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A Lab-based Study for the Generation and Characterization of Particle Emission from Composite Materials Containing Carbon Nanotubes

Jonathan Kang

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A Lab-based Study for the Generation and Characterization of Particle Emission from Composite Materials Containing Carbon Nanotubes.

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Thesis submitted to the Statler College of Engineering and Mineral Resources
at West Virginia University

in partial fulfillment of the requirements for the degree of

Master of Science

in

Industrial Hygiene

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Abstract

A Lab-based Study for the Generation and Characterization of Particle Emission from Composite Materials Containing Carbon Nanotubes.

Jonathan Kang

An experimental setup was designed to measure and characterize the emission of particles during the sanding of composite materials containing carbon nanotubes (CNTs). The experimental setup consisted of a sand-blasting cabinet with HEPA-filtered air intakes. An electrical motor outside the cabinet was connected to a pulley through a v-belt. A material feeder with constant force was constructed. The system was tested with a belt sander by sanding 1) glass fiber/epoxy resin, 2) glass fiber/epoxy resin containing post-coated multi-walled carbon nanotubes (MWCNTs), 3) acrylonitrile butadiene styrene (ABS) 4), ABS containing MWCNTs, 5) ABS containing glass-fiber-infused MWCNTs, 6) ABS containing carbon black, and 7) ABS containing carbon black and MWCNTs. Total number concentrations, respirable mass concentrations, and particle size number/mass distributions of the emitted particles were measured using a scanning mobility particle sizer, an optical particle counter and a condensation particle counter . Additionally, samples for electron microscopy analysis were collected with a thermophoretic sampler and filter samples. Measurements were repeated with coarse (150 grit) and fine (320 grit) sandpaper. The addition of CNTs did not consistently increase particle emission for all of the materials, while the choice of sandpaper grit had a more consistent association with particle emission from the materials. Micron-sized particles with CNT-protrusions were observed on microscopy analysis. No free-standing CNTs were observed on microscopy analysis.

DEDICATION

The author wishes to dedicate this thesis to Ozge Uslu, Tom Lasorsa, and Mike Bonadies.

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CHAPTER 1: Introduction

The International Organization for Standardization (ISO) defines a nanomaterial as a material with any external dimension in the nanoscale or having internal structure or surface structure in the nanoscale. The size range for the nanoscale is approximately 1 nm to 100 nm (ISO 2010). A class of nanomaterials are carbon nanotubes (CNTs), which are allotropes of carbon with a hollow cylindrical structure (ISO 2010). Multi-walled carbon nanotubes (MWCNTs) consist of multiple rolled layers of graphene, and have several unique properties, such as thermal/electrical conductivity and mechanical strength, that allows them to be used in a wide range of industrial applications (Ajayan and Zhou 2001). MWCNTs are used to strengthen structural composites made of carbon or glass fiber by enhancing the properties of the matrix material (Baughman *et al.* 2002).

Products that utilize CNT nanocomposites include sporting goods, automotive parts, and electronics. It is expected that the use of CNT nanocomposites in industry will continue to increase as their production costs decrease (Huang *et al.* 2012). The increase of CNT use in industrial applications leads to the potential for increased exposure of CNTs to humans. There have been several animal studies performed to examine the respirable toxic effects of CNT exposure. Adverse toxicological effects include acute inflammation, granuloma, and lung fibrosis (Shvedova *et al.* 2005; Ma-Hock *et al.* 2009). In vitro studies with human lung cells have shown that CNT exposure can cause genotoxicity and mitotic spindle abnormalities (Sargent *et al.* 2011).

Life-cycle events associated with nanocomposite materials have the potential to release CNTs into the air. The events during the life-cycle of a nanocomposite material that are conducive to CNT release include biodegradation, washing, diffusion, matrix degradation, incineration, and mechanical forces (Food and Environment Research Agency 2009). Furthermore, studies have shown that CNTs pose as a health risk after they have been aerosolized (Food and Environment Research Agency 2009). A study examining the effect of nanofillers on particle emission found no significant difference in airborne concentrations compared to their nanoparticle-free counterparts during dry cutting of CNT composites (Wohlleben *et al.* 2011). Additionally, it was determined that the nanoparticle emissions from surface coating depended largely on the coating material

rather than the presence of nanomaterial (Wohlleben *et al.* 2011). Schlagenhauf *et al.* found an increase in nanoparticle number concentration when a Taber Abraser was used to simulate mechanical wear on CNT composites (2012). Another Taber Abraser done by Vorbau *et al* found no significant increase in number concentration when compared to background (2009). Cena and Peters measured particle emission from a manual sanding process of CNT-epoxy nanocomposites, and found an increase in respirable mass but not number concentration when compared to background.

The objective of this study was twofold. The first objective was to develop an experimental setup designed to measure and characterize the emission of particles during the sanding of composite materials containing CNTs. The second objective was to determine how the addition of CNTs affected particle emissions by comparing number/respirable mass concentrations, size distributions, and morphology of different materials containing CNTs. To achieve these goals, an adaptable system was developed to simulate a sanding process. The system consisted of a sand-basting cabinet with HEPA-filtered air intakes. An electrical motor outside the chamber was connected to a pulley through a v-belt. Inside the cabinet, the pulley was connected to a shaft that could accommodate various types of equipment such as a belt sander, a saw blade or a drill chuck. A material feeder with constant force was constructed to deliver the test materials toward the belt sander.

CHAPTER 2: Literature Review

2.1 Health Effects

Nanoparticles have a high large surface-to-volume ration which enhances any type of surface toxicity they may have (Tran *et al.* 2000). Particles with relatively non-toxic surface areas are capable of producing toxic affects if their surface area is large enough (Duffin *et al.* 2002). CNTs have very high surface areas, a nanotube of 20 x 2000 nm would have a surface area 100 times that of a spherical 20 nm particle (Donaldson *et al.* 2006). Due to their large surface area, nanoparticles will immediately adsorb onto the surface of cells they come into contact with and in turn affect cellular processes (Duffin *et al.* 2002). The high surface area of nanoparticles increases the rate of protein adsorption in cells. Adsorption of proteins affects their structure and functions (Donaldson *et al.* 2006).

The fiber shape of CNTs also contributes to their toxicity potential to the human body. Fibers are capable of traveling to the deepest part of the lung by aligning their longitudinal axis with the airstream (Kennedy and Kelly 1993). Fibers are able to deposit around the alveolar ducts where the net flow of air becomes zero (Lippmann 1993). The deposition of CNT fibers will depend on the form it takes when they are aerosolized (Brody *et al.* 1984). CNT fibers are capable of forming into aggregates which resemble particles of similar aerodynamic diameters. A free standing CNT will follow the deposition principals of other similarly shaped fibers (Lippmann 1993).

The length of a fiber has a significant impact in determining the extent of its toxicity. Macrophages are unable to efficiently clear long fibers because the fiber length surpasses the size of the macrophage (Coin *et al.* 1994). Fibers are capable of causing fibrosis and mesothelioma when exposed to the lung (Bernstein *et al.* 2005). A study of amosite fiber exposure to rats found that long amosite fibers produced more fibrosis and mesothelioma than shortened amosite fibers (Davis *et al.* 1986).

A study done by Muller *et al.* exposed rats to different lengths of multi-walled carbon nanotubes (MWCNTs) (2005). The longer MWCNTs were found to last longer in the lungs than shorter MWCNTs. Furthermore, the MWCNTs were found to initiate fibrosis and inflammation in the lungs. Shvedova *et al.* (2005) exposed mice to single-walled carbon nanotubes (SWNCTs) via

pharyngeal aspiration, and observed the different toxicological effects of SWCNT aggregates and free standing SWCNTs. The SWCNT aggregates were found to cause granulomatous inflammation, while areas dominated by free standing SWCNT exposure were predominated by interstitial fibrosis. There have been several studies that have examined the effect of CNTs on different cell types in the human body. Studies found that CNTs are capable of localizing and causing cellular toxicity in human keratinocyte cells (Monterio-Riviere *et al.* 2005). Human T-lymphocytes exposed to MWCNTs were found to have a decrease in cellular viability via an apoptotic mechanism. SWCNT exposure to kidney cells caused cell inhibition as well as the induction of apoptosis (Bottini *et al.* 2006). Alveolar macrophages were exposed to both MWCNTs and SWCNTs, with the latter being more cytotoxic at equal dosage (Searl *et al.* 1999).

2.2 Release Scenarios

Particle release from materials containing CNTs is dependent on the type of mechanical, thermal, and/or chemical forces applied to said materials (Huang *et al.* 2012; Bello *et al.* 2009). Mechanical disruption of CNT infrastructure will result in an increase in nanoparticle generation (Food and Environment Research Agency 2009). Kohler *et al.* (2008) studied the particle emission for Li-ion batteries and textiles containing CNTs. It was found that particle emission from the Li-ion batteries was dependent on irregular recharge attempts and whether or not the Li-ion batteries were subjected to mechanical force or heat (Kohler *et al.* 2008). In textiles, the CNTs were generally very stable and potential release was dependent on external factors. Extreme temperatures and UV light were found to increase particle release from textiles containing CNTs (Food and Environment Research Agency 2009).

2.2.1 Release Scenarios: Production

There are three main CNT production methods: catalytic chemical vapour deposition (CCVD), arc-vapour route, and laser-oven route. CNT release is possible during all three of the leading CNT production methods (Food and Environment Research Agency 2009). CCVD is the most commonly used method to produce CNTs on a commercial basis. During the CCVD process a hydrocarbon catalyst is cracked over a metallic catalyst, it is during this process that CNTs then grow. CNT aerosols formed during the process present a potential inhalation hazard (Food and Environment Research Agency 2009). Other processes of the CCVD method that are capable of

producing CNT exposures include removal of CNTs from the reactors, cleaning/maintenance of the reactor, batch mixing, and post-production cutting/shaping of CNTs (Food and Environment Research Agency 2009).

The arc-vapour route is a physical vapor deposition technique where an electric arc is used to vaporize material from a cathode target, the vaporized materials are then subsequently deposited on the cathode and walls of the chamber (Food and Environment Research Agency 2009). The laser oven route consists of an Nd-YAG laser that is used to vaporize a graphite target, that is then subsequently water-cooled and deposited. Sources of CNT release with the arc-vapour and laser oven route are similar to the CCVD-produced CNTs (Food and Environment Research Agency 2009).

2.2.2 Release Scenarios: Cutting

Bello *et al.* (2009) examined particle release from nanocomposites during dry band saw and wet rotary cutting. The nanocomposites tested were an epoxy resin layer laminate and an alumina fiber cloth; both of which contained CNTs. The authors reported ultra-fine particles were released with both nanocomposites, regardless of the presence or absence of CNTs. Furthermore, it was found that a higher nanocomposite thickness was associated with an increase in particle generation. The dry-cutting process was found to produce more ultra-fine particles than the wet-cutting process. Transmission electron microscope and scanning electron microscope analyses revealed micron sized fibers, but no free-standing CNTs or aggregates were found.

A four day workplace safety study conducted by NIOSH investigated the release of carbon nanofibers (CNF) from epoxy based nanocomposites undergoing cutting, grinding, and sanding. Nanoscale debris was detected during wet saw cutting. Furthermore, transmission electron microscopy (TEM) analysis found free-standing and matrix bound CNFs were identified during the sanding process (Methner *et al.* 2012).

2.2.3 Release Scenarios: Grinding

Ogura *et al.* (2013) examined the particle release from polystyrene-based composites with and without CNTs (2013). Significant increase in nano-sized particle were observed regardless of whether or not the composite contained CNTs. After a thermodenuder was applied, the number of released nanoparticles was reduced by over 99.9% which indicates that the source of nanoparticle

generation was from the friction heat produced by grinding the composite. Scanning electron microscopy (SEM) analysis found several micron sized particles with CNT protrusions, but no free-standing CNTs were observed.

2.2.4 Release Scenarios: Sanding

Koponen *et al.* (2009) used a hand-held orbital sander to simulate sanding for paints and lacquer with added nanomaterials applied to medium-density fibreboard plates. The particles released were predominantly in the 100-300 nm size range regardless of the coating choice. Furthermore, the authors identified the sander motor as the source for particles under 50 nm in diameter size. The authors note that the addition of SEM analysis would help in identifying released CNT aggregates. Gohler *et al.* (2010) used a Dremel tool to simulate the sanding of different coatings containing nanomaterial. TEM analysis found nanofiller embedded within the released particles, while no free dissociated nanomaterial was observed.

Wohlleben *et al.* (2011) measured the release of CNTs from cementitious and thermoplastic nanocomposites being abraded by a Taber Abraser. The experiment was conducted in an enclosed chamber. The authors found nanosized particles regardless of the addition of MWCNTs. SEM analysis observation did not find any CNTs dissociated from the composite matrix. CNT protrusions were found on the nanocomposite surfaces. Furthermore, the authors of the study hypothesized that the electrical sander motor could have been a source of nanoparticle generation. Schlagenhauf *et al.* (2012) performed a similar Taber Abraser study with epoxy resin MWCNTs. However, no particles smaller than 100 nm were observed, which conflicts with the findings of Wohlleben *et al.* (2011).

Cena and Peters (2012) compared background to process particle emissions from CNT-epoxy nanocomposites during bulk weighing and sanding processes. The process to background ratio (P/B ratio) for the weighing process did not show a substantial increase, indicating that the weighing process did not have a significant impact on particle emission. The sanding process showed a high P/B ratio indicating that the sanding process had a significant impact on particle emission. TEM analysis revealed that the sanding process generated micron sized particles with CNT protrusions.

Huang *et al.* (2012) used a sand blasting chamber and a disk sander to evaluate particle emission from epoxy resin sticks with different CNT levels. The epoxy resin sticks were sanded with three different grit sizes and three different disk sander speeds. The highest number concentrations were produced by the coarse sandpaper and medium disk sander speed, while the fine sandpaper produced the highest respirable mass concentrations and medium disk sander speed. Particles around 100 nm were recorded on the size distributions for the materials. Micron sized particles with CNT protrusions were observed on TEM analysis. Free-standing CNTs were only found with the epoxy resin sticks containing 4% CNTs. Furthermore, the 4% CNT sticks produced the highest number and respirable mass concentrations. The authors speculated that the addition of CNTs made the materials more brittle, and in turn increased particle emission.

2.2.5 Release Scenarios: Weathering

Nanoparticle emission of TiO₂ nanopowder coated on different substrates (wood, polymer, and tile) was evaluated in a simulation chamber. The chamber box contained an UV light, fan, and rubber knife in order to simulate weathering and physical conditions. The study results showed that particle number concentration decreased significantly after 60 and 90 min for TiO₂/polymer and TiO₂/wood. After 120 min, the number concentration started to increase (Hsu and Chen 2006). Gorham *et al.* (2012) used simulated photodegradation via high energy radiant exposure to examine the effect of varying UV light levels on silica nanocomposites. Scanning electron microscopy (SEM) analysis revealed physical surface transformations to the nanocomposites.

2.2.6 Release Scenarios: Incineration

Bouillard *et al.* (2013) examined particle emission from the incineration of thermoplastic nanocomposites containing MWCNTs. Particles under 30 nm were detected during incineration. Furthermore, free-standing and MWCNT aggregates were seen on TEM grids. Motzkues *et al.* (2011) examined the incineration of thermoplastic matrices added with nanofillers. The authors found that the incineration of the matrices alone resulted in nanoparticle generation, and the addition of the nanofiller reduced the rate and concentration of nanoparticle generation.

2.3 Occupational Regulations

There are currently no regulatory standards for nanomaterials in the United States (NIOSH 2010). NIOSH has two current intelligence bulletins that pertain to nanomaterials. NIOSH

recommends exposure limits of 2.4 mg/m^3 and 0.3 mg/m^3 for fine and ultrafine TiO_2 particles (NIOSH 2011). For CNTs, NIOSH recommends an exposure limit of 1 ug/m^3 . NIOSH recommends Method 5040 to quantify exposure to airborne carbon nanotubes (NIOSH 2010). The OSHA permissible exposure limit for graphitic synthetic total dust is 15 mg/m^3 (OSHA 2011). The ACGIH threshold limit value for graphitic synthetic total dust is 2 mg/m^3 (OSHA 2011).

2.4 Literature Summary

The literature has shown that nanocomposites undergoing mechanical manipulation and weathering will release nanoparticles to some degree. Microscopy analysis reveals that nanomaterials often remain embedded in the matrix of the material. However, it is difficult to compare results of different studies because the methods, materials, and instrumentation vary between studies.

CHAPTER 3: Research Design and Methods

3.1 Objectives of Study

The objective of this study was twofold. The first objective was to develop an experimental setup designed to measure and characterize the emission of particles during the sanding of composite materials containing CNTs. The second objective was to determine how the addition of CNTs affected particle emissions by comparing number/respirable mass concentrations, size distributions, and morphology of different materials containing CNTs.

3.2 Experimental Setup

The setup used in this study consisted of a modified sand blasting cabinet with HEPA-filtered air intakes and aerosol sampling ports (Figure 1). An exhaust port located on the rear of the cabinet extracted air at a flow rate of 18.4 L/min via a valve-controlled local exhaust system. Total airflow through the HEPA filters was measured at 0.12 L/min. An electrical motor was located outside of the cabinet and connected to a pulley through a v-belt. Inside the cabinet the pulley was connected to a shaft that held the belt sander in place. The belt sander was operated through the use gloves located on the front of the cabinet. The sand blasting cabinet could be accessed through panels located on the front and both sides. Coarse (P150) and fine (P320) sandpaper (R228, Norton, Saint-Gobain Abrasives, Inc. Worcester, MA) were used to sand the material. A silicon-aluminum based sandpaper was used during the sanding process.

The sample materials were pushed towards the sanding belt by a gravity-fed carriage located above the sander (Figure 2). The gravity fed carriage consisted of a vertical carriage loader with a weight at the top that served as the constant downward force to push the materials towards the belt sander. The weight was held in place by a screw and metal plate, by turning the screw the weight was allowed to fall and in turn drive the material toward the belt sander. A weight of 25 grams was used to supply a constant force on the sanded samples. The speed of the sander (5.6 m/sec) was kept constant for all test trials.

Figure 1: Sand blasting cabinet

Figure 2: Belt sander and DRI inlets

3.2.1 Sample Materials

The baseline materials tested were glass fiber (GF) with an epoxy resin laminate, acrylonitrile butadiene styrene (ABS), and acrylonitrile butadiene styrene with carbon black. Different percentages of CNTs were added by the manufacturer to each of the baseline materials. The materials were labeled into three material categories. The fiber glass materials were labeled in the material I category. The fiber glass material without CNT loading was labeled as material IA while the fiber glass material with 0.15% CNT loading was labeled as material IB. The ABS materials were labeled in the material II category. The ABS material without CNT loading was labeled as material IIA. The ABS materials with CNT 3% loading were labeled as material IIB and IIC; both IIB and IIC had the same level of 3% CNT additive but were incorporated with different methods. The CNTs used in material IIB were coated post production with a proprietary polyurethane and described by the manufacturer as CNS Flake. The CNTs for material IIC were also coated with polyurethane and chopped prior to incorporation in the ABS material.. The production phase and incorporation of CNTs was proprietary to the manufacturer. The ABS materials with carbon black were labeled in the material III category. The ABS materials without carbon black were labeled as material IIIA while the material with 3% CNT additive was labeled as material IIIB. The mean length and width of the CNTs used in the fiber glass material IB were 0.77 μm and 0.015 μm respectively. The mean length and width of the CNTs used in the ABS materials IIB, and IIIB were 2.08 μm and 0.017 μm respectively. The mean lengths and widths of the chopped CNTs for material IIC were not given. Refer to Table 1 for a material listing.

Table 1: Material Descriptions

Material	Composition	CNT additive
Material IA	Glass Fiber/Epoxy Resin Laminate	0% CNT loading
Material IB	Glass Fiber/ Epoxy Resin Laminate	0.15% CNT loading
Material IIA	Acrylonitrile Butadiene Styrene	0% CNT loading
Material IIB	Acrylonitrile Butadiene Styrene	3% CNT loading
Material IIC	Acrylonitrile Butadiene Styrene	3% CNT loading
Material IIIA	Acrylonitrile Butadiene Styrene with carbon black	0% CNT loading
Material IIIB	Acrylonitrile Butadiene Styrene with carbon black	3% CNT loading

3.2.2 Instrumentation

All direct-read instruments (DRIs) were located outside of the cabinet with sampling lines (91 cm long) that were used to carry the aerosol to the instruments. The inlets of the sampling lines were located inside the cabinet 20 cm from the belt sander. A scanning mobility particle sizer (SMPS, Model 3080, TSI, Inc., Shoreview, MN) at a flow rate of 0.6 L/min was used to measure the particle number concentration and mass concentration in 32 channels that ranged from 10.4 nm to 406.8 nm. Three SMPS scans were taken for each run, with each scan lasting two minutes and twenty-four seconds. An optical particle counter (OPC, Model 1.109, Grimm Technologies, Atlanta, GA) at a flow rate of 1.2 L/min was used to measure particle number and mass concentration in 16 channels that ranged from 0.25 μm to 32 μm . The OPC recorded measurements on a one minute interval for a total of seven minutes. The total number concentration of particles from 0.004 μm to 3 μm was measured using a condensation particle

counter at a flow rate of 1.5 L/min (CPC, Model 3775, TSI, Inc., Shoreview, MN). The CPC recorded measurements every second for a total of seven minutes.

Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were used to characterize the morphology of the emitted particles. A thermophoretic sampler (TPS, RJLEE, Monroeville, PA) collected particles on a transmission electron microscope grid at a flow rate of 0.05 ml/min for TEM analysis. The TPS was used to collect nanoparticles and determine if any free standing CNTs were released from the composite matrices. A three piece 25 mm cassette with a 0.8 μ m poly-carbonate filter connected to a sampling pump (SKC Inc., Eighty Four, PA. 15330 USA) operating at 1.5 L/min was used to collect particles for SEM analysis. Computer controlled scanning electron microscopy (CCSEM) was performed on more than 500 particles in order to acquire morphology and chemical composition. The energy-dispersive X-ray spectroscopy (EDS) test was done to determine the amount of silica particles that were among the airborne particles.

3.3 Protocol

Prior to each test, a new sandpaper band was loaded onto the belt sander. The sandpaper grit choices consisted of P320 (Fine) and P150 (Coarse). A sample was placed in the gravity-fed loader and the airflow and DRIs were turned on. The sampling time for the OPC was set to 1 minute averages while the CPC recorded measurements every second. The SMPS reported concentrations every 2 minutes and 24 seconds. Background measurements inside the sand blasting cabinet were taken for 5 minutes with the DRIs when the belt sander was off (no sanding occurred). During background measurements the TPS and sampling pump were off. Following the background measurements, the belt sander was turned on and allowed to warm-up for 30 seconds, then the gravity fed carriage was operated to allow the sample to be fed towards the belt sander. The TPS and sampling pump were turned on when the sanding started. Particle concentrations inside the chamber were allowed to stabilize for 8 minutes after which measurements were recorded with the DRIs for 7 minutes. Following the sampling period, the sample was lifted, the belt sander was turned off, the sandpaper was replaced with a new band of the same grit type, and the experiment was repeated.

Each sampling period lasted a total of 20 minutes, which can be broken down into 5 minutes of background concentration measurements where no sanding took place, 8 minutes of sanding to ensure stabilization of the generation of particles, and another 7 minutes of sanding for particle measurements. The TPS and filter cassette were active for the 15 minutes of sanding that occurred. The DRIs were active during the 5 minutes of background measurements and during the 7-min sanding after the stabilization period. Each sandpaper grit was tested in triplicate following the same procedures. One cumulative TPS sample was collected for all repetitions while the filter cassettes were replaced before each repetition.

The internal surfaces of the sand blasting cabinet were wiped when switching between sandpaper type and the cabinet was cleaned with a vacuum between test sample types. Field blank tests were taken to ensure that no cross contamination occurred between samples. During the field blank tests all protocols of a regular trial were followed with the exception that no material was fed to the sander. The field blank samples also served as a test to determine if the belt sander contributed to particle generation.

3.4 Data Analysis

The data from the DRIs were averaged from the triplicate runs for each material. The number concentrations were obtained from the OPC and CPC measurements. The data obtained from the CPC and OPC were used to calculate respirable mass (M) concentrations using the following equation (Peters *et al.* 2006)

$$M = \frac{\pi}{6} d_{CPC}^3 \rho N S_R(d_{CPC}) + \sum_{i=1}^{15} \frac{\pi}{6} d_{OPC,i}^3 \rho N_{OPC,i} S_R(d_{OPC,i}) \dots \dots \dots \text{Equation 1}$$

In this equation d_{CPC} is the midpoint diameter of the CPC channel (120 nm), ρ is the particle density, N is the number concentration designated by the CPC, S_R is a function for the fraction of respirable mass, $d_{OPC,i}$ is the midpoint diameter of the OPC channel, I , $N_{OPC,i}$ is the number concentration designated by the OPC for a given size channel, i . The particle size distribution graphs were obtained from the OPC and SMPS measurements. The midpoint diameter channels that ranged from 10.4 nm to 283.9 nm were used from the SMPS, while the midpoint diameter channels that ranged from 300 nm to 32,000 nm were used from the OPC. The number and

respirable mass concentrations were averaged from the triplicate runs for each material. The DRI background values were subtracted from the final measurement values. All particle number and respirable mass concentrations were tested for normality using Shapiro-Wilk test in the statistical analysis program R. Not all data passed the Shapiro-Wilk test for normality, so the values were also analyzed by the nonparametric Kruskal-Wallis test. Background measurements were subtracted from the final measurements to account for background values. Analysis of variance (ANOVA) was used to test the hypothesis that the number concentration was statistically different for the sandpaper grit and CNT additive test conditions. Similar analysis was performed for respirable mass concentrations. The Tukey Kramer Honestly Significant Difference HSD at $\alpha=0.05$ was used to compare number and respirable mass concentrations for different test conditions. Background measurements were subtracted from the final measurements to account for background values. Any background subtractions that resulted in negative values were replaced with zero. The value zero was used to represent the lack of particle production in a particular midpoint diameter channel.

CHAPTER 4: Results

The results of the comparison between baseline materials and their respective CNT additive materials are summarized in figures 3 through 9. The upper and lower boundaries of the boxplots represent the 75th and 25th percentiles, the central line represent the median, and the whiskers above and below represent the maximum and minimum values. The size distribution graphs show the number and mass concentration values over a size range of midpoint diameters. The number and respirable mass concentrations computed from the triplicate runs are shown in Table 2.

Table 2: Number and Respirable Mass Concentrations for Materials I, II, and III. SD = Standard Deviation

Material	Sandpaper	Number Concentration, Particles/cm ³ (SD)	Respirable Mass Concentration mg/m ³ (SD)	CNT Additive
IA	Coarse	48,631 (7,159)	0.39 (0.056)	0%
IA	Fine	3,472 (951)	0.68 (0.065)	0%
IB	Coarse	42,596 (4,322)	0.68 (0.065)	0.15%
IB	Fine	2,105 (438)	0.45 (0.034)	0.15%
IIA	Coarse	523 (66)	0.04 (0.04)	0%
IIA	Fine	356 (92)	0.06 (0.05)	0%
IIB	Coarse	8,217 (1,628)	0.06 (0.01)	3%
IIB	Fine	1,473 (527)	0.11 (0.03)	3%
IIC	Coarse	193 (176)	0.04 (0.01)	3%
IIC	Fine	27 (19)	0.03 (0.01)	3%
IIIA	Coarse	2,556 (1,211)	0.03 (0.004)	0%
IIIA	Fine	2,390 (499)	0.03 (0.007)	0%
IIIB	Coarse	1,473 (92)	0.09 (0.012)	3%
IIIB	Fine	174 (50)	0.03 (0.005)	3%

4.1 Comparison of particle emissions for epoxy fiber glass with sandpaper grit

The highest particle number concentrations were produced with the coarse sandpaper compared to the fine sandpaper for the fiber glass material IA (0% CNT) and IB (0.15% CNT). The average number concentrations for the coarse sandpaper were substantially greater than those associated with the fine (Figure 3, Panels A and C). The average coarse sandpaper number concentrations for material IA and material IB were 48,631 particles/cm³ and 42,596 particles/cm³ respectively, whereas the average fine sandpaper number concentrations were 3,472 particles/cm³ and 2,105 particles/cm³ for material IA and material IB respectively (Table 2). The greatest respirable mass concentrations were produced with the fine sandpaper for material IA, while material IB did not have any statistical difference in respirable mass concentrations between the coarse and fine sandpaper ($p=0.55$). The average fine sandpaper respirable mass concentrations were 0.68 mg/m³ and 0.45 mg/m³ for material IA and material IB respectively. The average coarse sandpaper respirable mass concentrations were 0.39 mg/m³ and 0.47 mg/m³ for material IA and IB respectively (Table 2).

4.2 Comparison of particle emissions for epoxy fiber glass with CNT additive

Material IA (0% CNT additive) produced a higher number concentration than material IB (0.15% CNT additive) for the coarse sandpaper test condition (Figure 3, Panels A and C). The fine sandpaper test condition showed no statistical difference between the two materials ($p=0.72$).

Material IA produced a higher respirable mass concentration than material IB for the fine sandpaper test condition (Figure 3, Panels B and D). The fine sandpaper respirable mass concentration for material IA averaged 0.68 mg/m³ compared to the average of 0.45 mg/m³ for material IB. However, the respirable mass concentration for material IB with coarse sandpaper produced a higher average of 0.47 mg/m³ compared to the material IA average of 0.39 mg/m³ (Table 2). There was no statistical difference between the coarse and fine test conditions for material IB when it came to respirable mass concentrations ($p=0.55$).

Figure 3: Boxplots of (A) number concentration and (B) respirable mass concentration for material IA. Boxplots of (C) number concentration and (D) respirable mass concentration for material IB.

4.3 Particle size distribution for epoxy fiber glass

The particle count size distribution graphs for material IA (0% CNT) and IB (0.15% CNT) both produced size modes seen around 20 nm in midpoint particle diameter. The coarse sandpaper was associated with higher concentrations than that of the fine sandpaper (Figure 4, Panels A and B). There were no size modes seen past 200 nm for the particle count distribution.

The particle mass distribution graphs for material IA and IB produced size modes at 5 μm , 10 μm , and 20 μm in midpoint particle diameter (Figure, 4 Panels C and D) for both the coarse and fine sandpaper. Material IA had a higher size mode than that of material IB at 20 μm for the coarse sandpaper condition, while material IB had a higher size mode located at 5 μm for the same grit.

Figure 4: Material I number concentration for the coarse sandpaper grit (A) and fine sandpaper grit (B). Mass concentration for the coarse sandpaper grit (C) and fine sandpaper grit (D).

4.4 Comparison of particle emission for Acrylonitrile Butadiene Styrene with sandpaper grit

The highest particle number concentrations were produced with the coarse sandpaper compared to the fine sandpaper for the Acrylonitrile Butadiene Styrene (ABS) materials IIA (0% CNT), IIB (3% flaked CNT), and IIC (3% chopped CNT) (Figure 5, Panels A and C). The higher respirable mass concentrations were produced with the fine sandpaper for materials IIB and IIC, while the Tukey HSD test showed that sandpaper had no statistical effect on respirable mass concentrations for material IIA ($p=0.62$).

4.5 Comparison of particle emission for Acrylonitrile Butadiene Styrene with CNT additive

Material IIB (3% CNT) produced a higher number concentration than that of material IIA (0% CNT) and material IIC (3% CNT additive) for both of the sandpaper test conditions (Figure 5, Panels A and C). The average number concentrations for material IIB with coarse and fine sandpaper were 8,217 particles/cm³ and 1,473 particles/cm³ respectively, while the averages for material IIA were 523 particles/cm³ and 356 particles/cm³ respectively (Table 2). The average respirable mass concentrations for material IIB with coarse and fine sandpaper were 0.063 mg/m³ and 0.11 mg/m³ respectively, while the averages for material IIA were 0.038 mg/m³ and 0.061 mg/m³ respectively (Table 2). However, there was no statistical difference for Material IIB with coarse sandpaper and material IIA with fine sandpaper ($p=0.94$). Material IIC had the lowest number concentrations for the coarse and fine sandpaper test conditions with an average of 193 particles/cm³ and 27 particles/cm³ respectively.

(A)

(B)

(C)

(D)

Figure 5: Boxplots of (A) number concentration and (B) respirable mass concentration for material IIA. Boxplots of (C and E) number concentration and (D and F) respirable mass concentration for material IIB.

4.6 Particle size distribution for Acrylonitrile Butadiene Styrene

The particle count distribution for material IIA did not show any discernable size modes around 100 nm for both sandpaper grit choices, while material IIB showed a size mode around 100 nm. (Figure 6, Panels A and B). Material IIB had consistent size modes located at 20 nm in the particle count distribution for both the coarse and fine sandpaper (Figure 7, Panels A and B). In size ranges beyond 100 nm for the particle count distribution there was no noticeable difference between material types. The size modes associated with the coarse sandpaper were higher than those of the fine sandpaper for material IIB.

The coarse and fine sandpaper test conditions for material IIB material produced size modes at 20 nm for the particle count distribution (Figure 6, Panels A and B). The coarse sandpaper was associated with a higher peak than that associated with the fine sandpaper. The

particle mass distribution for material IIB had two size modes located at 5 μm and 20 μm for both of the sandpaper grits (Figure 6, Panels C and D).

The particle mass distribution for the coarse sandpaper had size modes at 5 μm and 20 μm , with material IIA having a higher peak at 5 μm and material IIB having a higher peak at 20 μm (Figure 6, Panels C and D). The particle mass distribution for materials IIA and IIB with the fine sandpaper had similar size modes to the coarse sandpaper, with the exception that material IIA did not have a size mode located at 20 μm . The size mode for material IIA with the fine sandpaper was higher than the size mode for the coarse sandpaper at 5 μm . Material IIC produced smaller size modes at 5 μm and 20 when compared to materials IIA and IIB (Figure 7, Panels C and D).

Figure 6: Material II number concentration for the coarse sandpaper grit (A) and fine sandpaper grit (B). Mass concentration for the coarse sandpaper grit (C) and fine sandpaper grit (D).

Figure 7: Material II number concentration for the coarse sandpaper grit (A) and fine sandpaper grit (B). Mass concentration for the coarse sandpaper grit (C) and fine sandpaper grit (D).

4.7 Comparison of particle emission for Acrylonitrile Butadiene Styrene/carbon black with sandpaper grit

The highest number concentrations were produced by the coarse sandpaper for material IIIB, while the Tukey HSD analysis showed that sandpaper did not produce any statistical difference for material IIIA in terms of number concentration ($p=0.53$). The highest respirable mass concentrations were produced with the coarse sandpaper for materials IIIA (0% CNT) and IIIB (3% CNT). The Tukey HSD analysis found no statistical difference between the respirable mass concentrations for material IIIB fine sandpaper and material IIIA coarse sandpaper test levels ($p=0.62$).

4.8 Comparison of particle emission for Acrylonitrile Butadiene Styrene/carbon black with CNT additive

Material IIIA (0% CNT additive) produced a greater number concentration than material IIIB (3% CNT additive) for both the coarse and fine sandpaper test conditions (Figure 8, Panels A and C). The average number concentrations for material IIIA with coarse and fine sandpaper were 2,556 particles/cm³ and 2,390 particles/cm³ respectively; compared to material IIIB average of 1,473 particles/cm³ and 174 particles/cm³ respectively (Table 2). Material IIIB produced a greater respirable mass concentration than material IIIA for the coarse and fine sandpaper test conditions (Figure 8, Panels B and D). The average respirable mass concentrations for material IIIB with coarse and fine sandpaper were 0.088 mg/m³ and 0.033 mg/m³ respectively; compared to material IIIA average of 0.028 mg/m³ and 0.026 mg/m³ respectively (Table 2). There was no statistical difference for the respirable mass concentrations between the coarse and fine sandpaper test conditions for material IIIA ($p=0.89$). There was also no statistical difference in respirable mass concentrations between material IIIB fine sandpaper and material IIIA coarse sandpaper test conditions ($p=0.62$).

Figure 8: Boxplots of (A) number concentration and (B) respirable mass concentration for material IIIA. Boxplots of (C) number concentration and (D) respirable mass concentration for material IIIB.

4.9 Particle distribution for Acrylonitrile Butadiene Styrene/carbon black

Material IIIA and material IIIB both produced particle count size modes at 20 nm for the coarse sandpaper; the size mode associated with material IIIA had a higher peak than that of material IIIB. (Figure 9, Panels A and B). For the fine sandpaper, material IIIA again produced a size mode around 20 nm while material IIIB produced a less well-defined size mode at 100 nm.

Material IIIA and material IIIB both have particle mass distribution size modes at 5 μm and 20 μm for the coarse sandpaper; with material IIIB associated with higher peaks as well as having another size mode located around 10 μm (Figure 9, Panels C and D). Both materials produced a size mode just around 10 μm for the fine sandpaper. The average mass concentration for material IIIB with coarse and fine sandpaper were 0.104 mg/m^3 and 0.019 mg/m^3 respectively; compared to material IIIA average of 0.034 mg/m^3 and 0.017 mg/m^3 respectively (Table 2).

The coarse and fine sandpaper test conditions had similar size modes located around 100 nm for the particle count distribution, and the coarse sandpaper was associated with a higher peak than that associated with the fine sandpaper (Figure 8, Panels A and B). The particle mass distribution had size modes at 5 μm and just above 10 μm for the coarse sandpaper, while the fine sandpaper was associated with single size mode at 5 μm (Figure 9, Panels C and D).

Figure 9: Material IIA number concentration for the coarse sandpaper grit (A) and fine sandpaper grit (B). Mass concentration for the coarse sandpaper grit (C) and fine sandpaper grit (D).

4.10 Microscopy Analysis

Filter and TPS images of airborne particles are presented in Figures 10-15. The TPS samples were lightly loaded, which indicates that few nanoparticles were being generated during the sanding process. No free-standing CNTs or CNT aggregates were found on either TPS grids or the filter samples. Particles collected for microscopy analysis were micron-sized and irregular in shape. There was no difference in morphology for the particles generated from the coarse and fine sandpaper grits. Particles with protruding features were seen with the materials containing CNTs. Materials without CNTs did not have protruding features similar to the materials with CNTs. This morphology would indicate that the protrusions are CNTs and not a part of the baseline material. The CNT protrusions ranged from around 500 nm to 700 nm in length, and 10 nm to 15 nm in width.

The filter samples and TPS grids for the field blank collections were lightly loaded, indicating little to no cross-contamination between material test runs. Very few particles with CNT protrusions were found. The CCSEM results revealed that silica rich particles made up 0.1% of the 525 particles analyzed. Silicon-aluminum and calcium made up 1.4% and 6.1% of the particles analyzed.

Table 3: CCSEM Results for material IIB (Particles > 2 μm in average diameter)

Classes	#	No.%	Wt.%
C-rich	461	87.8	91.8
Si-Al	21	4.0	1.4
Ca-rich	20	3.9	6.1
Other	14	2.7	0.2
Ca-Mg	6	1.1	0.4
Si-rich	3	0.6	0.1
Totals	525	100	100

Figure 10: SEM image of material IA (coarse sandpaper)

Figure 11: SEM image of material IB (coarse sandpaper)

Figure 12: SEM image of material IIB (coarse sandpaper)

Figure 13: TEM image of material IA (coarse sandpaper)

Figure 14: TEM image of material IIB (fine sandpaper)

Figure 15: CCSEM analysis of silica particle

4.11 Field Blank Samples

The average number concentrations for the before and after cleaning field blank samples were 169 particles/cm³ and 64 particles/cm³ respectively. While the respirable mass concentration averages for the before and after cleaning field blank samples were 0.015 mg/m³ and 0.009 mg/m³ respectively. The TPS grids were lightly loaded with no discernable particles. The filter samples were also lightly loaded, but a microscopic image revealed one particle with a CNT protrusion. After background subtractions, the nano-sized number concentrations throughout the size distribution varied with numerous negative values indicating that little to no nanoparticles were being produced.

Figure 16: TPS grid of Field Blank Sample

Figure 17: SEM Image of Field Blank Particle with Protrusion

CHAPTER 5: Discussion

5.1 Effects of CNTs on Concentrations

The fiber glass materials IA (0% CNT) and IB (0.15 % CNT) did not show any increase in number or respirable mass concentration with the addition of CNTs. The particle count and mass distribution graphs for material IA (0% CNT) and IB (0.15%) were similar which suggests that the addition of CNTs did not produce any discernable change in particle emission. For the ABS materials IIA (0% CNT) and IIB (3% CNT), the addition of CNTs lead to an increase in number and respirable mass concentration. The particle count distribution also showed that material IIB (3% CNT) produced a greater amount of sub-100 nm particles than material IIA (0% CNT). However, the ABS material IIC (3% CNT) did not produce higher number or respirable mass concentrations than material IIA, and had a particle count distribution that did not produce a substantial amount of sub 100-nm particles.

Material IIB (3% CNT) and IIC (3% CNT) had the same baseline material, but had different CNT incorporation methods. Both materials had CNTs grown on glass fibers and then post coated with polyurethane. After the post coating process, the CNTs for material IIC were chopped before incorporation into the plastic. The precise details of the CNT incorporation methods are proprietary to the manufacturer and are not reported. The manufacture did not specify what was involved with the “chopping” process, but it stands to reason that the process would shorten the CNTs. A study done by Jo *et al.* (2004) found that emission properties of CNT enhanced plastics can be decreased by increasing the length of CNTs, which would be in conflict with the results of this study since the particle emission for the material with shorter CNTs was less than the same material with longer CNTs. More information is needed on the length and manufacturing methods of the chopped CNTs to come to a conclusion about the effect of CNT length on particle emission. From the results for material IIB and IIC it would seem that the CNT incorporation method had a greater impact on particle emission than CNT addition since both materials had the same level of CNT additive. The chopped fibers for material IIC may have reduced the brittleness of the ABS material and in turn reduced the number of small particles that break apart during the sanding process. The idea that CNTs increase the brittleness of materials is

supported by studies done by Gohler *et al.* (2010), Wohlleben *et al.* (2011) and Huang *et al.* (2012).

For the ABS materials with carbon black (IIIA and IIIB) it was found that material IIIB (3% CNT) produced a higher respirable mass concentration and a lower number concentration when compared to the baseline material IIIA (0% CNTs). This result is consistent with a study done by Cena and Peters (2011) who found that respirable mass concentrations were higher than number concentrations when CNT epoxy sticks were sanded. The particle count distribution graphs also show that material IIIB did not produce any discernable size modes around 100 nm. From these results it would appear that the addition of CNTs did not increase the release of nanoparticles.

Previous studies such as Huang *et al.* (2012) suggested that the addition of CNTs would increase the brittleness of a material which would then allow the sanding process to break away more of the material. Wohlleben *et al.* (2011) suggested that the rigidity and brittleness of the test samples had a greater effect on particle emission than the presence of nanofillers. The brittleness of the materials was not tested in this study, so no conclusion can be made on whether or not the addition of CNTs increased the brittleness of materials. Based on the results from this study, no clear conclusion can be made about the effect of CNTs on particle emission. Results from a study done on the same base material with different concentrations of CNTs would provide a clearer effect of CNTs on particle emission.

5.2 Effects of Sandpaper on Concentration

Particle number and respirable mass concentrations showed a more consistent association with the grit of the sandpaper. For both the ABS and fiber glass materials, the highest particle number concentrations were produced with the coarse sandpaper, while the highest respirable mass concentrations were produced with the coarse sandpaper. The coarse sandpaper abraded away more of the material than the fine sandpaper during the test runs. The increase in dust generation is a possible explanation for the higher number concentrations associated with the coarse sandpaper. Furthermore, the coarse sandpaper was associated with higher size modes located around 100 nm for the particle count distribution graphs. The fine sandpaper was able to abrade away the material into more respirable-sized particles. The finding that the highest number concentrations were

associated with the coarse sandpaper while the highest respirable mass concentrations were associated with the fine sandpaper are consistent with the findings by Huang *et al.* (2012).

The overall shape of the particle count and mass distributions stayed constant with the material type and sandpaper grit. The particle mass distributions were multi-modal and had size modes located from 1 μm to 10 μm . The magnitude of the size modes varied depending on the sandpaper grit. In general the fine sandpaper was associated with higher modes for the micron sized particles. The particle count distributions were unimodal with one size mode located around 100 nm. The size mode located around 100 nm is associated with mass concentrations for nanoparticles.

5.3 Nanoscale Release

The source of the sub 100 nm particles may be attributed to degradation of the sandpaper grit. According to previous studies and literature, particles generated from mechanical breakage are typically in the micron size (Hinds, 1998). Silicon-based sanding belts were used during the trials, and the CCSEM analysis found silicon particles in the generated aerosols during sanding. The presence of silicon particles indicates that the sandpaper grit was deteriorating and subsequently released in the chamber. Out of the 525 particles analyzed by CCSEM, 21 were found to be silic-particles. The analysis done by the CCSEM is not a true reflection of the aerosolized particles due to the small selection size. However, the presence of silic- suggests that the degradation of the sandpaper could be a possible source for nano-sized particles. Koponen *et al.* (2009) attributed the generation of nano-sized particles to the wearing of the sandpaper as opposed to the material itself. Additionally, the same group found that the motor for the sander also contributed to the generation of nano-sized particles. In this study, the motor for the belt sander was housed outside of the chamber to reduce the sources of particle generation.

Material IIA (0% CNT) and the field blank samples had similar number size distributions for particles around 100 nm, which indicates that the sandpaper may not be a source of nanoparticle generation. While material IIA and material IIIB did not produce peaks around 100 nm (similar to the field blank samples), the other materials did produce peaks seen around 100 nm. The type of CNTs used in the different materials and their related incorporation method may have

an effect on nanoparticle generation. Ambient air leaking into the chamber may be a source for some of the nanoparticles recorded on the DRIs.

Subtracting particle count background values from the final particle count measurement values for material IIA (0% CNT) and IIC (3% CNT) resulted in several negative values for channels around 100 nm (Figure 7, Panels A, B, E, and F). The negative values indicate that no nanoparticles were being recorded in those channels of the DRIs. This would suggest that nanoparticles were not being produced during the sanding procedure for that material. As a result, the particle count distribution for material IIA and IIC did not show any discernable size modes around 100 nm for both sandpaper grit choices.

5.4 Background Concentrations

The field blank samples with the belt sander running but with no sanding, produced an average number concentration of 64 particles/cm³ and 168 particles/cm³ for the coarse and fine sandpaper grits. The low number concentrations indicate that the belt sander motor did not have a significant contribution to particle generation within the chamber. Thorough examination of the field-blank samples revealed one particle with a protrusion, which indicates minor cross-contamination potential between material samples. Cleaning the chamber in between materials reduces the amount of cross-contamination to where it has little to no quantifiable effect on the results. The field blank TPS and filter samples were lightly loaded to almost clear, which supports the notion that the cross-contamination occurring had a negligible effect.

5.5 Morphology of Released Particles

There were no free standing CNTs found in the microscopy analysis, which is consistent to the results of previous studies done by Cena & Peters (2011) and Schlagenhauf *et al.* (2012). CNTs have high tensile strength (Huang *et al.* 2012), so when they are subjected to mechanical stress they are less likely to break free and instead protrude out from the particle. No aggregate bundles of CNTs were found in the microscopy images as well. The lack of CNT aggregates can be attributed to the nature of CNTs staying embedded within the matrix of the baseline material. Most of the microscopy images came from the filter samples, while the TPS grids were very lightly loaded. The lack of loading on the TPS grids supports the notion that the CNTs did not dissociate from the nanomaterial matrix. Furthermore, the lightly loaded TPS grids suggest a low

nanoparticle production, which is in conflict with the sub-100 nm size modes seen in the particle count distribution. Ambient air leaks into the chamber may be the source of sub-100 nm particles found in the particle count distributions.

The particles collected on the filter samples were micron sized, irregular in shape, and some had protrusions extending from their surfaces. The protrusions were between 6-10 microns in length, and 10-50 nanometers in width. Furthermore, the protrusions had parallel sides (*i.e.*, the protrusions were tube shaped). The morphology would suggest that the protrusions seen were CNTs.

There was no clear distinction in particle morphology between the ABS and fiber glass materials. The silicon particles collected on the filter samples did not have the same irregular shape as the previously mentioned particles. The observed silicon particles had a smoother surface appearance and did not have any clear protrusions sticking out from the particle surface.

5.6 Standardization and Repeatability

This study demonstrates a reliable and consistent methodology for conducting tests on particle emission from nanocomposites during a sanding process. The design setup is able to produce repeatable runs for comparison. The number and respirable mass concentrations were consistent throughout the trial runs for the materials (Refer to appendix B). The particle size distribution graphs produced consistent size modes for all materials and sandpaper grit choices.

The instrumentation used in this study has been used in other studies related to the same topic, and provide a size distribution of the particles emitted. Furthermore, the chamber can be modified to accommodate drilling, cutting or other potential release scenarios. Future research regarding this study should include testing different percentage loadings of CNTs. Inhalation toxicity studies of CNT aerosols can be conducted using this experimental setup. Toxicological studies will provide understanding on toxicity exposures at various stages of the CNT life-cycle process.

5.6 Limitations

The materials had different mechanical properties, which resulted in them breaking away at different rates (the amount of material left after a trial was different for certain materials). The

amount of material released can influence the number concentrations measured by the DRIs. However, to create equal feed rates for all of the materials, the force and trial duration would have to be altered, which would in turn increase the amount of test variables to control for. Utilizing a constant force instead of a constant feed rate reduced the amount of variables.

There was no clear method of identifying protrusions as CNTs. The protrusions seen may have been a part of the baseline material stretching out. However, the protrusions specified as CNTs had parallel sides and widths within the range of those measured for CNTs. The number and respirable mass concentrations found in this study were only used for comparison among material samples and do not have regulatory applications. Given the length of the sampling lines (91 cm), there may have been some line losses of particles being carried to the DRIs. To minimize the losses, the lines were kept as short as possible (91 cm) with no sharp bends.

5.7 Conclusions

No clear association can be made regarding the effect of CNTs on particle emission. The comparison of baseline materials with the CNT additive material showed increased particle emission for certain ABS materials and decreased particle emission for the fiber glass materials. The coarse sandpaper was associated with a higher number concentration in terms of particle emission, while the fine sandpaper was associated with a higher respirable mass concentration. Sanding of the CNT-containing materials produced micron-sized particles with CNT protrusions; no free-standing CNTs were found. Nano- to micron-sized particles were generated during sanding. The degradation of sandpaper grit may have been a source of the nanoparticle generation. The testing apparatus with different materials resulted in repeatable tests.

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Appendix A: Experimental Setup

Sandblasting Cabinet

Air Exhaust/Intake

Belt Sander, gravity fed loader, and DRIs

Belt Sander Motor

Scanning mobility particle spectrometer, condensation particle counter, and optical particle counter

Thermophoretic sampler and SKC air pump

Appendix B: Trial Run Data

Material	Run	Sandpaper	Number Concentration, particles/cm ³ (SD)	Respirable Mass Concentration, mg/m ³ (SD)
IA	1	Fine	2,721 (325)	0.62 (0.062)
IA	2	Fine	4,562 (749)	0.71 (0.047)
IA	3	Fine	3,132 (3,132)	0.72 (0.032)
IB	1	Fine	1,662 (169)	0.44 (0.041)
IB	2	Fine	2,043 (165)	0.46 (0.041)
IB	3	Fine	2,611 (230)	0.44 (0.020)
IIA	1	Fine	421 (8)	0.045 (0.006)
IIA	2	Fine	404 (41)	0.12 (0.044)
IIA	3	Fine	243 (64)	0.024 (0.014)
IIB	1	Fine	809 (79)	0.068 (0.010)
IIB	2	Fine	1,560 (94)	0.13 (0.0085)
IIB	3	Fine	2,048 (69)	0.13 (0.0061)
IIC	1	Fine	51 (16)	0.029 (0.002)
IIC	2	Fine	14 (2)	0.028 (0.003)
IIC	3	Fine	17 (1)	0.031 (0.002)
IIIA	1	Fine	2,355 (250)	0.033 (0.002)
IIIA	2	Fine	2,934 (321)	0.018 (0.001)
IIIA	3	Fine	1,882 (1.07)	0.028 (0.001)
IIIB	1	Fine	108 (17)	0.038 (0.003)
IIIB	2	Fine	202 (22)	0.027 (0.002)
IIIB	3	Fine	211 (7)	0.034 (0.001)

Material	Run	Sandpaper	Number Concentration, particles/cm ³ (SD)	Respirable Mass Concentration, mg/m ³ (SD)
IA	1	Coarse	48,490 (1,754)	0.39 (0.0064)
IA	2	Coarse	56,618 (3,556)	0.46 (0.017)
IA	3	Coarse	40,786 (2,983)	0.33 (0.011)
IB	1	Coarse	43,150 (2,342)	0.44 (0.013)
IB	2	Coarse	44,537 (6,322)	0.49 (0.039)
IB	3	Coarse	45,956 (3,498)	0.49 (0.033)
IIA	1	Coarse	458 (72)	0.04 (0.002)
IIA	2	Coarse	555 (30)	0.039 (0.003)
IIA	3	Coarse	556 (32)	0.035 (0.005)
IIB	1	Coarse	8,560 (481)	0.08 (0.003)
IIB	2	Coarse	8,781 (2,378)	0.06 (0.016)
IIB	3	Coarse	7,308 (1,218)	0.05 (0.007)
IIC	1	Coarse	143 (35)	0.044 (0.003)
IIC	2	Coarse	412 (99)	0.042 (0.004)
IIC	3	Coarse	24 (3)	0.041 (0.005)
IIIA	1	Coarse	4,041 (958)	0.025 (0.004)
IIIA	2	Coarse	1,709 (201)	0.028 (0.006)
IIIA	3	Coarse	1,917 (215)	0.030 (0.003)
IIIB	1	Coarse	1,447 (83)	0.099 (0.011)
IIIB	2	Coarse	1,432 (22)	0.082 (0.008)
IIIB	3	Coarse	1,539 (115)	0.083 (0.010)

Material	Sandpaper	Mass Concentration, mg/m ³ (SD)
IA	Fine	0.031 (0.075)
IB	Fine	0.019 (0.043)
IB	Coarse	0.018 (0.049)
IA	Coarse	0.017 (0.038)
IIB	Fine	0.16 (0.37)
IIB	Coarse	0.12 (0.30)
IIA	Fine	0.079 (0.025)
IIA	Coarse	0.053 (0.014)
IIC	Coarse	0.022 (0.063)
IIC	Fine	0.021 (0.048)
IIIB	Coarse	0.104 (0.022)
IIIA	Fine	0.034 (0.009)
IIIB	Coarse	0.019 (0.045)
IIIA	Fine	0.017 (0.050)

Background Concentrations (Particles/cm ³)	Sandpaper Grit
64	Coarse
168	Fine

Appendix C: Raw Data

Average Runs of Material IA w/coarse sandpaper OPC/CPC Number concentration (#/L)							
MidD (um)	Min. 1	Min. 2	Min. 3	Min. 4	Min. 5	Min. 6	Min. 7
0.12	9995	10435	10325	10246.67	9865	10465	10386.67
0.25	8640	9021.667	9215	9043.333	8618.333	9071.667	8818.333
0.28	7533.333	7565	7778.333	7550	7516.667	7851.667	7611.667
0.3	7395	7528.333	7736.667	7515	7230	7795	7543.333
0.35	4250	4438.333	4690	4421.667	4191.667	4663.333	4256.667
0.4	3238.333	3401.667	3486.667	3358.333	3283.333	3520	3303.333
0.45	4543.333	4688.333	4700	4728.333	4475	4860	4306.667
0.5	4326.667	4355	4381.667	4266.667	3983.333	4535	4155
0.58	1910	1945	1906.667	1825	1715	1938.333	1840
0.65	2156.667	2148.333	2150	2206.667	2030	2295	2086.667
0.7	1773.333	1920	1925	1823.333	1728.333	1763.333	1698.333
0.8	2338.333	2153.333	2366.667	2243.333	2065	2418.333	2125
1	1093.333	1128.333	1091.667	1023.333	1035	1165	1005
1.3	1706.667	1613.333	1660	1693.333	1548.333	1735	1533.333
1.6	2129.333	2384.333	2314	2243.667	1872	2593	2091
2	1620	1935	1818.667	1816	1655.333	1987	1866.667
2.5	1236	1207.333	1274.333	1312.333	1274	1235	1285.667
3	922	898	932.3333	983.3333	932.3333	910	953.3333
3.5	1489	1465	1490.667	1512	1522	1446.667	1473
4	819.3333	814.3333	812.3333	847.3333	812.3333	771	801.6667
5	221	205.6667	242.6667	247.6667	228.3333	211	224
6.5	136.3333	138.3333	126.6667	150.3333	133.3333	122	127
7.5	120.6667	118	133.6667	115.6667	122	95	111.3333
8.5	120	82.33333	115.6667	106.6667	106	91	94
10	21.33333	24.33333	25.33333	28.33333	26	18.66667	20
12.5	17	14.33333	17	14.33333	13	12	14
15	9.333333	6	8.333333	8.333333	9.333333	5.666667	8.666667
17.5	15	13.66667	9.666667	15	12	9	10.66667
20	13.66667	13.33333	10	9.666667	9.333333	10.66667	10.66667
25	3.333333	3	4	4.666667	2.333333	1	1
30	0	0	0	0	0	0	0

Average Runs of Material IA w/fine sandpaper OPC/CPC Number Concentration (#/L)							
MidD(um)	Min. 1	Min. 2	Min. 3	Min. 4	Min. 5	Min. 6	Min. 7
0.12	25028.67	24998.33	23760	24840	24596.67	24430	25218.33
0.25	20531.67	20135	19076.67	19913.33	19558.33	19260	20078.33
0.28	16325	16386.67	15638.33	16490	16628.33	16356.67	16851.67
0.3	17165	17153.33	16261.67	17108.33	17115	17046.67	17585
0.35	9040	8963.333	8100	8725	8881.667	8843.333	9100
0.4	6065	5920	5773.333	5928.333	5988.333	6031.667	6256.667
0.45	7828.333	7933.333	7348.333	7700	7940	8023.333	8270
0.5	9290	9095	8316.667	8735	9141.667	9070	9211.667
0.58	4266.667	4348.333	3960	4210	4211.667	4118.333	4461.667
0.65	4393.333	4315	4075	4370	4341.667	4140	4581.667
0.7	2780	2711.667	2590	2716.667	2841.667	2776.667	2986.667
0.8	3523.333	3546.667	3348.333	3435	3578.333	3576.667	3796.667
1	1840	1783.333	1853.333	1816.667	1796.667	1815	1980
1.3	2968.333	2901.667	2598.333	2806.667	2891.667	2956.667	3086.667
1.6	4534	4528.333	3699	4565.667	4002.667	3818.333	4178
2	4142	4118.333	3484.333	4152	3719.667	3645.333	3858
2.5	2854.333	2836	2858.667	2830	3017.667	2950.667	3041.667
3	2302	2314.667	2242.667	2308.667	2399.667	2334.333	2436.667
3.5	3882.333	3857.333	3800.333	3803.333	4057.333	3845.667	4081
4	2275.667	2246.667	2261.667	2292.667	2429	2251.333	2440.667
5	692.3333	689.3333	674.3333	697.3333	701	700.6667	744.6667
6.5	386	400	419	416	404.6667	420.6667	427.3333
7.5	298	296.3333	304.6667	304.6667	328.6667	334.6667	329.6667
8.5	169.3333	164.6667	190.3333	175.6667	198	176.6667	201.3333
10	26	32	42	30	31.66667	34.33333	35
12.5	10.66667	10.66667	10.33333	7.666667	13.66667	11	11.66667
15	5.666667	4	7.333333	6	6	5.666667	10.33333
17.5	12	9.333333	8.333333	8.333333	12.66667	9.666667	10.33333
20	8.333333	12.33333	12	7.333333	10.33333	10	11.66667
25	2.333333	3.333333	2	3	2.333333	3.666667	3
30	0	0	0	0	0	0	0

Average Runs of Material IB w/coarse sandpaper OPC/CPC Number Concentration (#/L)							
MidD (um)	Min. 1	Min. 2	Min. 3	Min. 4	Min. 5	Min. 6	Min. 7
0.25	18783.33	19015	18220	17900	18190	18236.67	18136.67
0.28	13315	13351.67	13275	12803.33	12606.67	13016.67	12990
0.3	10570	10843.33	10440	10216.67	10423.33	10458.33	10456.67
0.35	10425	11038.33	10093.33	10043.33	9835	10163.33	10335
0.4	5261.667	5565	4803.333	5060	4846.667	5215	5290
0.45	3446.667	3818.333	3523.333	3298.333	3348.333	3505	3468.333
0.5	4786.667	4985	4448.333	4463.333	4550	4481.667	4780
0.58	5411.667	5693.333	4925	4953.333	4803.333	5146.667	5180
0.65	2411.667	2623.333	2318.333	2471.667	2393.333	2355	2351.667
0.7	2625	2775	2416.667	2438.333	2513.333	2543.333	2550
0.8	1851.667	1930	1585	1620	1766.667	1670	1605
1	2218.333	2370	2161.667	2058.333	2001.667	2163.333	2203.333
1.3	1101.667	1140	1061.667	1070	1070	1043.333	1093.333
1.6	1733.333	1736.667	1723.333	1731.667	1718.333	1668.333	1776.667
2	2126.333	2477.667	2359	2519	2065.333	2393.333	2266.333
2.5	1952	2295.667	2090	2116.333	1985.667	2141	2144
3	1728.333	1694	1549.333	1512.333	1513.333	1565.667	1600.667
3.5	1346	1353	1209	1187.333	1207.667	1206.333	1249
4	2231	2178.667	1984	1952.667	2003	2020.667	2119.667
5	1396	1376	1251.667	1212.667	1240	1240.333	1256.333
6.5	411.6667	411.3333	409	374	393.6667	408.6667	396.3333
7.5	262.3333	249	231	237.3333	227	225	253
8.5	203.3333	188.6667	184	171	181	185.6667	207
10	134	124.6667	102.3333	108.3333	116.6667	137.3333	114.6667
12.5	37	26	29	20	23.66667	31	31.33333
15	12.33333	6.666667	9.333333	7	8.666667	10	13.33333
17.5	9	4.333333	5.333333	1.666667	5	9.333333	8.333333
20	16	3.666667	8	3.666667	9.333333	6.333333	12.66667
25	8.333333	4.333333	6.333333	3.666667	4.333333	6.333333	8
30	2	0.666667	2	0	2	0.666667	0.666667
32	0	0	0	0	0	0	0

Average Runs of Material IB w/fine sandpaper OPC/CPC Number Concentration (#/L)							
MidD (um)	Min. 1	Min. 2	Min. 3	Min. 4	Min. 5	Min. 6	Min. 7
0.25	23981.67	25211.67	25453.33	25430	25103.33	25855	25073.33
0.28	14423.33	15185	15541.67	15348.33	15640	16186.67	15813.33
0.3	10491.67	11195	11658.33	11658.33	11378.33	12213.33	11721.67
0.35	10173.33	10921.67	11610	11798.33	11651.67	12678.33	11881.67
0.4	5326.667	5480	6050	6128.333	6013.333	6613.333	5950
0.45	3555	4088.333	4138.333	4300	4238.333	4523.333	4138.333
0.5	4873.333	5220	5800	6085	5820	6283.333	5621.667
0.58	5248.333	6123.333	6465	6670	6678.333	6868.333	6721.667
0.65	2490	2898.333	3038.333	3266.667	2961.667	3533.333	3276.667
0.7	2678.333	2920	3280	3180	3375	3640	3180
0.8	1828.333	2096.667	2010	2010	2223.333	2285	2338.333
1	2253.333	2395	2750	2946.667	2818.333	2900	2831.667
1.3	1183.333	1270	1343.333	1341.667	1348.333	1430	1301.667
1.6	1688.333	1933.333	2031.667	2170	2068.333	2255	2203.333
2	2192.667	2888	2631.667	2909	2729.667	3375.667	2651.333
2.5	2008	2426	2342.667	2614	2328	2969.333	2514.333
3	1589.667	1750.333	1978.333	1861.333	1904	2027	1969
3.5	1345	1412.333	1579	1470	1494	1576	1583.333
4	2194.333	2387	2661	2450.333	2566.333	2720.667	2678
5	1422	1502.667	1652.667	1522.333	1618	1708	1637
6.5	443.6667	469.6667	529	478.3333	545.6667	544.3333	553
7.5	278.6667	286.3333	320	308.3333	307	349	328
8.5	195	208	243.6667	207	236	254.3333	241
10	122.3333	122.6667	144	121	134.3333	131.6667	131
12.5	29.33333	25.66667	26.33333	18.33333	15.66667	21	20.66667
15	4.333333	5.666667	4	3.333333	5.666667	4.333333	4
17.5	0	4	2	0.666667	1.333333	1	0.333333
20	2.333333	5	0.333333	1	3.333333	1.666667	3
25	2.666667	3.666667	2.666667	1.333333	2	4	1
30	1.333333	2.333333	0	0	0.666667	2.666667	0
32	0	0	0	0	0	0	0

Average Runs of Material IIA w/coarse sandpaper OPC/CPC Number Concentration (#/L)							
MidD (um)	Min. 1	Min. 2	Min. 3	Min. 4	Min. 5	Min. 6	Min. 7
0.25	5886.667	6090	5675	5831.667	5571.667	6090	6211.667
0.28	3845	3780	3765	3828.333	3425	3843.333	4061.667
0.3	2646.667	2646.667	2546.667	2575	2513.333	2805	2808.333
0.35	2870	2786.667	2825	2885	2650	2968.333	3208.333
0.4	1356.667	1345	1283.333	1373.333	1275	1368.333	1428.333
0.45	958.3333	860	886.6667	885	860	943.3333	1010
0.5	1200	1093.333	1118.333	1125	1025	1130	1166.667
0.58	1633.333	1428.333	1526.667	1461.667	1326.667	1446.667	1671.667
0.65	715	716.6667	673.3333	720	630	790	810
0.7	588.3333	593.3333	555	641.6667	563.3333	630	728.3333
0.8	260	283.3333	253.3333	263.3333	271.6667	233.3333	288.3333
1	316.6667	313.3333	253.3333	340	281.6667	266.6667	360
1.3	165	148.3333	165	153.3333	148.3333	165	155
1.6	226.6667	233.3333	238.3333	226.6667	213.3333	250	278.3333
2	462.6667	345	346.3333	323.3333	253	395.3333	395.3333
2.5	434	352.6667	329.3333	322	241.3333	388	387.6667
3	299.3333	283	296	284	267.3333	284.3333	299
3.5	270.3333	299.3333	264.3333	283	267.3333	270.3333	303.3333
4	575.3333	580.3333	606.6667	543	562.6667	642.6667	699.3333
5	454.6667	430.6667	466.6667	486.6667	447.3333	503.3333	542.3333
6.5	144.6667	144	155.3333	154.3333	149	154	161.6667
7.5	79.66667	72.33333	77.33333	90.33333	78	79	90.66667
8.5	41.66667	45	47.33333	58.33333	46	47.66667	53.66667
10	20	25.66667	18.33333	29.66667	17	28.66667	28
12.5	2.333333	4.666667	0.666667	7	5.333333	2.333333	5.333333
15	0	1	1	3.666667	0.666667	0.333333	3
17.5	0.333333	1.666667	0.333333	3.666667	1	1.333333	2.666667
20	0	1.666667	3.333333	3.666667	2.333333	1.333333	2
25	0	1.333333	0	6.666667	1.666667	2.666667	3
30	0.333333	0.333333	0.333333	1.333333	0	0.666667	0.333333
32	0	0	0	0	0	0	0

Average Runs of Material IIA w/fine sandpaper OPC/CPC Number Concentration (#/L)							
MidD (um)	Min. 1	Min. 2	Min. 3	Min. 4	Min. 5	Min. 6	Min. 7
0.25	8963.333	8796.667	8700	8943.333	8913.333	8855	7518.333
0.28	5368.333	5183.333	5211.667	5411.667	5381.667	5378.333	3978.333
0.3	3893.333	3666.667	3673.333	3836.667	3720	3551.667	2448.333
0.35	4613.333	4386.667	4288.333	4760	4470	4526.667	2245
0.4	1976.667	1895	1961.667	2013.333	2008.333	1900	1056.667
0.45	1298.333	1258.333	1235	1333.333	1271.667	1256.667	750
0.5	1628.333	1533.333	1568.333	1571.667	1561.667	1503.333	911.6667
0.58	2591.667	2426.667	2480	2610	2703.333	2408.333	1158.333
0.65	1165	1070	1075	1168.333	1046.667	1116.667	413.3333
0.7	771.6667	731.6667	775	851.6667	701.6667	838.3333	350
0.8	258.3333	255	233.3333	218.3333	230	226.6667	208.3333
1	341.6667	306.6667	231.6667	258.3333	256.6667	290	218.3333
1.3	195	131.6667	133.3333	113.3333	140	148.3333	146.6667
1.6	223.3333	230	236.6667	223.3333	198.3333	210	151.6667
2	265.3333	329	424	433.6667	308.6667	333	199
2.5	353.3333	369	485.6667	551	385	357.3333	170.6667
3	483.3333	479.3333	403	446.6667	439.6667	458.6667	245
3.5	554.3333	501.3333	478.6667	483.3333	518.3333	524	229.6667
4	1301.667	1147.333	1090.333	1194.333	1228.667	1205.333	443.3333
5	1005.667	911.6667	859.6667	921.3333	976.6667	938.6667	331.6667
6.5	292	250	246	277	290.6667	277.3333	98.33333
7.5	134.6667	118.6667	117	124.6667	134.6667	125.6667	47
8.5	73.33333	65	60.33333	64	74.33333	65.33333	22
10	25.66667	20	20	18	27	15.33333	6.666667
12.5	2	2.333333	2	2.333333	3	2	2
15	1	1	2	0	2	0	1
17.5	1.333333	0	1	0.666667	0.666667	0	0
20	0.666667	0.333333	0.666667	0	1.333333	0	0.333333
25	0.333333	1	0	0.666667	0	0	0
30	0	0.333333	0.333333	0.333333	0.333333	0	0
32	0	0	0	0	0	0	0

Average Runs of Material IIB w/coarse sandpaper OPC/CPC Number Concentration (#/L)							
MidD (um)	Min. 1	Min. 2	Min. 3	Min. 4	Min. 5	Min. 6	Min. 7
0.25	23770	23998.33	23816.67	23841.67	24331.67	24496.67	24523.33
0.28	17756.67	17375	17380	17610	17443.33	17141.67	18005
0.3	13403.33	13198.33	13366.67	13108.33	13058.33	13216.67	13890
0.35	9676.667	9378.333	9426.667	9346.667	9193.333	9436.667	9535
0.4	4020	3996.667	3943.333	3750	3891.667	4003.333	4170
0.45	2135	2231.667	2148.333	2093.333	2121.667	2190	2260
0.5	2063.333	2036.667	1883.333	1881.667	1878.333	2001.667	2068.333
0.58	1703.333	1648.333	1566.667	1551.667	1468.333	1706.667	1640
0.65	765	665	690	685	640	718.3333	811.6667
0.7	970	851.6667	858.3333	861.6667	906.6667	896.6667	1095
0.8	898.3333	860	750	731.6667	788.3333	803.3333	905
1	1245	1190	1163.333	1021.667	1086.667	1106.667	1195
1.3	618.3333	621.6667	590	593.3333	596.6667	640	638.3333
1.6	1030	961.6667	1021.667	936.6667	960	968.3333	1011.667
2	1445.667	1466.333	1368.333	1337.333	1472.333	1344.667	1591
2.5	1219.333	1201.667	1128	1120.333	1230	1195.667	1348.667
3	756.6667	758.6667	721	721.3333	700.6667	774.3333	797.6667
3.5	533.3333	493.6667	509.6667	499.3333	485.3333	517	579.3333
4	674	642.6667	634.6667	594.6667	609.3333	658.6667	751.6667
5	309.6667	282	309	268.3333	272.6667	314.6667	387.3333
6.5	86.33333	81.66667	86	70.33333	90.33333	97	105.6667
7.5	51	58.33333	61.66667	56	61	57.66667	88.66667
8.5	70.66667	64.33333	66.33333	71.33333	75.66667	72.33333	99.66667
10	90.33333	98.33333	96.33333	92.66667	113.6667	106	152.3333
12.5	56.66667	58.33333	65	53	65.66667	64.33333	95
15	28.66667	27	32	34.33333	34	33.33333	50.33333
17.5	14.66667	12	21.66667	10.66667	19.66667	20.66667	20
20	14	11.66667	16.33333	10.66667	15.66667	15.66667	22.66667
25	6	8	9.666667	10.66667	11.66667	12	18
30	1.333333	2	1.333333	1.666667	1.333333	1.333333	3.333333
32	0	0	0	0	0	0	0

Average Runs of Material IIB w/fine sandpaper OPC/CPC Number Concentration (#/L)							
MidD (um)	Min. 1	Min. 2	Min. 3	Min. 4	Min. 5	Min. 6	Min. 7
0.25	19030	19788.33	19601.67	18753.33	19225	19485	18925
0.28	14065	14731.67	14891.67	14333.33	13745	14148.33	13866.67
0.3	10906.67	11096.67	11358.33	10880	10658.33	10528.33	10328.33
0.35	7466.667	7993.333	8211.667	7801.667	7430	7686.667	7336.667
0.4	3485	3695	3990	3643.333	3460	3426.667	3338.333
0.45	2178.333	2225	2391.667	2265	2166.667	2166.667	1980
0.5	2625	2641.667	2916.667	2750	2520	2640	2420
0.58	2571.667	2623.333	2848.333	2636.667	2465	2503.333	2451.667
0.65	1118.333	1125	1311.667	1085	1121.667	1121.667	920
0.7	1631.667	1751.667	1816.667	1546.667	1600	1568.333	1426.667
0.8	1776.667	1908.333	1935	1753.333	1653.333	1670	1651.667
1	2733.333	2915	2935	2710	2603.333	2391.667	2430
1.3	1490	1673.333	1635	1473.333	1368.333	1315	1383.333
1.6	2408.333	2688.333	2606.667	2381.667	2245	2241.667	2276.667
2	3259.667	3459.333	3643	3240.333	3359	3558.333	3092.333
2.5	2685	2880	2878.667	2686	2760.667	3000.667	2499.333
3	1740	1729.667	1819.333	1693	1565	1469.333	1542
3.5	1090.667	1083	1145.667	1080	981	909.3333	1001.667
4	1217.333	1246.667	1327	1250	1146.333	1089.333	1189.667
5	410	433	482.6667	447.3333	385	359	407.3333
6.5	88.66667	107	114	88	79.33333	76.66667	95.33333
7.5	49	68	76	60.66667	58.33333	59	58
8.5	63.66667	80.66667	96	64.66667	64	65	66.33333
10	107	105.3333	149	104	95	101.6667	111.3333
12.5	69	73.66667	89	71.66667	70.66667	68.66667	75.66667
15	33.66667	47	46.33333	40.66667	39.66667	39.66667	40.33333
17.5	12.66667	19.33333	20.66667	18	19	18.66667	18.66667
20	10.33333	8	12.33333	11.33333	11.33333	10.66667	9.333333
25	3.666667	4	4	4	3.666667	5.333333	4
30	0.333333	0.666667	1.333333	0	0.333333	1	0
32	0	0	0	0	0	0	0

Average Runs of Material IIC w/coarse sandpaper OPC/CPC Number Concentration (#/L)							
MidD (um)	Min. 1	Min. 2	Min. 3	Min. 4	Min. 5	Min. 6	Min. 7
0.25	20543.33	20955	20708.33	20546.67	21018.33	20415	20011.67
0.28	12883.33	13155	12885	12910	12950	12720	12180
0.3	8980	9220	9223.333	8926.667	8883.333	8868.333	8568.333
0.35	6213.333	6208.333	6330	6020	5935	6066.667	5640
0.4	2665	2816.667	2773.333	2536.667	2790	2603.333	2520
0.45	1613.333	1696.667	1726.667	1645	1578.333	1571.667	1326.667
0.5	1861.667	1953.333	1986.667	1788.333	1880	1750	1580
0.58	1655	1656.667	1723.333	1685	1741.667	1420	1256.667
0.65	846.6667	888.3333	811.6667	763.3333	743.3333	668.3333	588.3333
0.7	1196.667	1131.667	1208.333	1058.333	1101.667	983.3333	890
0.8	1196.667	1175	1256.667	1081.667	1113.333	1041.667	1000
1	1503.333	1600	1553.333	1495	1533.333	1348.333	1331.667
1.3	768.3333	805	803.3333	705	628.3333	661.6667	636.6667
1.6	1093.333	1116.667	1181.667	1096.667	1090	1103.333	1013.333
2	1487.667	1614.333	1645	1598	1575.333	1312.333	1151
2.5	1190.667	1249.667	1287	1141.333	1202	1035.333	908.3333
3	613.3333	635.3333	671.6667	614.6667	592	602.6667	523.3333
3.5	382.3333	379.3333	393	382.3333	363.3333	353	344.3333
4	414.6667	392	433	428.6667	410.3333	390.3333	361.3333
5	149	149	152.6667	140	134	139	116.6667
6.5	49.33333	42.33333	40	48	42	49	33
7.5	37	32	38.66667	40.66667	31	40	30.33333
8.5	39	37.33333	41	49	44.66667	46.33333	32.66667
10	51	52.66667	56	46.66667	59	74.33333	52.33333
12.5	22	22	22	25.33333	22.66667	28.66667	22
15	9	7.666667	10	9	9.333333	12.66667	10
17.5	4.333333	5.666667	3.666667	3.333333	3	3.333333	4.666667
20	3.333333	4	2.333333	2.666667	1	4	2.333333
25	0.666667	1.333333	2	1	0.333333	2.666667	2
30	0	0	0	0.333333	0	0	0.666667
32	0	0	0	0	0	0	0

Average Runs of Material IIC w/fine sandpaper OPC/CPC Number Concentration (#/L)							
MidD (um)	Min. 1	Min. 2	Min. 3	Min. 4	Min. 5	Min. 6	Min. 7
0.25	58976	58526	58446	58626	58571	58597.67	58724.33
0.28	36443.33	36635	36086.67	36470	36026.67	36655	36470
0.3	21476.67	21426.67	21411.67	21168.33	21458.33	21086.67	21471.67
0.35	10990	11063.33	10863.33	10911.67	10758.33	11045	10896.67
0.4	3610	3591.667	3486.667	3476.667	3595	3450	3543.333
0.45	1763.333	1796.667	1716.667	1561.667	1626.667	1616.667	1763.333
0.5	1623.333	1691.667	1670	1628.333	1625	1590	1641.667
0.58	1295	1480	1298.333	1196.667	1266.667	1173.333	1250
0.65	671.6667	655	638.3333	545	561.6667	560	563.3333
0.7	975	961.6667	948.3333	913.3333	815	868.3333	958.3333
0.8	1051.667	1013.333	1130	953.3333	923.3333	908.3333	983.3333
1	1438.333	1321.667	1243.333	1243.333	1218.333	1286.667	1296.667
1.3	641.6667	615	583.3333	616.6667	543.3333	510	573.3333
1.6	925	991.6667	886.6667	815	855	920	913.3333
2	1226.667	1246.333	1134.667	1054	1097	1003.667	1098
2.5	788	864	787.3333	791	796.6667	707	787
3	480.3333	460.6667	425	411.6667	414.6667	432.6667	433
3.5	278.6667	262.3333	251.3333	243	242.3333	261	265.6667
4	281.6667	275.6667	260.3333	236	252.6667	250.3333	270
5	74.66667	65	65.66667	57.66667	63.33333	72.66667	75.33333
6.5	19.66667	13	15	13	14	14	19
7.5	9.333333	8.333333	6	8.333333	7	7.333333	8.333333
8.5	13.33333	6.333333	8.333333	8.333333	9.666667	11.33333	11.33333
10	19	13	15	16.33333	12.66667	17	17.66667
12.5	10.33333	7.333333	5.333333	5.333333	4.666667	9	6
15	5.666667	1.666667	1.333333	0.666667	4.333333	6	3
17.5	2	0.333333	1.666667	1.333333	0.666667	1.333333	3
20	1.666667	1	0.666667	0	0.666667	1	1.333333
25	0	0	0	0	1.333333	0.666667	0.666667
30	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0

Average of runs for Material IIIA w/coarse sandpaper OPC/CPC Particle Concentration (#/L)							
MidD (um)	Min.1	Min.2	Min.3	Min.4	Min.5	Min.6	Min.7
0.25	21499.41	21299.41	21711.07	21857.74	21489.41	21707.74	21882.74
0.28	10127.57	10304.24	10539.24	10675.91	10467.57	10602.57	10619.24
0.3	5805.494	5725.494	5962.16	6203.827	5968.827	6062.16	6087.16
0.35	3827.982	3747.982	4092.982	4379.649	3982.982	4034.649	4284.649
0.4	1666.436	1636.436	1796.436	1878.103	1738.103	1774.77	1871.436
0.45	947.7253	987.7253	1027.725	1059.392	971.0587	1009.392	1032.725
0.5	854.1523	894.1523	1009.152	1035.819	969.1523	1030.819	954.1523
0.58	879.9217	896.5883	1069.922	1213.255	979.9217	1066.588	1069.922
0.65	322.9803	359.647	411.3137	486.3137	396.3137	399.647	456.3137
0.7	249.98	291.6467	293.3133	306.6467	318.3133	339.98	353.3133
0.8	163.32	129.9867	131.6533	153.32	136.6533	129.9867	134.9867
1	180.6493	172.316	165.6493	200.6493	203.9827	203.9827	202.316
1.3	90.32633	85.32633	100.3263	113.6597	91.993	105.3263	98.65967
1.6	144.99	136.6567	163.3233	161.6567	149.99	159.99	159.99
2	217.315	192.9817	294.6483	335.9817	234.315	274.6483	283.6483
2.5	206.3866	196.7199	288.0533	363.7199	234.3866	282.3866	295.0533
3	175.5964	192.9297	235.2631	249.2631	219.2631	248.2631	263.5964
3.5	178.0636	193.0636	216.0636	243.3969	223.7303	230.3969	251.7303
4	353.8615	383.8615	438.8615	542.1948	468.8615	493.1948	527.5281
5	228.1978	242.5311	284.8645	340.5311	324.5311	302.5311	348.8645
6.5	59.66567	64.33233	77.33233	97.66567	78.66567	77.66567	90.33233
7.5	28.5328	25.5328	40.86613	45.86613	40.19947	44.5328	43.5328
8.5	19.33267	12.99933	23.99933	31.99933	23.666	18.33267	22.33267
10	4.066267	8.732933	10.06627	11.73293	7.3996	10.3996	13.3996
12.5	4.1998	2.533133	3.866467	4.533133	5.1998	1.866467	3.866467
15	0.333333	1	1.333333	5.333333	2.333333	2	2.333333
17.5	3.399933	2.0666	2.0666	6.733267	3.399933	2.399933	2.0666
20	3	2.333333	1	6	2.333333	2.333333	3.666667
25	0.666667	0.333333	3	2	0.666667	0.333333	1.666667
30	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0

Average of runs for Material IIIA w/fine sandpaper OPC/CPC Particle Concentration (#/L)							
MidD (um)	Min.1	Min.2	Min.3	Min.4	Min.5	Min.6	Min.7
0.25	7523.65	7443.65	7261.983	7326.983	7210.316	7298.65	7303.65
0.28	4065.959	3894.293	3917.626	3892.626	3912.626	3780.959	3939.293
0.3	2722.227	2748.894	2635.56	2648.894	2703.894	2690.56	2742.227
0.35	2175.234	2306.901	2140.234	2108.568	2111.901	2088.568	2170.234
0.4	1283.142	1198.142	1129.808	1104.808	1098.142	1204.808	1154.808
0.45	851.883	780.2163	746.883	796.883	776.883	740.2163	818.5497
0.5	1021.548	943.215	1006.548	983.215	1009.882	976.5483	916.5483
0.58	912.9153	1004.582	892.9153	866.2487	839.582	972.9153	862.9153
0.65	359.304	350.9707	317.6373	320.9707	292.6373	255.9707	294.304
0.7	386.6283	369.9617	334.9617	346.6283	303.295	328.295	323.295
0.8	286.9747	281.9747	290.308	263.6413	286.9747	286.9747	275.308
1	378.2967	411.63	371.63	366.63	348.2967	356.63	366.63
1.3	211.317	202.9837	191.317	156.317	172.9837	176.317	189.6503
1.6	327.3127	290.646	302.3127	295.646	297.3127	280.646	310.646
2	466.6297	442.6297	403.2963	448.6297	419.2963	492.6297	417.2963
2.5	435.2414	424.5747	384.2414	398.5747	420.9081	408.9081	392.5747
3	322.7173	330.0506	314.7173	317.0506	313.0506	330.7173	348.7173
3.5	236.7892	261.4559	250.1225	259.7892	252.4559	248.1225	265.7892
4	389.5135	400.1801	387.8468	411.1801	401.5135	399.5135	453.8468
5	203.4569	193.7902	195.4569	178.7902	198.1235	178.7902	202.7902
6.5	37.99667	43.66333	36.66333	29.33	37.66333	35.99667	40.33
7.5	18.7316	16.06493	14.39827	19.06493	20.39827	20.39827	20.06493
8.5	11.99867	11.332	8.665333	8.332	10.66533	10.66533	8.998667
10	7.1988	5.1988	3.865467	5.865467	4.865467	3.865467	3.532133
12.5	1.933067	1.599733	1.2664	0.933067	1.599733	1.599733	0.2664
15	0.666667	0.333333	0.333333	1	0.333333	0	0
17.5	1.333333	0	0.333333	0.666667	1.333333	0	0.666667
20	1	0.333333	0.333333	0	1.666667	0.333333	0
25	1	0	0	0.333333	0.333333	0	0
30	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0

Average of Runs for Material IIIB w/coarse sandpaper OPC/CPC Number Concentration (#/L)							
MidD (um)	Min. 1	Min. 2	Min. 3	Min. 4	Min. 5	Min. 6	Min. 7
0.25	22651.67	22155	22180	22270	21740	21116.67	21616.67
0.28	14398.33	13655	13926.67	14153.33	13305	13110	12816.67
0.3	9761.667	9371.667	9590	9706.667	9050	8605	8506.667
0.35	7070	6738.333	6818.333	7046.667	6356.667	6030	5843.333
0.4	3605	3306.667	3558.333	3491.667	3160	2993.333	2803.333
0.45	2385	2380	2163.333	2261.667	2055	1823.333	1835
0.5	2965	2715	2940	2880	2496.667	2388.333	2156.667
0.58	2728.333	2493.333	2511.667	2566.667	2343.333	2008.333	1951.667
0.65	1151.667	1078.333	1136.667	1115	990	898.3333	893.3333
0.7	1605	1483.333	1431.667	1496.667	1413.333	1216.667	1223.333
0.8	1583.333	1440	1451.667	1473.333	1300	1228.333	1136.667
1	2058.333	2006.667	2045	2140	1755	1670	1536.667
1.3	1073.333	1035	1033.333	1025	918.3333	916.6667	785
1.6	1781.667	1808.333	1778.333	1668.333	1411.667	1468.333	1450
2	2750.667	2387.667	2532.667	2678.333	2209	2199.333	1810.667
2.5	2354.667	2088.667	2154.667	2315	1970	1837.333	1683.667
3	1371.667	1349.333	1326.333	1330.667	1197	1154.667	1120.333
3.5	891.3333	893	879.6667	855.6667	800.6667	756.3333	725.3333
4	1095.333	1059.667	1067.333	1055.333	989.3333	873.3333	858.6667
5	391.6667	369	368.6667	363.6667	371	317	315.6667
6.5	90	99	107	82.66667	86.33333	76	78.66667
7.5	57	68	58.33333	50.33333	63.33333	48	54.66667
8.5	62	59	63.66667	45	55.33333	42.33333	56.33333
10	69.33333	88.66667	81.66667	60.33333	92.66667	60.66667	67.33333
12.5	39.66667	40.33333	32	38	44.66667	27.66667	39
15	15.66667	22.66667	11.66667	13.33333	24	12.66667	16.66667
17.5	6.333333	4	6.333333	7	13.33333	5	6.666667
20	6.666667	6.666667	5	6.333333	12	3	5.666667
25	2.333333	2.333333	4	1.333333	6	0.666667	1.666667
30	1	0.333333	1	0.666667	1.333333	0	1.333333
32	0	0	0	0	0	0	0

Average of Runs for Material IIIB w/fine sandpaper OPC/CPC Number Concentration (#/L)							
MidD (um)	Min. 1	Min. 2	Min. 3	Min. 4	Min. 5	Min. 6	Min. 7
0.25	13850	13783.33	13781.67	13593.33	13535	13713.33	13686.67
0.28	8273.333	8020	7995	7685	7676.667	7626.667	7895
0.3	5706.667	5495	5655	5358.333	5538.333	5316.667	5428.333
0.35	3641.667	3633.333	3766.667	3498.333	3581.667	3366.667	3598.333
0.4	1813.333	1815	1871.667	1731.667	1800	1698.333	1810
0.45	1113.333	1098.333	1150	1025	1046.667	968.3333	1078.333
0.5	1131.667	1186.667	1181.667	1126.667	1303.333	1110	1195
0.58	1058.333	996.6667	995	975	1006.667	913.3333	938.3333
0.65	443.3333	390	435	360	361.6667	395	415
0.7	808.3333	760	696.6667	691.6667	668.3333	641.6667	645
0.8	910	858.3333	940	793.3333	853.3333	780	800
1	1345	1260	1268.333	1213.333	1245	1120	1180
1.3	690	661.6667	608.3333	646.6667	683.3333	581.6667	606.6667
1.6	1111.667	995	1035	918.3333	983.3333	961.6667	1026.667
2	1420	1400	1585.333	1203.333	1229.333	1228.333	1443
2.5	1108.333	1090.667	1161.667	1000	1068.667	980.3333	1077.667
3	643	603.3333	613	616	610.6667	571.6667	602
3.5	386.3333	367.3333	353.3333	365.6667	358.3333	340	365.6667
4	410	366.3333	330.6667	399	367.6667	342.6667	372.3333
5	93	99.66667	86.33333	112.6667	96.33333	78	88.66667
6.5	17.33333	16.33333	9.666667	12.33333	13.66667	12.66667	14.66667
7.5	9	7	5	4.666667	6	4.666667	5.333333
8.5	8.333333	6.666667	3.666667	5	6.666667	5	5
10	9	6	3	7.333333	5.666667	5.333333	7.333333
12.5	2.666667	5	2.666667	3.666667	6	2.333333	3.333333
15	2.333333	2.333333	2.333333	1.333333	1.666667	2.333333	1.666667
17.5	1	0	0.666667	1.333333	1	0.333333	0.666667
20	0.333333	0.333333	0	0	3.333333	0.666667	0.666667
25	0	0	0	0	1.333333	0.333333	0.333333
30	0	0.666667	0	0	0	0	0
32	0	0	0	0	0	0	0

Material IA w/coarse SMPS Particle Count				Material IB w/coarse SMPS Particle Count			
MidD (nm)	Run 1	Run 2	Run 3	MidD (nm)	Run 1	Run 2	Run 3
10.4	23378.97	22862.13	17430.9	10.4	19815.93	19682.6	20899.67
11.1	26014.43	26657.9	19878.03	11.1	21928.57	22814.97	21013.67
12	29812.33	31251.87	20558.2	12	24280.87	24015.43	23671.4
12.9	32434.33	33078.7	22395.17	12.9	27338.7	26924.27	25050.47
13.8	34503.1	32644.43	23161.9	13.8	28621.5	26906.17	25069.4
14.9	38162.4	34831.1	24295.6	14.9	30003.63	28229.27	26618.5
16	39199.8	34796.63	24147.67	16	30897.5	30021.27	26680.47
17.2	37188.63	34955.23	22946.67	17.2	32530.6	28775.5	26868.8
18.4	36015.17	33604.6	23490.27	18.4	33034.1	28414.7	26347.53
19.8	35860.2	33208.3	22507.8	19.8	32505.7	28634.9	25204
21.3	36784.73	32603.4	21222.1	21.3	30605	28366.33	23546.17
22.9	34912.97	30651.23	21387.23	22.9	30421.43	26847.07	23447.33
24.6	33028.07	30102.77	20259.5	24.6	28238.97	25689.47	22635.3
26.4	30041.6	28894.57	18177.1	26.4	27551.13	25410.6	20384.57
28.4	27119.1	28793.23	16907.8	28.4	24311.77	22878.97	19829.17
30.5	25144.07	26024.7	15187.77	30.5	23117.87	22052.1	18757.83
32.8	22323.17	23779.67	14649.1	32.8	21917.7	21308.7	18170.7
35.2	20034.7	20491.23	13327.2	35.2	19351.2	19592.37	17424.5
37.9	18362.57	18486.53	12439.7	37.9	17248.47	18088.9	16613.63
40.7	15833.53	17111.17	10768.63	40.7	15314.7	17395.2	14907.8
43.7	14532	15103.2	9584.677	43.7	13445.7	15346.2	13827.57
47	12202.43	13383.47	8469.69	47	11729.57	13112.13	12125.27
50.5	11312.19	11917.6	7657.993	50.5	9999.087	11375.83	10804.04
54.2	9931.507	10773.82	6734.957	54.2	8846.517	9166.267	9421.487
58.3	8880.37	9638.983	5961.353	58.3	7872.257	7461.61	7403.16
62.6	7601.107	8364.05	5306.453	62.6	6675.267	6308.333	6297.563
67.3	6715.037	7169.257	4401.923	67.3	5728.847	5388.873	5048.823
72.3	5885.107	6347.483	3966.55	72.3	4536.243	4139.857	4349.397
77.7	4991.877	5093.84	3421.183	77.7	4108.707	3603.153	3450.073
83.5	4247.463	4455.42	3140.633	83.5	3189.45	3022.2	2703.33
89.8	3906.007	3918.457	2838.24	89.8	2695.53	2735.977	2382.36
96.5	3043.163	3482.56	2481.35	96.5	2136.243	2231.873	1761.22
103.7	2565.477	2820.767	2056.743	103.7	1603.383	1904.38	1525.217
111.4	2161.26	2411.503	1869.733	111.4	1460.513	1525.01	1306.21
119.7	1562.353	1840.37	1588.753	119.7	1270.857	1527.407	1080.73
128.6	1121.807	1360.287	1358.21	128.6	942.3573	1269.32	821.0247
138.2	936.34	1031.882	1052.868	138.2	881.235	1012.311	738.302

148.6	775.2403	904.864	887.1637	148.6	700.24	950.542	671.9727
159.6	697.9767	666.766	762.474	159.6	594.151	798.2553	531.2707
171.5	501.4293	577.507	664.4127	171.5	502.8853	627.6427	481.7673
184.3	448.4357	448.4697	557.104	184.3	461.616	604.712	453.2137
198.1	400.2337	413.1203	374.8453	198.1	404.748	465.8263	379.957
212.9	308.131	308.375	283.275	212.9	385.5073	418.324	247.625
228.8	230.5877	232.3737	214.3847	228.8	291.16	253.0817	225.6433
245.8	181.8343	141.6767	189.238	245.8	247.0507	188.858	177.609
264.2	156.808	161.234	137.9733	264.2	189.1533	150.29	124.8187
283.9	115.7303	103.9093	102.0552	283.9	166.579	143.446	102.4034

Appendix D: Quantile-Quantile plots for materials I, II, and III

Appendix E: Data Analysis

Material I Count

RSquare	0.9648
RSquare Adj	0.96348
Root Mean Square Error	4212.822
Mean of Response	24201.63
Observations (or Sum Wgts)	84

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	3.8916e+10	1.297e+10	730.9061
Error	80	1419829292	17747866	Prob > F
C. Total	83	4.0336e+10		<.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Sandpaper	1	1	3.8514e+10	2170.063	<.0001*
Material	1	1	287618873	16.2058	0.0001*
Sandpaper*Material	1	1	114458801	6.4492	0.0130*

Material I Resp Mass

RSquare	0.83283
RSquare Adj	0.826561
Root Mean Square Error	0.050174
Mean of Response	0.497126
Observations (or Sum Wgts)	84

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	1.0033493	0.334450	132.8512
Error	80	0.2013981	0.002517	Prob > F
C. Total	83	1.2047474		<.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Sandpaper	1	1	0.37673420	149.6476	<.0001*
Material	1	1	0.12606517	50.0760	<.0001*
Sandpaper*Material	1	1	0.50054997	198.8301	<.0001*

Material II Count

RSquare	0.947075
RSquare Adj	0.94487
Root Mean Square Error	704.2937
Mean of Response	1798.482
Observations (or Sum Wgts)	126

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	1065159268	213031854	429.4741
Error	120	59523546.1	496029.55	Prob > F
C. Total	125	1124682814		<.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Material	2	2	587013019	591.7117	<.0001*
Sandpaper	1	1	175270802	353.3475	<.0001*
Material*Sandpaper	2	2	302875446	305.2998	<.0001*

Material II Resp Mass

RSquare	0.560076
RSquare Adj	0.541745
Root Mean Square Error	0.023914
Mean of Response	0.057432
Observations (or Sum Wgts)	126

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	0.08736975	0.017474	30.5548
Error	120	0.06862658	0.000572	Prob > F
C. Total	125	0.15599633		<.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Material	2	2	0.05754902	50.3149	<.0001*
Sandpaper	1	1	0.01109781	19.4056	<.0001*
Material*Sandpaper	2	2	0.01872292	16.3694	<.0001*

Material III Count

RSquare	0.685109
RSquare Adj	0.673301
Root Mean Square Error	657.2281
Mean of Response	1648.554
Observations (or Sum Wgts)	84

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	75183429	25061143	58.0188
Error	80	34555898	431948.72	Prob > F
C. Total	83	109739327		<.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Sandpaper	1	1	11257936	26.0631	<.0001*
Material	1	1	57178277	132.3728	<.0001*
Sandpaper*Material	1	1	6747217	15.6204	0.0002*

Material III Resp. Mass

RSquare	0.919488
RSquare Adj	0.916469
Root Mean Square Error	0.007729
Mean of Response	0.044132
Observations (or Sum Wgts)	84

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	0.05457480	0.018192	304.5477
Error	80	0.00477865	0.000060	Prob > F
C. Total	83	0.05935345		<.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Sandpaper	1	1	0.01661283	278.1173	<.0001*
Material	1	1	0.02325712	389.3502	<.0001*
Sandpaper*Material	1	1	0.01470485	246.1755	<.0001*