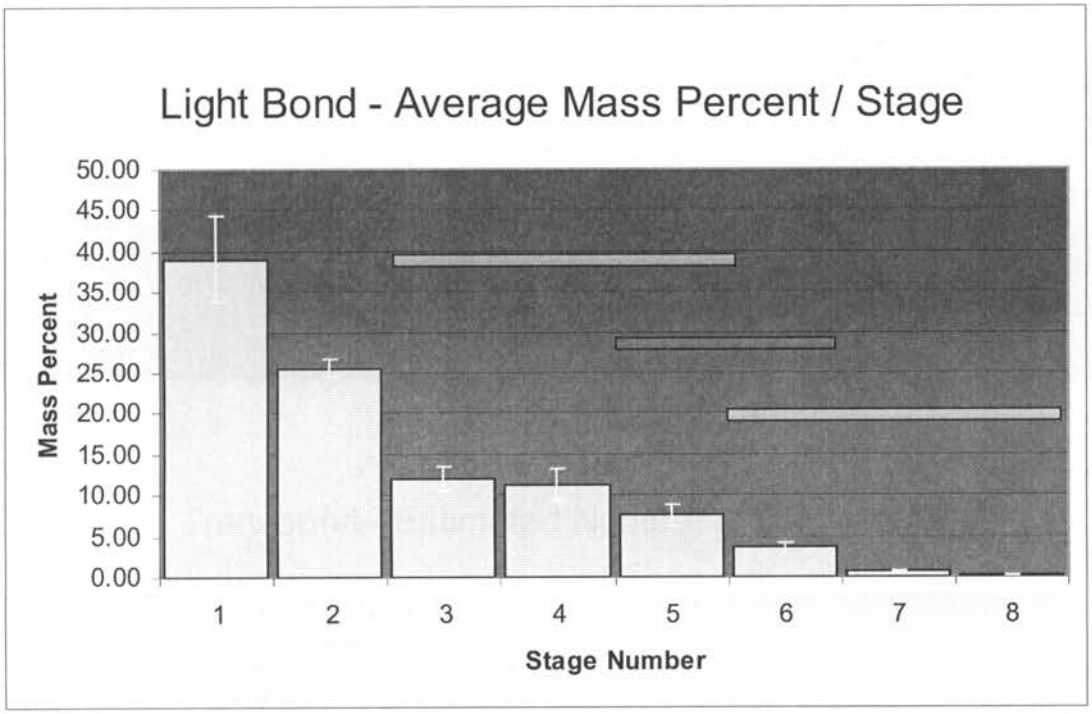


Figure 11. Light Bond – Average Mass Percent by Stage showing decreasing mass percent with increasing stage number. *horz. bars indicates sig. equivalent groups

Estimated Number of Particles / Stage:

Two-way ANOVA comparing Transbond's estimated number of particles vs. Light Bond's estimated number of particles vs. Stage was conducted (Appendix C, Table II). It showed that there was no difference in material type. There was a significant difference between the individual stages, and this was tested with Tukey's test. Finally, there was no interaction between material type and stage number.

The mass percent was not an indictor of the number of particles represented in each stage. In the Transbond sample, as particle size decreased, the number of particles found in each stage increased (Table IV, Fig. 12). Approximately, 4.4830×10^{10} were recovered from the aerodynamically respirable size fractions. Tukey's test showed that stages 1 – 5 were equivalent, and that stages 6-8 were equivalent.

Table IV. Estimated Number of Particles of Transbond / Stage

				Impactor Stage				
Trial	1	2	3	4	5	6	7	8
2	2.28E+08	5.60E+08	6.27E+08	1.75E+09	4.21E+09	1.29E+10	7.80E+09	2.09E+10
3	1.51E+08	3.93E+08	4.86E+08	1.46E+09	3.51E+09	1.08E+10	7.80E+09	8.95E+09
4	1.47E+08	4.95E+08	4.71E+08	1.62E+09	4.06E+09	1.56E+10	1.22E+10	2.09E+10
AVG	1.75E+08	4.83E+08	5.28E+08	1.61E+09	3.93E+09	1.31E+10	9.28E+09	1.69E+10
SD	4.57E+07	8.44E+07	8.63E+07	1.47E+08	3.70E+08	2.44E+09	2.57E+09	6.89E+09

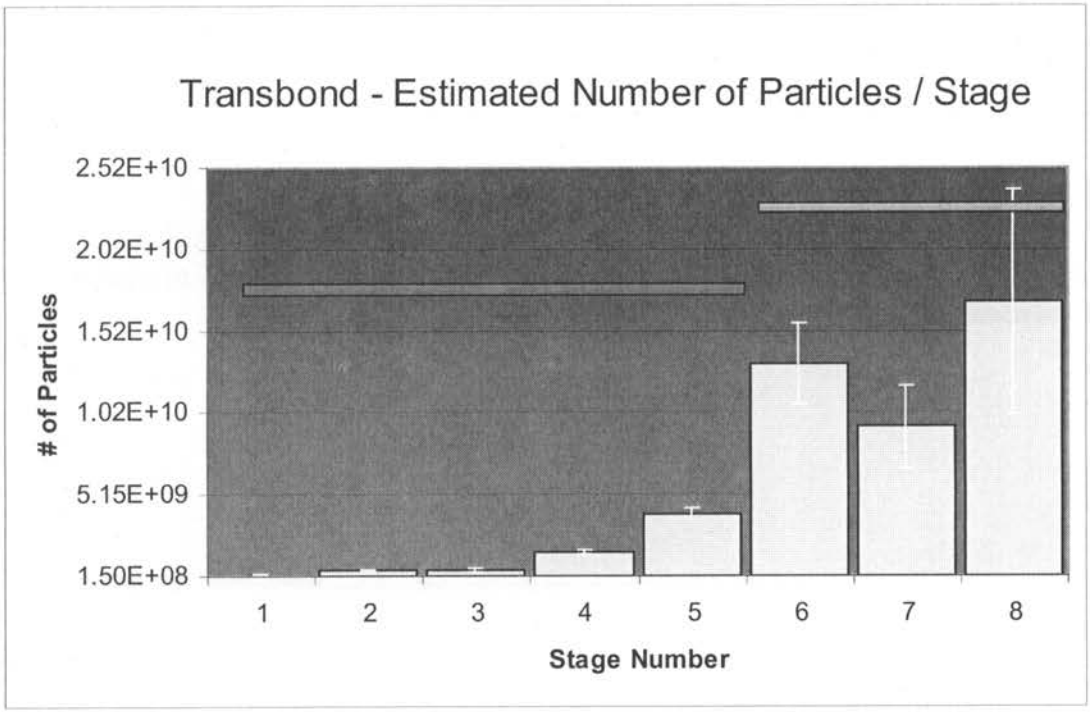


Figure 12. Transbond – Estimated Number of Particles / Stage *horz. bars indicates sig. equivalent groups

Light Bond showed similar trends with increasing particle counts as the particle size range decreased (Table V, Fig. 13). Approximately, 4.93 x 10^{10} were recovered from the aerodynamically respirable size range (stage 4-8). As with the Transbond sample, Tukey's test showed that stages 1-5 and 6-7 were equivalent.

Table V. Estimated Number of Particles of Light Bond / Stage

				Impactor Stage				
Trial	1	2	3	4	5	6	7	8
2	2.28E+08	6.59E+08	6.62E+08	1.89E+09	4.95E+09	1.61E+10	1.17E+10	1.49E+10
3	3.68E+08	7.79E+08	6.44E+08	1.82E+09	4.74E+09	1.52E+10	9.47E+09	1.49E+10
4	4.42E+08	1.08E+09	9.01E+08	2.17E+09	5.69E+09	1.94E+10	1.61E+10	8.95E+09
AVG	3.46E+08	8.39E+08	7.36E+08	1.96E+09	5.13E+09	1.69E+10	1.24E+10	1.29E+10
SD	1.09E+08	2.17E+08	1.44E+08	1.83E+08	4.99E+08	2.20E+09	3.40E+09	3.45E+09

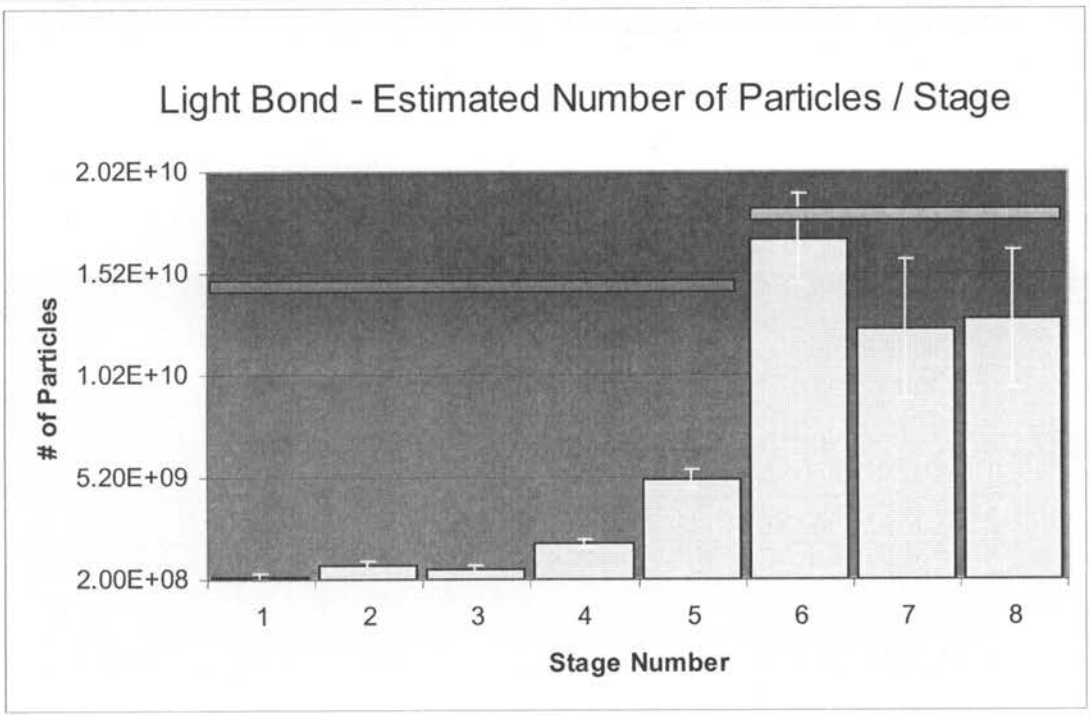


Figure 13. Light Bond – Estimated Number of Particles / Stage *horz. bars indicates sig. equivalent groups

Percent Filler / Stage:

The two-way ANOVA comparing Transbond filler percent vs. Light Bond filler percent vs. Stage (Appendix C, Table III) showed that there was a difference based on material type. There was a significant between the individual stages. Tukey's test was then used to determine which stages were different as previously discussed. Finally, there was no interaction between material type and stage number. The dust from stage 8 in both composites types represented only a fraction of a milligram. It could not

therefore be collected or manipulated because in doing so would result in the introduction of major weighing errors. For example, a miscalculation of only $1/10^{th}$ of a milligram would result in an overall 10% change in its experimental filler percentage. In order to ensure accurate measurements, it was decided to analyze only stages 1 – 7.

Transbond showed a decrease in the percent of inorganic filler in the dust as the particle size decreased (Table VI, Fig. 14). Yet even the smallest particle sizes showed at least an average percent filler of over 40%. This may be of biologic significance. The average filler mass percent of the aerodynamically respirable dust for Transbond is 50.22%. Tukey's test showed stages 1-4, 3-5, and 5-6 to be equivalent.

Table VI. Average Filler Mass Percent of Transbond / Stage

				Impactor Stage				
Trial	1	2	3	4	5	6	7	8
2	72.62	68.82	66.77	61.04	55.61	55.13	53.85	NR
3	71.81	67.18	63.60	61.71	55.09	51.35	27.27	NR
4	71.83	67.65	64.46	61.89	58.42	52.88	44.44	NR
AVG	72.09	67.88	64.94	61.55	56.37	53.12	41.85	NR
SD	0.46	0.84	1.64	0.45	1.79	1.90	13.47	NR

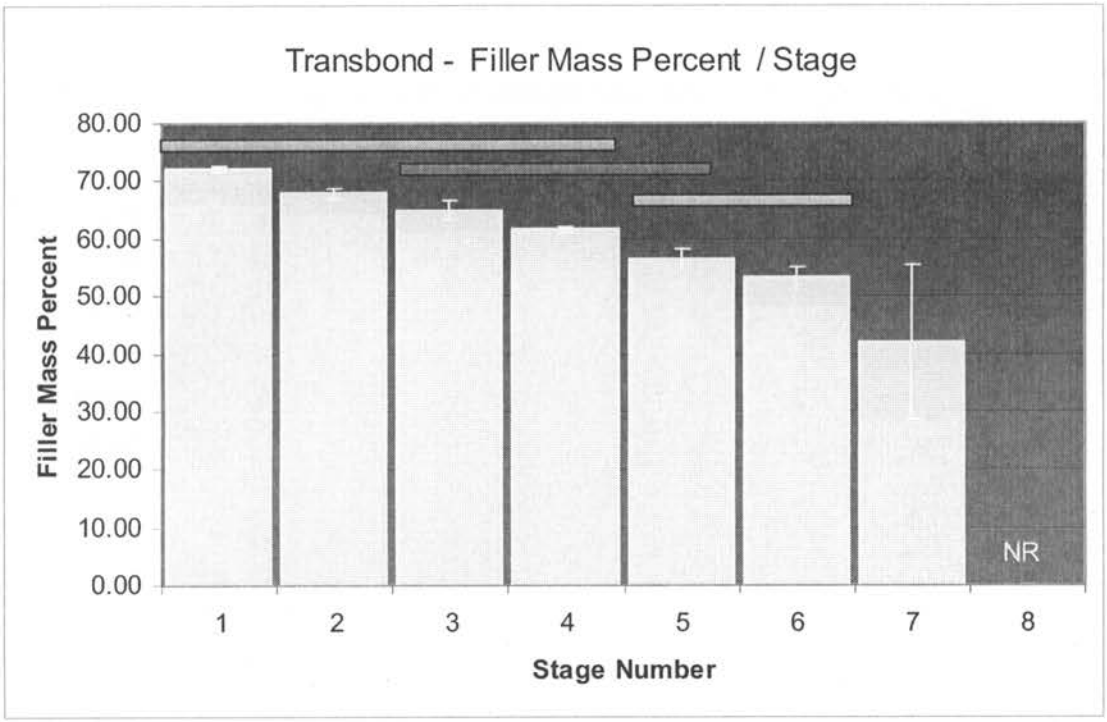


Figure 14. Transbond – Average Filler Mass Percent / Stage *horz. bars indicates sig. equivalent groups

Light Bond also displayed a decreased in filler percentage as the particle size fraction decreases (Table VII, Fig. 15). The average filler mass percent of the aerodynamically respirable dust for Light bond was 70.91%. Tukey's test showed stages 1-4, 3-5, and 5-6 to be equivalent.

Table VII. Light Bond – Average Filler Mass Percent / Stage

				Impactor Stage				
Trial	1	2	3	4	5	6	7	8
2	81.93	80.72	80.00	79.07	76.50	72.73	55.56	NR
3	81.77	81.09	79.94	80.24	76.86	75.25	60.00	NR
4	81.96	78.56	77.31	77.66	73.33	65.12	58.62	NR
AVG	81.88	80.13	79.08	78.99	75.56	71.03	58.06	NR
SD	0.10	1.37	1.54	1.29	1.94	5.27	2.27	NR

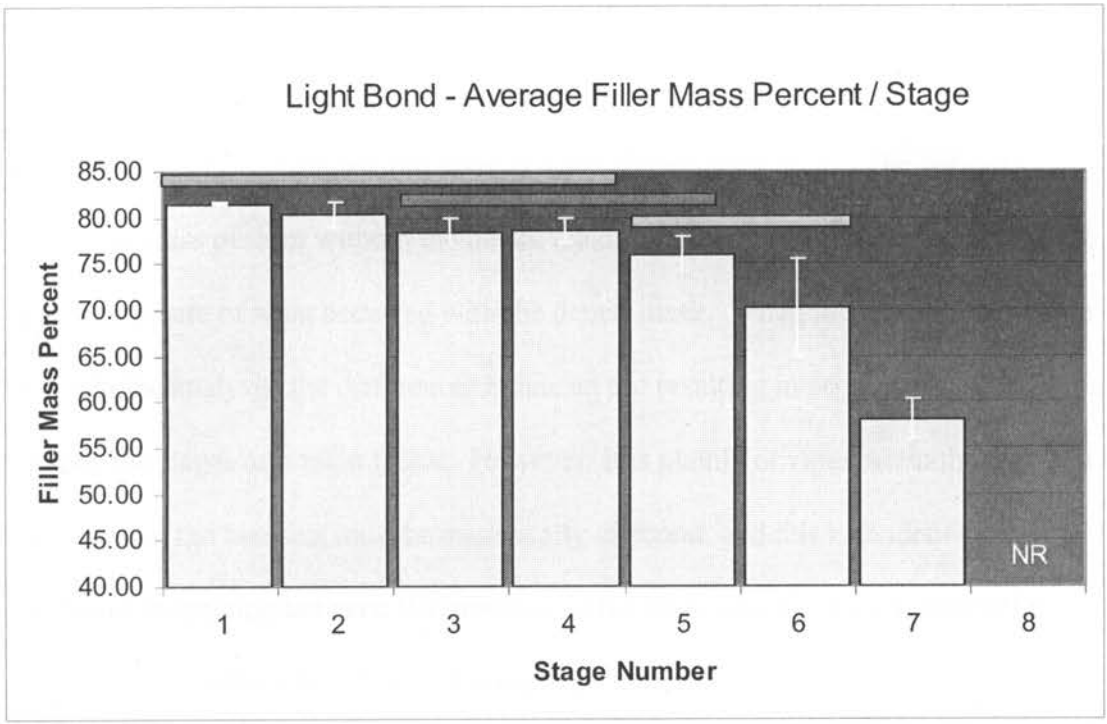


Figure 15. Light Bond – Average Filler Mass Percent / Stage *horz. bars indicates sig. equivalent groups

Mask Trial:

When a mask was placed over the intake port, it was found to reduce the collected dust mass by over 99%. Two way ANOVA comparing the mass percent of Transbond with and without a dental mask covering the impactor intake vs. stage was conducted (Appendix C, Table IV). It determined that the presence of a dental mask was significant. Also the number of particles between the stages was found to be significant. As with the other samples, Tukey's test was used to determine which stages were different. Finally, there was a significant interaction between the presence of the mask and the stages. A side by side comparison can be seen in Figure 17.

There was almost complete filtration of the larger particles in stages 1-4, a reduction in stages 5 and 6, and no reduction in the final stages (Table VIII, Fig. 16). All of the collected dust that passed through the mask was in the aerodynamically respirable range. Tukey's test suggests that stages 1-2, 2-5, and 4-8 were equal. As discussed

previously, when mass percents are compared, there can be no differences in the main variables, since the total is 100% with or without the mask. However, there also was no difference between the stages, but there is a significant interaction. The majority of the Transbond mass percent without the dental mask was found in the upper stages, which was the opposite of what occurred with the dental mask. When the two data sets were pooled in the analysis, the differences balanced out resulting in no statistical difference between the stages as a main factor. However, it is plainly obvious when the raw data is observed that the two sets must be statistically different, and this is evident by the significant interaction between the presence of the mask and the stage number (Fig. 17).

Table VIII. Mask – Average Mass Percent / Stage

				Impactor Stage				
Trial	1	2	3	4	5	6	7	8
1	0.00	0.00	0.00	0.00	25.00	25.00	12.50	37.50
2	0.00	0.00	0.00	8.33	16.67	20.83	41.67	12.50
3	0.00	0.00	0.00	0.00	0.00	33.33	33.33	33.33
AVG	0.00	0.00	0.00	2.78	13.89	26.39	29.17	27.78
SD	0.00	0.00	0.00	4.81	12.73	6.36	15.02	13.39

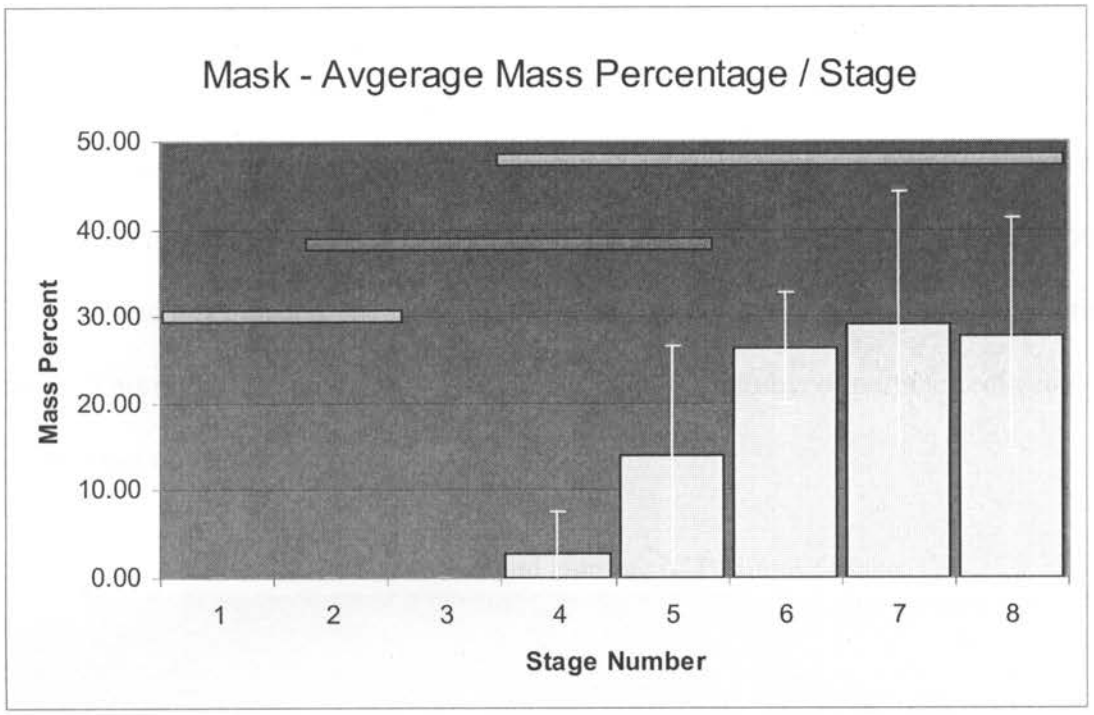


Figure 16. Mask – Average Mass Percent / Stage *horz. bars indicates sig. equivalent groups

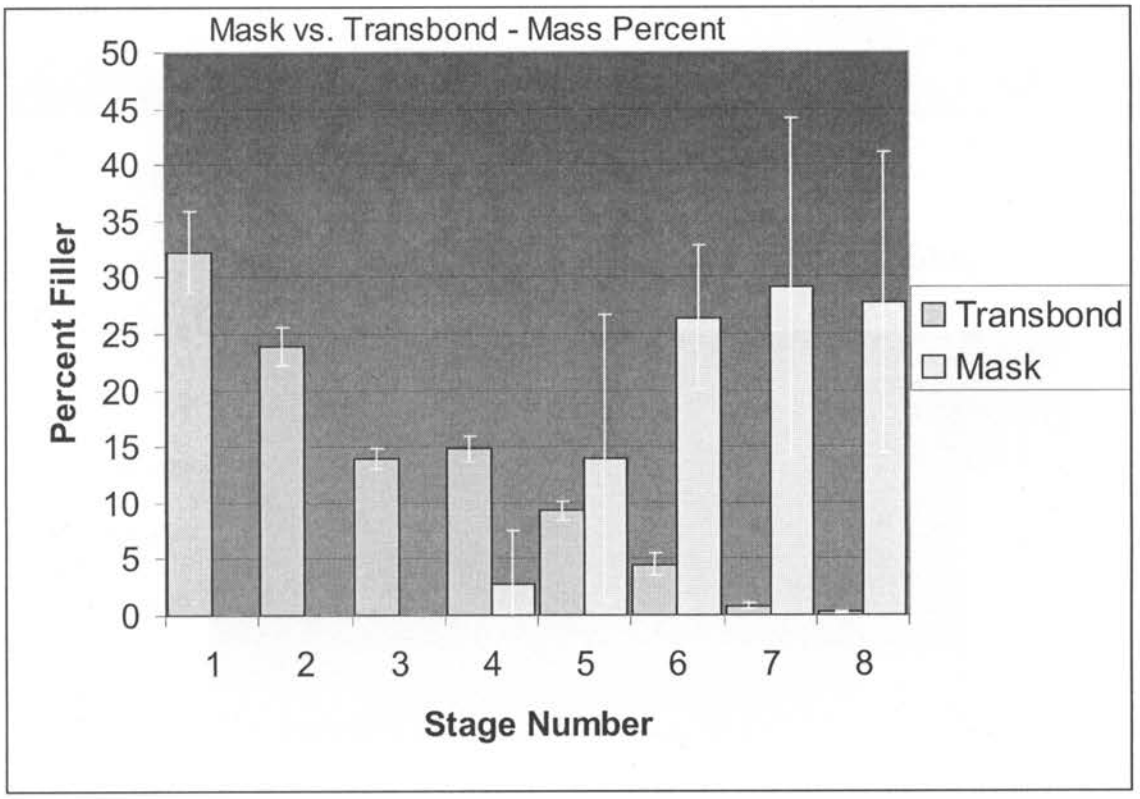


Figure 17. Mass Percent of Transbond vs. Mask / Stage

The estimated number of particles is essentially the same in stages 7 and 8, as was seen in the Transbond trials (Table IX, Fig. 18). There was a reduction in stages 4-6. As with the mass percent data, this also suggests that the mask has some filtering capabilities of particles in this size range. Regardless, 1.08×10^{10} particles were able to pass through the mask and be collected. All the particles were found in the aerodynamically respirable range. This represents no statistical difference from the number of particles collected without use of the dental mask.

Table IX. Mask - Estimated Number of Particles / Stage

				Impactor Stage				
Trial	1	2	3	4	5	6	7	8
1	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.12E+07	2.87E+08	5.57E+08	8.95E+09
2	0.00E+00	0.00E+00	0.00E+00	1.06E+07	8.25E+07	7.17E+08	5.57E+09	8.95E+09
3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.87E+08	1.11E+09	5.97E+09
AVG	0.00E+00	0.00E+00	0.00E+00	3.54E+06	4.12E+07	4.30E+08	2.41E+09	7.96E+09
SD	0.00E+00	0.00E+00	0.00E+00	6.14E+06	4.12E+07	2.49E+08	2.75E+09	1.72E+09

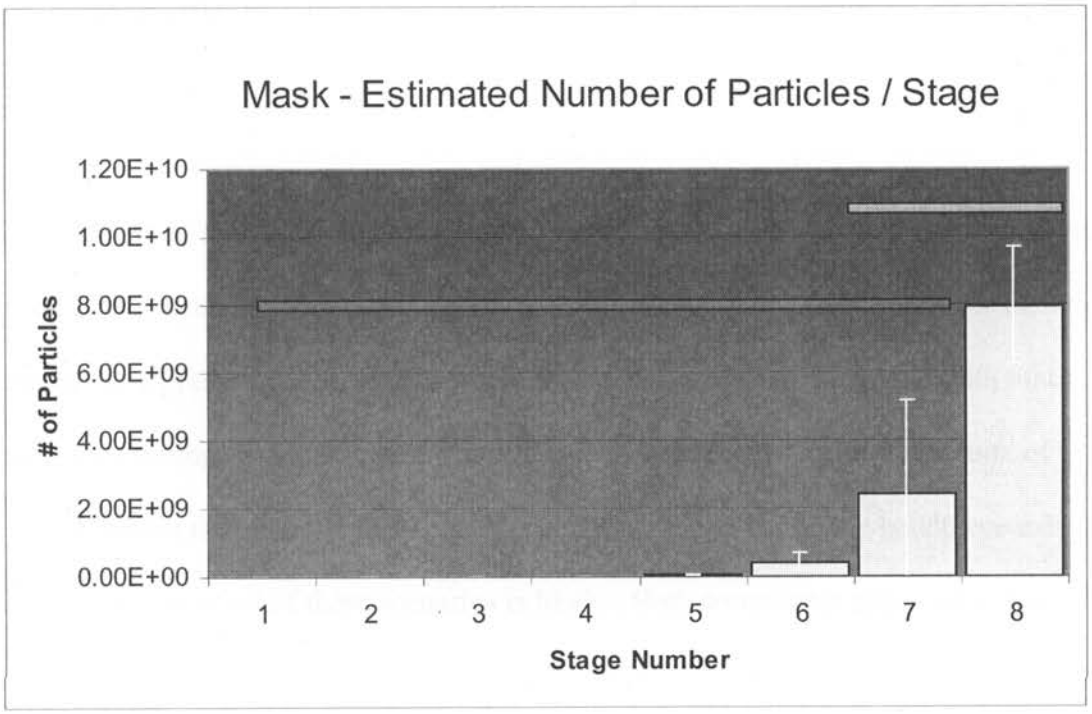


Figure 18. Mask – Estimated Number of Particles / Stage *horz. bars indicates sig. equivalent groups

Discussion

Mass Percent / Stage:

Results of this study showed a reduction of mass percent as the particles travel down the Cascade Impactor column was expected. Approximately 32% of the Transbond sample mass and 23% of the Light Bond sample mass was in the aerodynamically respirable size range. Of the total dust generated, approximately 18% was collected inside of the impactor, thus at least 5% of the total dust mass generated was aerodynamically respirable. This percentage is less than that found by Collard (1991), who reported 14-22% of the dust generated was aerodynamically respirable. This difference may be related to the composites analyzed where Collard (1991) analyzed restorative composites having much greater filler particle size ranges and filler percentages than those found in orthodontic composites analyzed in the present study.

In an effort to collect a representative cross section of dust an operator might be exposed to, in the present study over 80% of the dust mass generated inside the testing chamber never reached the impactor, and remained within the testing chamber. Reasons for this include 1) uncollected dust was too massive to remain airborne long enough to enter the impactor, 2) particles escaped through the ventilation port (present to maintain atmospheric pressure), 3) collection on the glove entry ports, 4) clumping with other particles creating larger and more massive collective particles, and 5) impaction of the particle within the collection chamber due to forces generated by the handpiece exhaust. A combination of all of these scenarios is likely. Both composites appeared to have behaved similarly, a reflection of the similar composition of the composite adhesives.

Even though the average filler particle differed between the composites, there was likely considerable overlap of the particle size range.

The mask trials showed that over 99% of the collected dust mass was filtered by the mask. This is far greater than the percentages that have been reported in the literature of 70-80% (Brune 1980, Harrel 2004). Reasons for the higher percentage may include; a complete seal around the intake port so that no dust may enter the Cascade Impactor without passing through the mask, an overloading of the mask's pores acting to increase filtration ability, or air flow dynamics inherent to the internal air flow within the collection chamber. Nevertheless, the mask was able to considerable reduce the number of particles in the 2-5 μm range, but was unable to reduce the amount of particles smaller than 2 μm. The ability of the smaller particles to pass through the mask represents a significant shortfall of the mask's ability to protect users from the most potentially harmful particle fractions. The mask does however show the ability to limit dust exposure to the upper respiratory tract, and therefore limit dust ingestion.

Estimated Number of Particles:

Even though only a small percentage of the total mass of the generated dust was of very small size, the amount corresponds to an enormous number of particles. In the Transbond sample, an estimated 4.5×10^{10} particles of aerodynamically respirable dust were collected. In the Light bond sample, that number increased to 4.9×10^{10} particles. Thus an estimated average of 4.7×10^{10} particles had the potential to penetrate the body's normal defense mechanism and settle the lungs. However, it should be kept in mind that the average starting sample size had a mass of about 3 g. This is a far greater amount of composite adhesive than an operator would expect to grind from one patient. This

amount was used in the experiment to ensure that enough dust was generated to collect and manipulate. However, an estimate of 3 mg may be clinically more relevant. Using the data from this study, one can extrapolate that an exposure in the order of 4.7×10^7 particles is possible, and may represent a potential to cause harm.

Even though the dental mask was able to reduce particles in the 2-5 μm range, an estimated 4.7×10^8 particles were collected in the impactor from within this size range. In the 2 μm fractions and below, an estimated 1.0×10^{10} particles were collected. These results were similar for both the Transbond and Light Bond samples, indicating that the mask has little ability to filter particles in this size fraction. Therefore, this type of dental mask cannot reduce the risk of exposure to these particles.

Percent Filler / Stage:

This study found a decreasing percentage of filler in the dust at the smaller particle sizes. This finding may be the result of the bur flute raking out the filler particles whole during the grinding of the composite. Alternatively, the bur may grind the filler particles into smaller particles as it generates the dust, an explanation that would account for the reasonably high percentages of filler found in the lower stages of the impactor. Another factor to consider is that the filler particle size reported by the manufacturer represents only the average particle size, and not the total range of particle sizes contained in the composite. Therefore, question remains as to which factor contributed most to finding filler particles in the lower stages; but it is likely that a combination of all the scenarios likely occurred.

Unfortunately for the clinician, the percent filler in the dust was 42% in the Transbond sample and 58% in the Light Bond sample. As a result, large portions of the

dust, even in the smallest of size fractions, contain quartz filler. What is unknown is whether or not this quartz exists freely, is bound in resin, or a combination of both. Scanning electron microscopy may help to clarify this, although the small size of the particles makes it difficult for even this method to produce definitive results.

Biological Significance:

To date, no reported cases of silicosis have been found in the orthodontic literature despite the exposure potential this study has demonstrated. Several factors beyond the scope of this study may be related to this phenomenon, foremost being the aerodynamically respirable dust distribution in a clinical setting. This study was conducted in a closed environment in order to maximize dust collection, whereas in a clinical setting, the dust would be free to distribute into a much larger volume of air. This fact may greatly limit exposure and allow the aerodynamically respirable particles to settle out onto clinic surfaces, later to be removed during house cleaning procedures or by the facility's air ventilation system. Conversely, these same systems may also be acting to maintain aerodynamically respirable dust in the air, allowing for secondary contamination of others within the clinic not directly involved with the debonding procedures. Another limitation of the study design is the role of chairside vacuum systems on the dust that is generated. As Brune (1980) and Collard (1991) point out, typical chairside vacuum systems are 16% of what they consider adequate. Further studies should focus on the effects of air evacuation systems on the quality and quantity of dust that escapes retrieval. Another concern is the patient's exposure to aerodynamically respirable dust. Being an acute, relatively low dose exposure it may be unlikely the individual patient is at any health risk. Further, the patient's acute exposure

may actually reduce the total aerodynamically respirable dust load released into the environment, and limit the chronic exposure to the operator.

From a mechanical standpoint, this study used a Cascade Impactor to collect and fraction dust particles into stages that theoretically correspond to pulmonary penetration depths. In order for this machine to function properly a constant vacuum must be maintained, a situation that does not resemble the human respiratory system functions. Aerodynamically respirable dust particles that are inhaled may also be exhaled. Without human studies, what the level of retention is for aerodynamically respirable dust cannot be determined. Although animal studies suggest that some level of retention is likely (Gross 1979). This leads us to ponder this studies final limitation, as to the human body's capacity for removal of this aerodynamically respirable dust. Is typical exposure to aerodynamically respirable dust through orthodontic procedures simply not enough to overwhelm the body's ability to remove these particles irregardless of the fact that it contains the known cancer causing agent quartz? As efficiency improves the clinician's ability to treat patients, some practices are able to see 100 or more patients per day. Does this mean that respiratory ailments due to aerodynamically respirable dust exposure require only a matter of more time before surfacing? Either way, the potential for a human health risk is clear and further research is required.

Conclusions

Conclusions from this study include:

1. High-speed air-rotary abrasion produced dust composed of particles of resin matrix and filler. Approximately 18% of the dust particles were collected in the impactor. Of this, approximately 27.5% of the collected dust mass was found to be aerodynamically respirable (0.5-5.0 μm).
2. The aerodynamically respirable dust mass from each composite sample was estimated to contain approximately 4.7×10^{10} particles.
3. Smaller particle size fractions contained increasingly less amounts of filler. However, even the smallest percentage (Transbond, stage 8) contained over 40% filler, which could be biologically significant.
4. Use of a dental mask reduced the amount of the dust mass that would normally be inhaled by 99%. However, this result is deceiving because it was mainly the larger, heaver particles that were filtered out, while particles in the 2-5 μm range were reduced but accounted for over 4.7×10^{8} particles. Particles smaller than 2 μm were not effectively reduced, and accounted for more than 1.0×10^{10} particles.
5. This study illustrates a potential exposure to aerodynamically respirable dust that contains quartz from the grinding of quartz containing composite adhesives used in orthodontics.

Appendix A:

Ambient (non-viable) 8-stage Cascade Impactor:

The Ambient Eight-Stage Cascade Impactor (Fig. 18) used in this experiment is a high sample-rate, multiple orifice and multiple stage inertial impactor. A Cascade Impactor is a multi-stage device used to separate airborne particles into aerodynamic size classes. The Impactor is fabricated from an aluminum alloy. It is designed to aerodynamically separate ambient particulate into multi fractions in the range of 10 μm AED (Aerodynamic Equivalent Diameter) to filtration collection of sub-micron particles 0 to 0.43 μm.

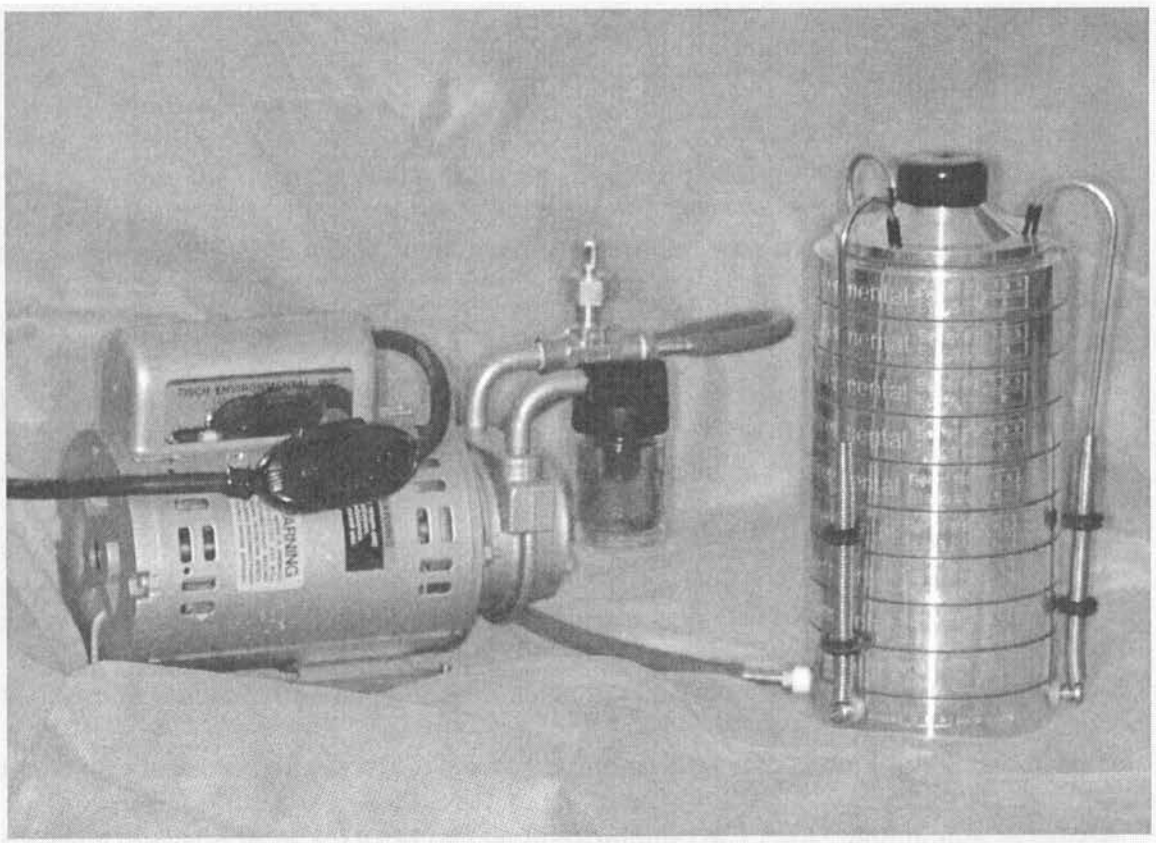


Figure 19. Tisch 8-Stage Cascade Impactor

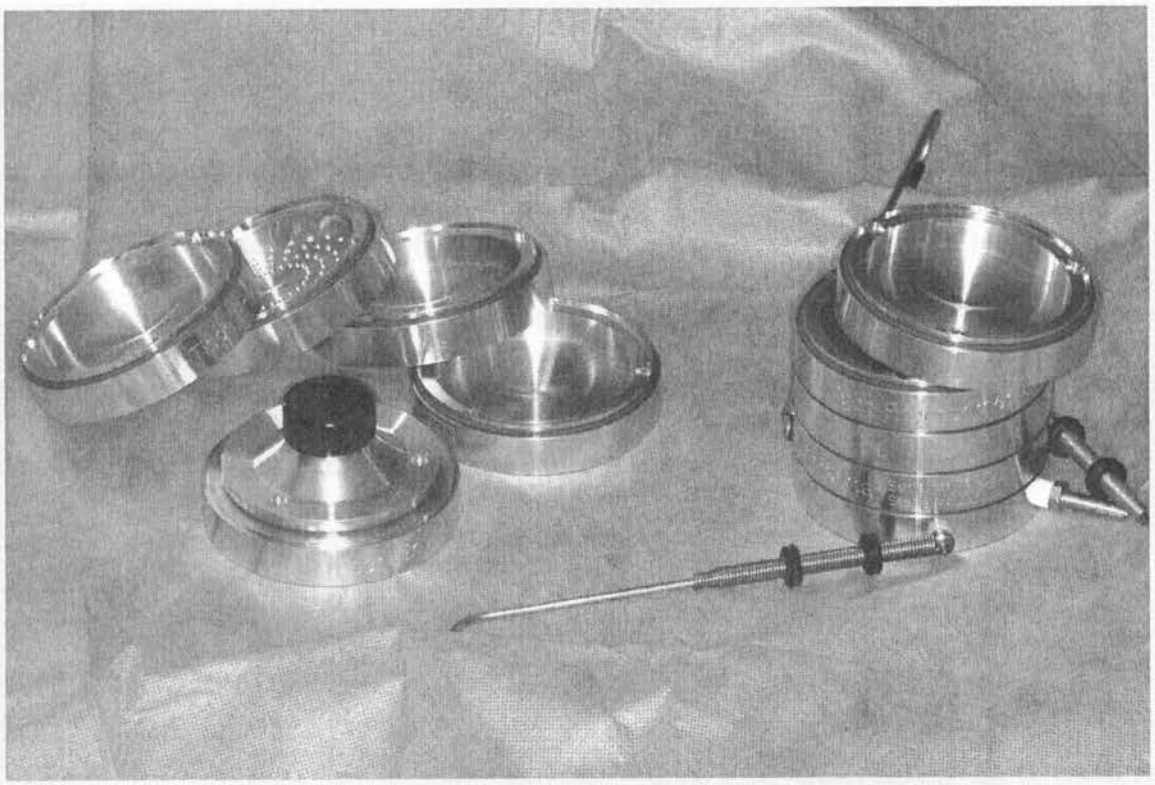


Figure 20. Cascade Impactor Stages

Within the Impactor, the particulate entrained in the aerosol is sampled through a series of stacked stages which contain multiple orifices with sequentially smaller diameters (Fig. 19). Ambient air enters the circular inlet cone and cascades through the succeeding orifice stages with successively higher orifice velocities from Stage #0 to Stage #7. Successively smaller aerodynamic sized particles are impacted by inertia onto a collection medium. The Sub-micrometer particles (<1.0 μm) passing through Stage #7, are collected by filtration on a glass micro-fiber or cellulose filter media. The sampled air is drawn through the Cascade Impactor using a calibrated vacuum pump designed to maintain a constant sample rate. The design sample flow rate of the Eight Stage Ambient Cascade Impactor is 28.3 ALPM (actual liters/minute) or 1 cubic foot/minute. A sample flow rate of ± 1.5 ALPM during a sample event ensures the aerodynamic separation of particles maintain the theoretical calibration curves.

This model 20-800 series of Cascade Impactors is designed for applications in ambient air where non-viable (non-biological) aerosol is to be collected and measured for its concentration by aerodynamic particle size. The concentration of particulate is calculated by pre and post weighing of the 81 mm sample substrates located below each Orifice Stage. As particles pass through each successively smaller diameter orifice stage the sample rate is accelerated. As the aerosol exits each orifice it will curve around the impaction sample substrate. Particles that have an aerodynamic diameter and inertia that cannot stay in the sample air stream break free from the flow and collect by impaction onto the sample substrate. By subsequently making the orifice diameter smaller on each Stage of the Cascade Impactor, the particles are increased in velocity and the aerodynamic separation of particles over a large range can be determined.

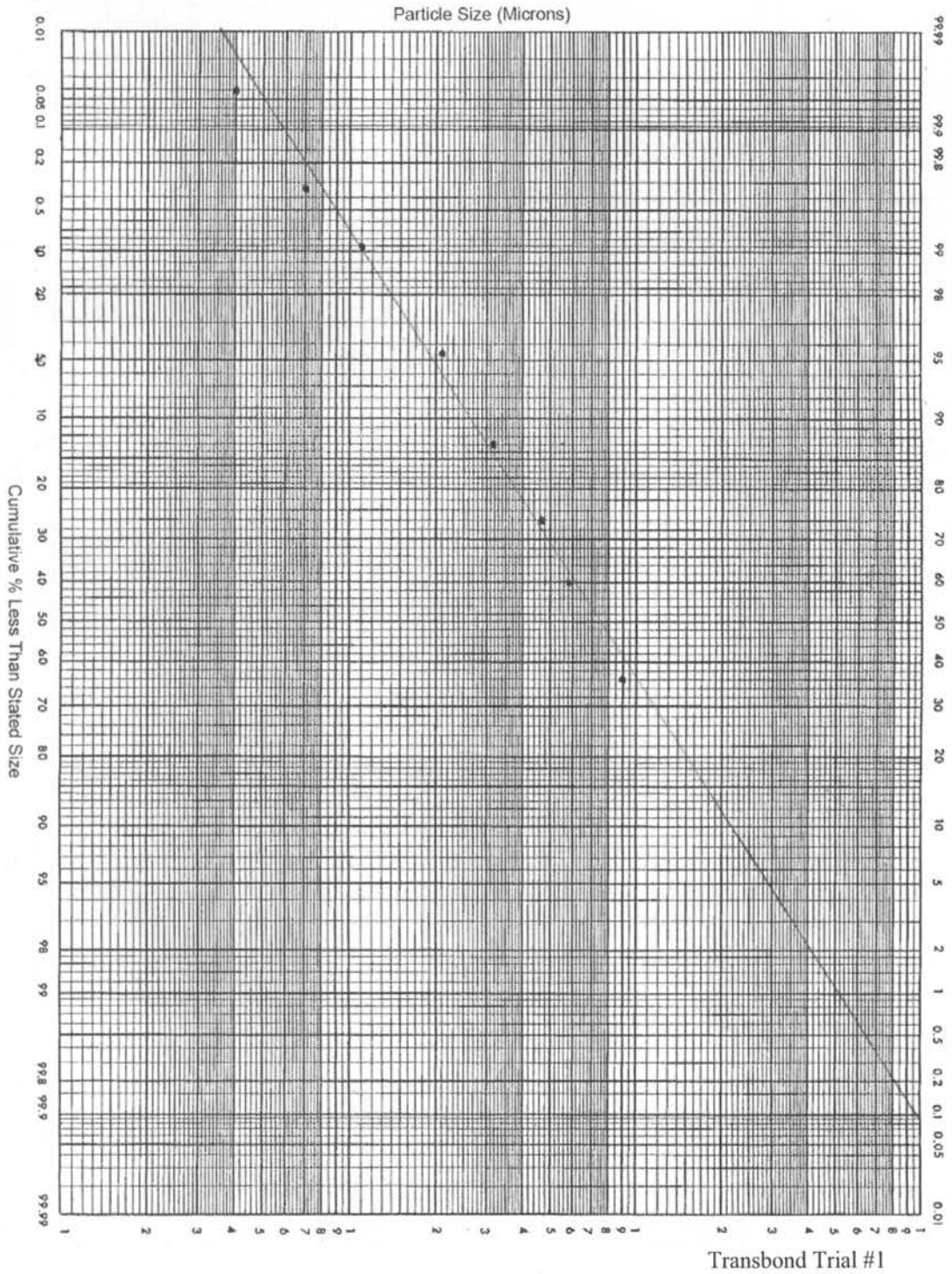
Dr. K. R. May, Ph.D, introduced the first commercial Cascade Impactor in 1945 in the United Kingdom and published its design and function in the Journal of Scientific Instruments #22. The design uses a single orifice jet impacting onto a glass microscope slide and four successive Stages with decreasing orifice diameters. The "May Impactor" remains a valuable laboratory tool even today with well-characterized and precise particle separation efficiency. Its only limitation is the sample flow rate is low and the glass slides require grease-coatings to collect the sample for analysis.

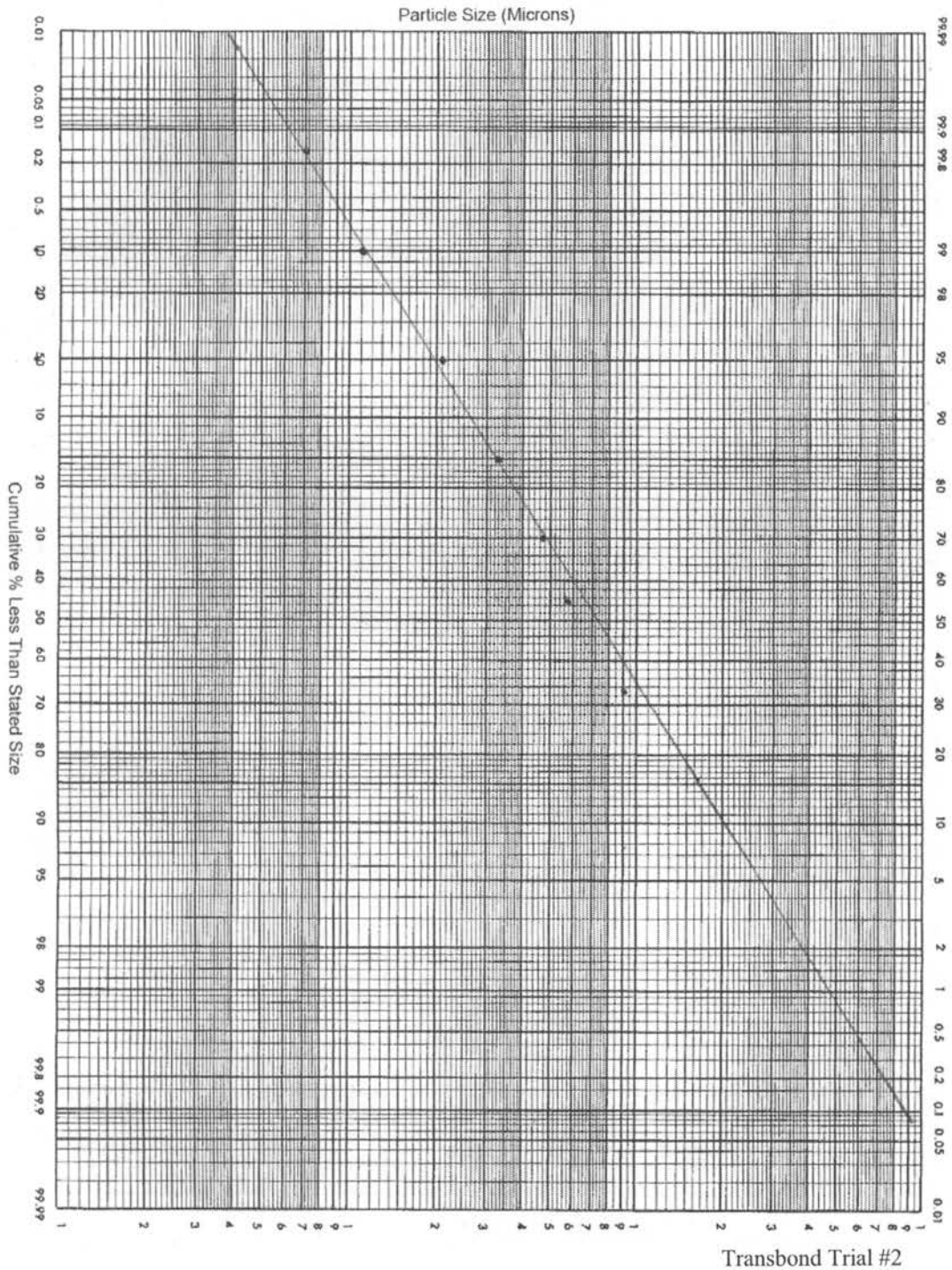
The Ambient Eight-Stage Cascade Impactor concept was designed and published by Dr. Aerial Andersen in Provo, Utah in 1958 (*Journal of Bacteriology* #76). In an attempt to improve collection efficiency Dr. Andersen developed the multiple stage, multiple-orifice Cascade Impactor. The unique design of multiple orifice jets in one stage allowed for higher sampler flow rates and a larger sample substrate to collect greater mass concentration for weighing accuracy and later chemical speciation analysis. The

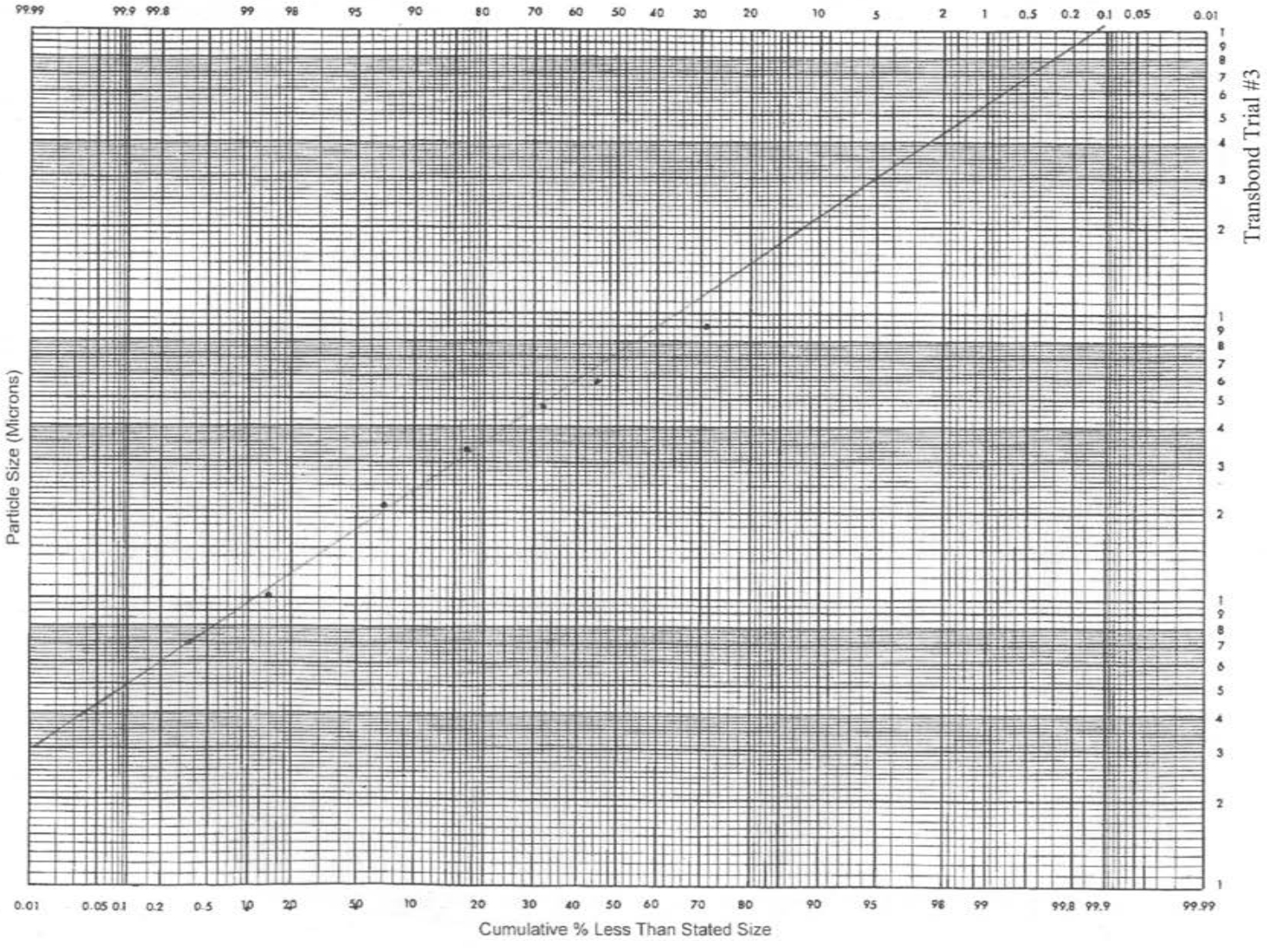
design has been utilized by many researchers in the Environmental, Industrial Hygiene and pharmaceutical industries for thirty years and has been extensively tested and verified for characterization. Several commercial copies of the original design are being fabricated today.

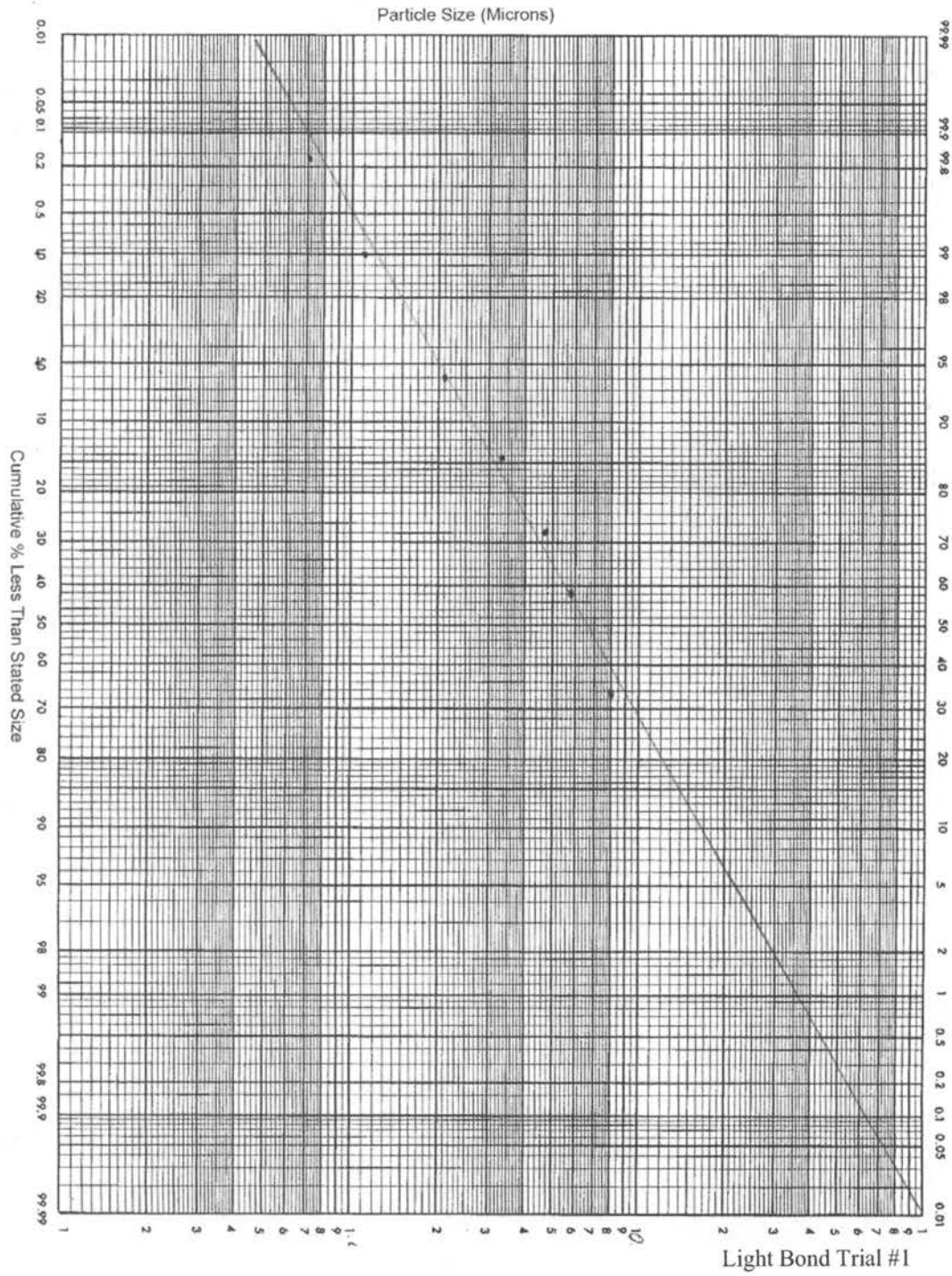
Appendix B:

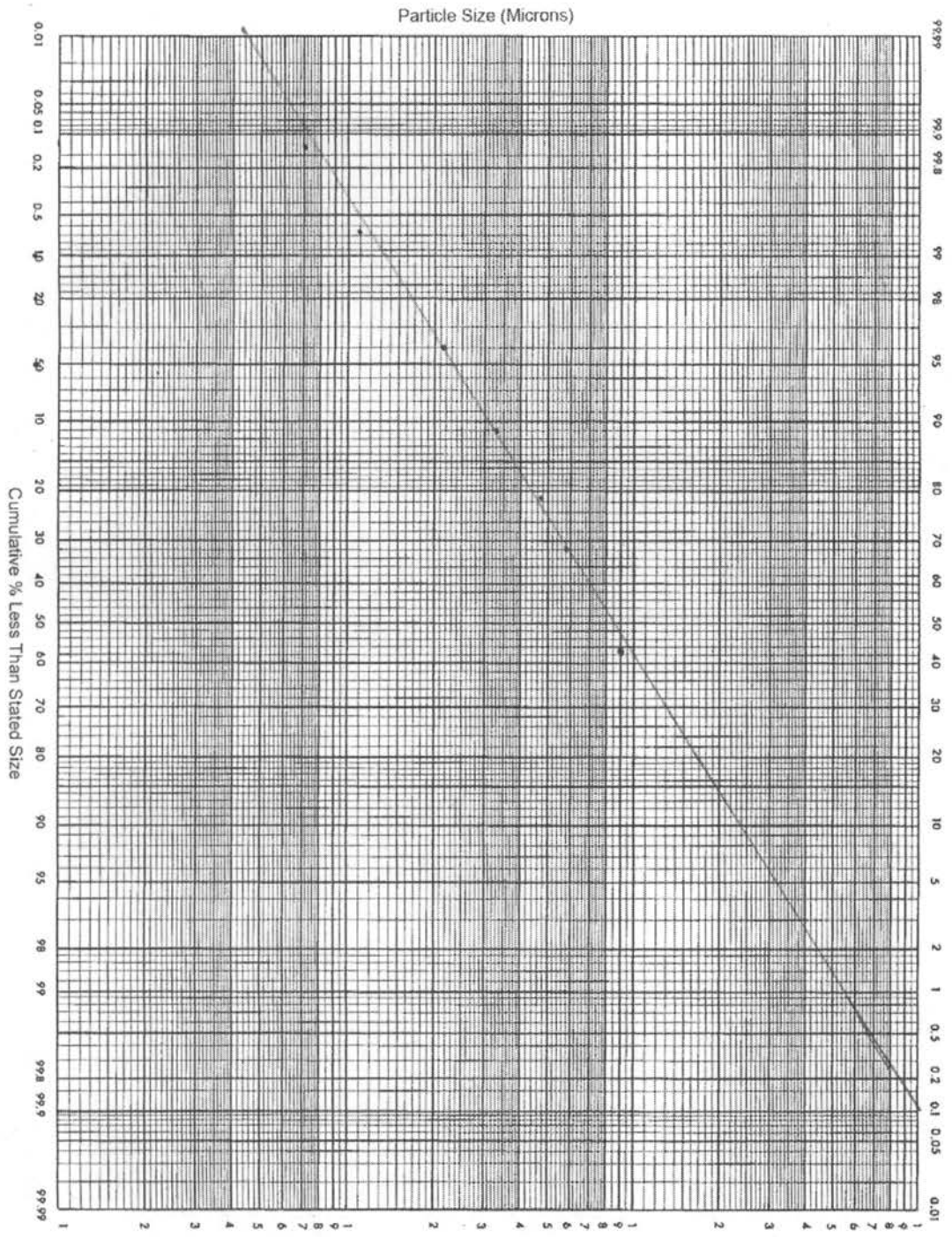
Log Probability Graphs

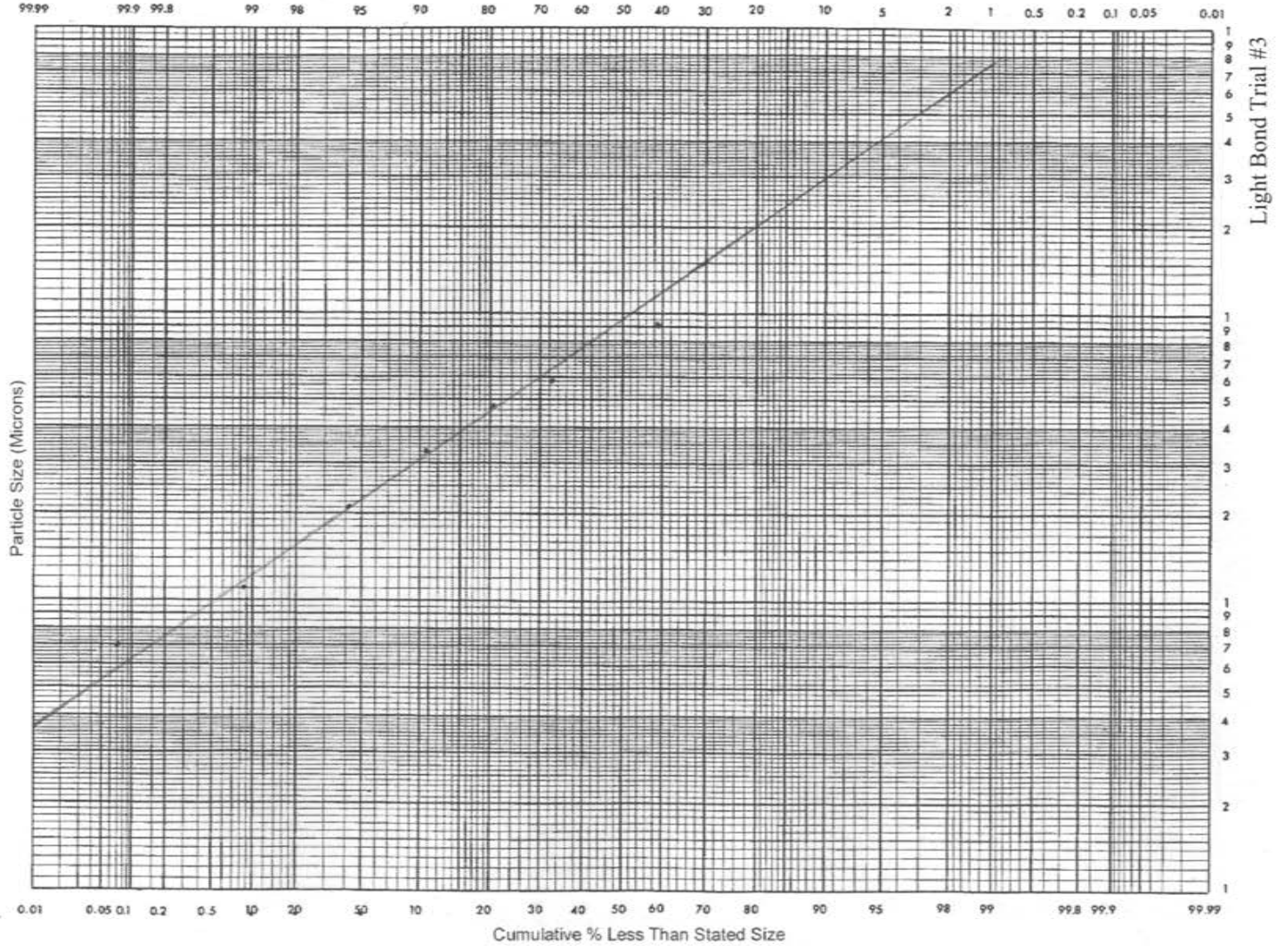



Particle Size (Microns)
Cumulative % Less Than Stated Size
Transbond Trial #2

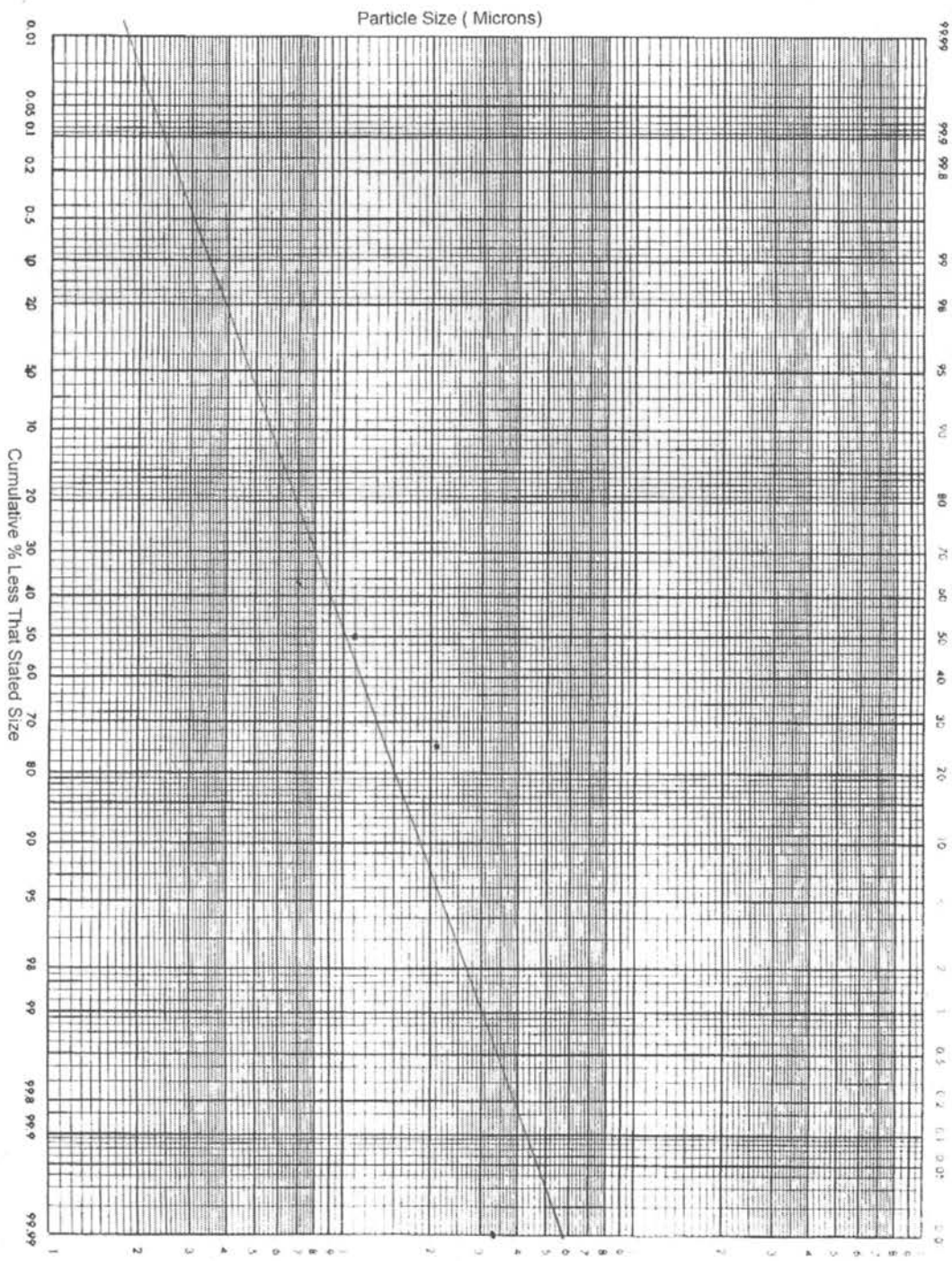

Transbond Trial #3
Particle Size (Microns)
Cumulative % Less Than Stated Size
99.99 99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.05 0.01
0.01 0.05 0.1 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.9 99.99


Particle Size (Microns)
Cumulative % Less Than Stated Size
Light Bond Trial #1

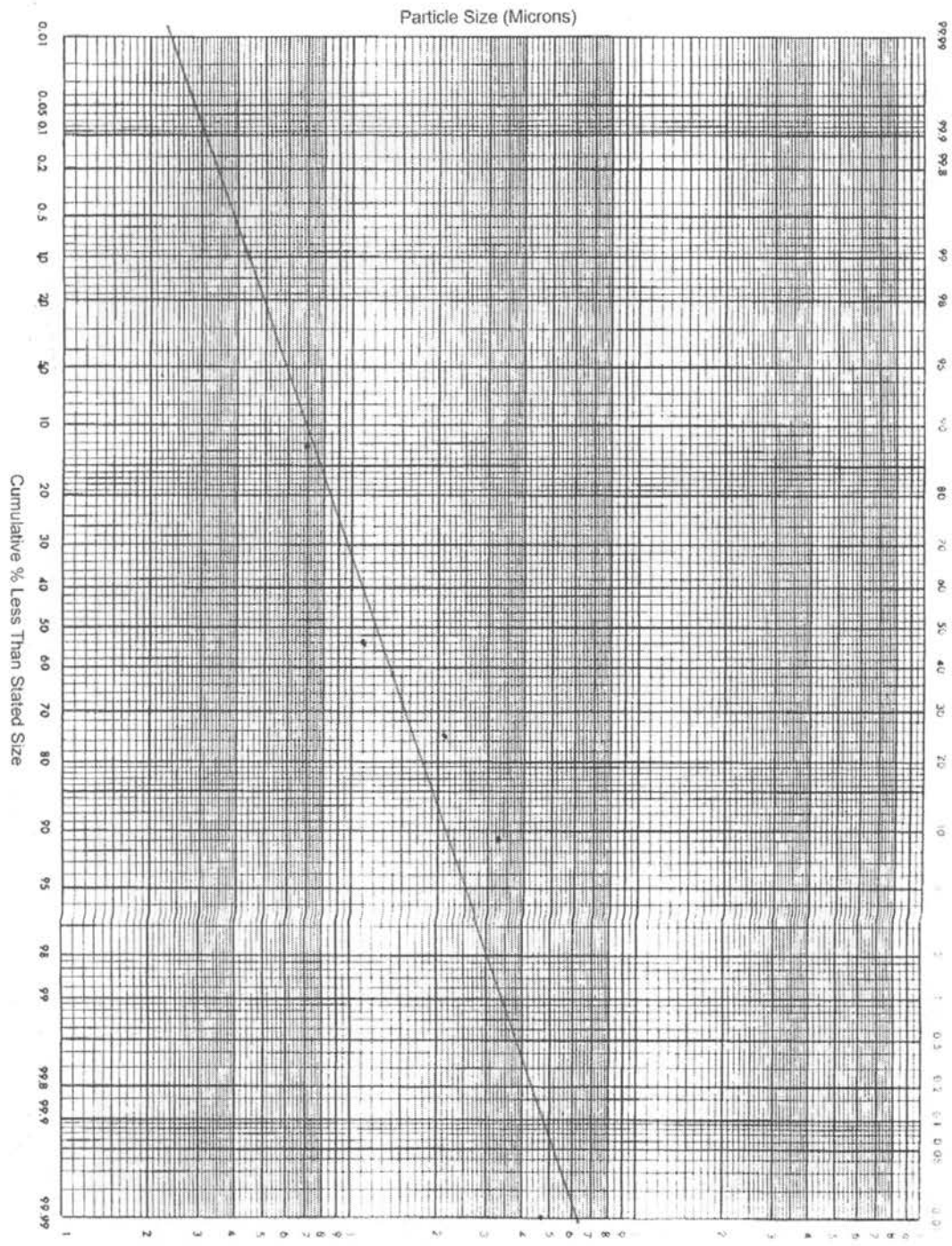

Particle Size (Microns)
Cumulative % Less Than Stated Size
Light Bond Trial #2



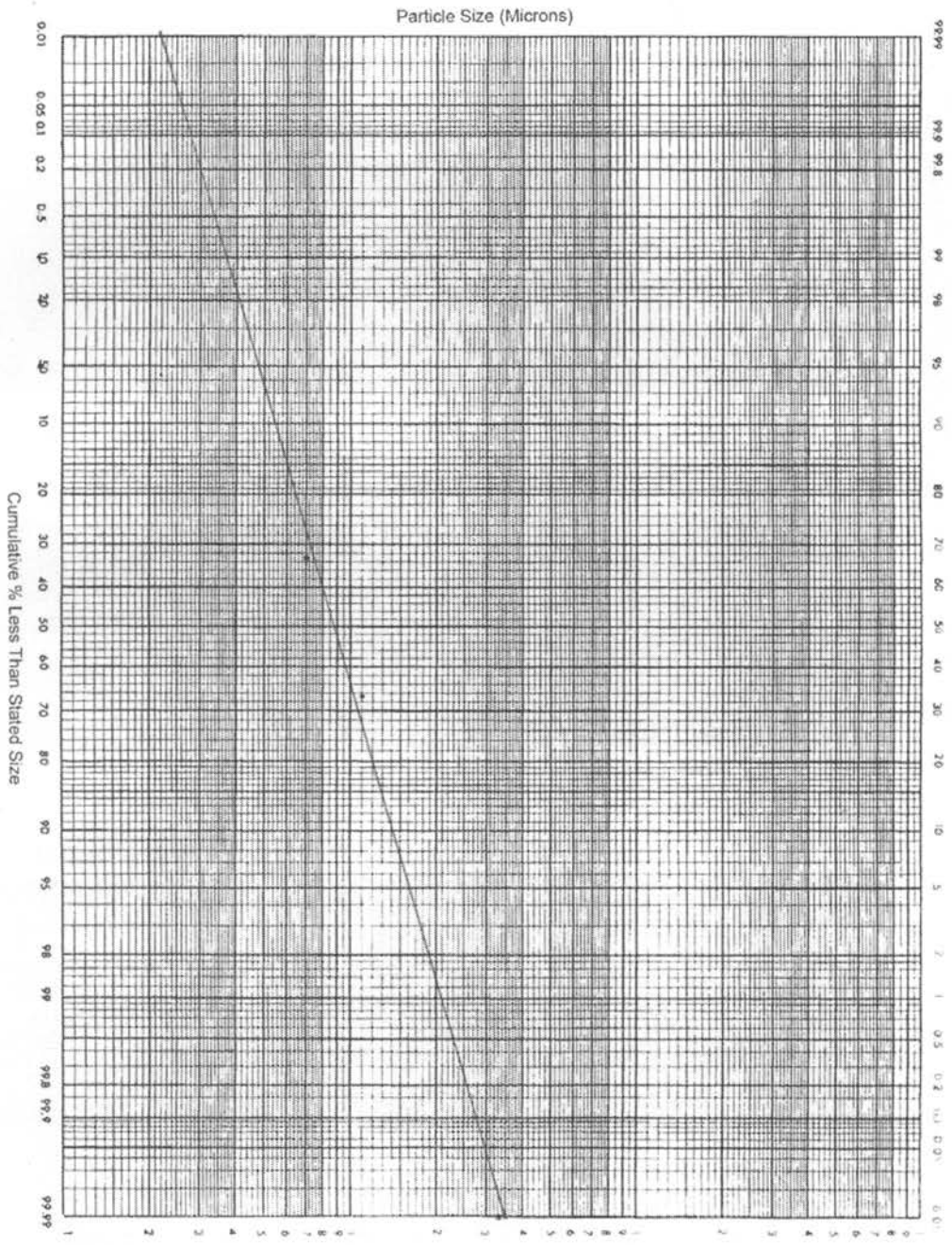
Light Bond Trial #3



Mask Trial #1



Mask Trial #2



Mask Trial #3

Appendix C:

Comparative Statistic Charts

Table I. Mass Percent / Stage for Transbond vs. Light Bond

Source of Variation	DF	SS	MS	F	P
Material Type	1	0.0000353	0.0000353	0.00000989	0.998
Stage Number	7	6384.279	912.04	255.242	<0.001
Material Type vs Stage	7	102.09	14.584	4.082	0.003
Residual	32	114.343	3.573		
Total	47	6600.712	140.441		

Table II. Estimated Number of Particles / Stage for Transbond vs. Light Bond

Source of Variation	DF	SS	MS	F	P
Material Type	1	5.160E+18	5.160E+18	0.929	0.342
Stage Number	7	1.765E+21	2.522E+20	45.392	<0.001
Material Type vs Stage	7	5.759E+19	8.228E+18	1.481	0.209
Residual	32	1.778E+20	5.556E+18		
Total	47	2.006E+21	4.268E+19		

Table III. Filler Percent / Stage for Transbond vs. Light Bond

Source of Variation	DF	SS	MS	F	P
Material Type	1	2449.831	2449.831	146.052	<0.001
Stage Number	6	2998.087	499.681	29.79	<0.001
Material Type vs Stage	6	102.494	17.082	1.018	0.434
Residual	28	469.662	16.774		
Total	41	6020.074	146.831		

Table IV. Mass Percent / Stage for Mask vs. Transbond

		Mask vs. Mass Percent Statistic			
Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Presence of Mask	1	0.0000353	0.0000353	0.000000869	0.999
Stage Number	7	453.010	64.716	1.592	0.174
Mask Presence vs Stage	7	6025.173	860.739	21.168	<.001
Residual	32	1301.204	40.663		
Total	47	7779.387	165.519		

Table V. Estimated Number of Particles / Stage for Mask vs. Transbond

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Presence of Mask	1	2.319E+20	2.319E+20	52.383	<.001
Stage Number	7	8.296E+20	1.185E+20	26.77	<.001
Mask Presence vs Stage	7	2.273E+20	3.248E+19	7.335	<.001
Residual	32	1.417E+20	4.427E+18		
Total	47	1.431E+21	3.044E+19		

References:

1. Andersen A. New sampler for the collection, sizing, and enumeration of viable airborne particles. *J Bacteriol.* 1958;76:471-84.
2. Bello D, Virjo MA, Kalil AJ, Woskie SR. Quantification of respirable, thoracic, and inhalable quartz exposures by FT-IR in personal impactor samples from construction sites. *Appl Occup Environ Hyg.* 2002;17:580-90.
3. Brune D, Beltesbredde H. Dust in dental laboratories. Part III: Efficiency of ventilation systems and face masks. *J Prosthet Dent.* 1980;44:211-5.
4. Brune D, Beltesbredde H. Dust in dental laboratories. Part I. Types and levels in specific operations. *J Prosthet Dent* 1980;43:687-692.
5. Collard SM, McDaniel RK, Johnston DA. Particle size and composition of composite dusts. *Am J Dent* 1989;2:247-253.
6. Collard SM, Vogel JJ, Ladd GD. Respirability, microstructure and filler content of composite dusts. *Am J Dent* 1991;4: 143-51.
7. Davis L, et. al. Mortality experience of Vermont granite workers. *Am J of Ind Med* 1983;4:702-723.
8. Donalson K, et. al. Epithelial and extracellular matrix injury in quartz-inflamed lung; role of alveolar macrophages. *Environmental Health Perspectives.* 1992;97: 221-224.
9. Dufresne A, Lesage J, Perrault G. Evaluation of occupational exposure to mixed dusts and polycyclic aromatic hydrocarbons in silicon carbide plants. Am Ind Hyg Assoc J. 1987;48:160-6.
10. Giodano R. Fiber reinforced composite resin systems. *Gen Dent.* 2000;48:244-9.

11. Gross P, et. al. The pulmonary response to fibrous dusts of diverse compositions. *Am Ind Hyg Ass J* 1970;31:125-32.

12. Harrel S, Molinari J. Aerosols and splatter in dentistry: a brief review of the literature and infection control implications. *JADA* 2004;134:429-37.

13. Hearl FJ. Industrial hygiene sampling and applications to ambient silica monitoring. *J Expo Anal Environ Epidemiol.* 1997;7:279-89.

14. Horvath A. Significance of the surface of crystalline silicoginic dusts in experimental silicosis. *Acta Morphol Acad Sci Hung.* 1976;24:213-22.

15. Hunter D. The pneumoconioses. In *The diseases of occupations.* Boston, Little, Brown & Co., 1955;848-854.

16. International Agency for Research on Cancer (IARC). Monographs Database on Carcinogenic Risks to Humans. Website. www.iarc.fr/

17. Ireland AJ, Moreno T, Price R. Airborne particles produced during enamel cleanup after removal of orthodontic appliances. *AmJOrthod Dentofacial Orthop* 2003;124:683-6.

18. Korn M, Ndhlovu D. Surgical masks – effective protection against cytostatic aerosols? *Dtsch Med Wochenschr.* 1989;114:1785-8.

19. Lee K, et. al. Pulmonary response of rats exposed to titanium dioxide (TiO_2) by inhalation for two years. *Toxicology and Applied Pharmacology* 1983;79:179-192.

20. Linch KD. Respirable concrete dust – silicosis hazard in the construction industry. *Appl Occup Environ Hyg.* 2002;17:209-21.

21. Luchtel DL, Martin TR, Boatman ES. Response of the rat lung to respirable fractions of composite fiber-epoxy dusts. *Environ Res.* 1989;48:57-69.

22. Mayer B, Raithel H, Weltle D, Neidermeier W. Pulmonary risk of intraoral surface conditioning using crystalline silica. *Int J Prosthodont.* 2003;16:157-60.

23. National Toxicology Program: 9th Report on Carcinogens. U.S. Department of Health and Human Services, Public Health Service, Washington, DC 2000.

24. Miller RL, Micik RE. Air pollution and its control in the dental office. *Dent Clin North Am* 1978;22:453-76.

25. Miller B, et. al. Risks of silicosis in coalworkers exposed to unusual concentrations of respirable quartz. *Occ and Env Med* 1998;55:52-58.

26. Mjor IA. *Dental Materials: Biological properties and clinical evaluations.* Boca Raton, CRC Pres, Inc., 1985;197-201.

27. Newman R. Association of biogenic silica with disease. *Nutr Cancer* 1986;8:217-221.

28. O'Neill CH, et. al. A fine fibrous silica contaminant of flour in the high esophageal cancer area of north-east Iran. *Int J of Cancer* 1982;26:617-628.

29. O'Neill CH, et. al. Silica fragments from millet bran in mucosa surrounding esophageal tumors in patients in northern China. *Lancet 1982;*29:1202-1206.

30. Page SJ. Comparison of coal mine dust size distributions and calibration standards for crystalline silica analysis. *AIHA J* (Fairfax, Va). 2003;64:30-9.

31. Pan G, et. al. Nested case-control study of esophageal cancer in relation to occupational exposure to silica and other dusts. *Am J Ind Med* 1999;35:272-280.

32. Reynolds IR A review of direct orthodontic bonding. *Br J orthod 1975; 2:171-178.*

33. Reiser KM, Last JA. Silicosis and fibrogenesis: fact and artifact. *Toxicology 1979;*13:51-72.

34. Rose EF. Carcinogens and esophageal insults. *S Afr Med J 1968a;*42:334-336.

35. Rose EF. Phytolithicosis – A disease entity? *Trans NY Acad Sci 1968b;*30:1196-1200.

36. Soutar C, et. al. Epidemiological evidence on the carcinogenicity of silica: factors in scientific judgement. *The Annals of occupational hygiene.* 1983;4: 3-14.

37. Yabuta J, Ohta H. Determination of free silica in dust particles: effect of particle size for the X-ray diffraction and phosphoric acid methods. *Ind Health.* 2003;41:249-59.