The Origin, Potential Health Effects, and Environmentally Conscious Control of Airborne Particulate in Manufacturing Operations

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1. Introduction

In recent years, increased attention has been devoted to the environmental performance of products and their associated manufacturing processes. Toward this end, tools such as life cycle analysis are being used more frequently to quantify the environmental effects of decisions made during the engineering design process. In many cases, for the first time, decision-makers have begun to place emphasis on the material and energy flows throughout the life cycle of a product, such as that depicted in Figure 1. In this context, it is worth noting that the manufacturing design community has historically largely ignored the waste streams produced by manufacturing operations. One of these waste streams, process generated airborne particulate, has received much emphasis within the scientific literature of the industrial hygiene and safety engineering communities; but, all too often, the individuals who have the power to do something about these emissions, manufacturing decision-makers, have never effectively dealt with these issues. With this in mind, this chapter is aimed at the manufacturing R&D community, and endeavors to address a variety of topics related to airborne particulate arising from manufacturing processes. Emphasis will be placed on the origins of the particulate and the potential hazards that it represents; the role of traditional control technologies in addressing particulate and more environmentally conscious approaches that focus on dealing with particulate at its source are also examined.

In considering the product life cycle depicted in Figure 1, importance is often given to the product use stage, often to the exclusion of all the other stages. Yet, manufacturing remains an important life cycle stage and accounts for a significant portion of environmental burdens, employment and community presence, and economic impacts of the product life cycle. The U.S. Census Bureau reports [U.S. Census, 2001] that “manufacturing” is the second largest industry sector, trailing only “wholesale trade.” In considering the analysis of manufacturing processes, it is often convenient to think of them in terms of their inputs and outputs. Figure 2 depicts the inputs and outputs associated with a typical manufacturing operation.

Airborne particulate is produced by a variety of manufacturing processes via such mechanisms as atomization, vaporization/condensation, and combustion. For example, the use of casting processes can create a number of combustion by-products; the application of metalworking fluids (MWF) in machining may result in metalworking fluid mist, and welding processes can produce
metal fumes. This airborne particulate can be in either liquid or solid form, and since it is exists within an air medium, it is termed an aerosol\(^1\). Workers that are exposed to this particulate-laden air may suffer a variety of health maladies as a result. Worker exposure can happen via three different pathways: ingestion, skin absorption, and inhalation. In the United States an employee may inhale from 4 to 10 m\(^3\) of air during a typical 8 hour workday, and this air may contain a variety of particles of differing material types [Peterson, 1977]. Adverse worker health effects associated with these airborne particles is most likely due to inhalation exposure, and these effects depend on the dose and the physical and chemical characteristics of the particles.

The human respiratory system takes in air from the atmosphere, and, as shown in Figure 3, the air passes through the nose, pharynx, larynx, trachea, bronchi and bronchioles, and enters the alveoli. Gas exchange takes place in the alveoli, with oxygen passing into the bloodstream and carbon dioxide entering the alveoli; upon exhalation, CO\(_2\) is removed from the body. As has been noted, particulate matter (or PM) differs in terms of chemical composition and size. As indicated in Table 1, particle size influences the depth to which the PM penetrates into the respiratory system. The human lung has evolved over many millennia to function in the particle-filled air of the natural environment [Wright, 1991]. Particle clearance mechanisms in the tracheobronchial and alveoli are effective at removing most deposited particles, but excessive particulate exposure can overwhelm the natural clearance mechanisms.

The U.S. Environmental Protection Agency (EPA) is required by law to set National Ambient Air Quality Standards (NAAQS) for pollutants (including PM) considered harmful to public health and the environment. While the EPA focuses on air pollution in the world around us, the mission of the U.S. Occupational Safety & Health Administration (OSHA) is to assure the safety and health of America’s workers by setting and enforcing standards – including those for workplace air quality. While OSHA works to protect workers, some publications suggest that existing air quality standards might not be protective of human health [Dockery et al., 1993; Utell and Frampton, 2000; Oberdorster, 2001]. One recent trend with respect to PM is the attention given to particles smaller than 2.5 \(\mu\)m, usually called fine particles, which epidemiology studies have linked to work-related diseases. Research findings over the last few years have advanced our knowledge of fine particles effects and work is progressing to achieve a comprehensive understanding of these effects at low exposure levels [Utell and Frampton 2000; Vincent, 2001; Oberdorster, 2001].

The responsibilities of a manufacturing enterprise extend far beyond that of designing and producing manufactured products and generating a profit for owners/shareholders. It is becoming ever clearer that to ensure long-term competitiveness, the enterprise must also provide a safe and healthy work environment and a company must responsibly consider social and environmental issues. The authors believe that corporate responsibility and profitability are not necessarily competing goals; product and process innovations focused on being more environmentally responsible can simultaneously create more profit. This approach to environmentally responsible manufacturing (ERM) calls for manufacturers to seek out win-win opportunities, and while this approach can be challenging, the resulting benefits can be significant.

\(^1\) An aerosol is a multi-phase substance in which solid or liquid particles are suspended in air [Hinds, 1999].
This chapter focuses on manufacturing air quality issues with an emphasis on airborne particulate. It starts with a discussion on particle characterization to help the reader understand the vocabulary and basic concepts used by the air quality community, and the instrumentation used to characterize particles. Then, a discussion of the health issues and regulations that relate to PM are presented. A process-by-process description of airborne particle emissions is then provided. The traditional engineering controls used to manage airborne particulate are described. This is followed by a discussion of innovations that seek to address particulate at its source. The chapter concludes with a section on manufacturing trends and potential concerns related to air quality.

2. Particulate Characterization

While it is of paramount interest to understand the health impacts associated with aerosol emissions from manufacturing processes, medical researchers are still developing knowledge regarding this linkage. It is understood, however, that the health impacts depend on the characteristics of the particles, e.g., the particle size, mass, number, surface area, and chemical composition. Depending on the chemical makeup of the particles, it has been suggested that the health effects of exposure depend on these particle characteristics. For example, the OSHA asbestos standard considers the particle number concentration rather than the particle mass concentration. Some have reported that the particle surface area is just as important as the particle chemistry [Lison et al, 1997, Spurny, 1998; Osunsanya, 2001, Oberdorster, 2001]. Hypotheses addressing particle number concentrations are largely independent of aerosol mass concentrations since fine particles dominate the number distribution [Oberdorster, 2001]. Historically, most air quality standards have focused on PM$_{10}$ particulate (particulate matter less than 10 µm), however since the fine particles penetrate to the gas-exchange region of the lungs, more attention has begun to be devoted to this size range [Hinds, 1999; Vincent, 2000]. In the absence of specific knowledge regarding particle health effects, emphasis focuses on quantifying various types of particulate characteristics.

2.1. Particulate Classification

A number of different words and phrases are used to describe aerosols. The American National Standards Institute (ANSI) has published definitions for dusts, fumes, and mists [Brandt, 1947]; Hinds [1999] has described other aerosol types. Table 2 describes the origin and typical size of above aerosols. These types of aerosols, which are frequently found in an industrial environment, are defined as follows.

**Dust** is a group of solid particles generated by the mechanical breakdown (e.g., handling, crushing, and grinding) of organic or inorganic materials such as rock, metal, and grain. Dust particles do not tend to adhere to one another except under electrostatic forces, and they do not diffuse in air but settle under the influence of gravity.

**Fumes** are solid particles generated by the condensation of a gas, often after volatilization from a molten metal, and are often accompanied by a chemical reaction such as oxidation. Fume particles often clump together (floculate) and sometimes combine or coalesce.
A **mist** is a set of suspended liquid droplets generated by condensation from the gaseous to the liquid state or by liquid breakup via splashing, foaming, and atomizing.

**Smoke** is an aerosol that results from incomplete combustion. Particles may be either solid or liquid.

A **spray** is a droplet aerosol formed by the mechanical breakup of a liquid.

An aerosol in which the particles have the same chemical composition is termed a **Homogeneous aerosol**.

A **monodisperse aerosol** is an aerosol that has particles of the same size.

A **polydisperse aerosol** is an aerosol with particles of different size and whose characterization requires statistical methods.

### 2.2. Particle Size

Particle size is one of the important attributes in terms of aerosol behavior and toxicological effects. The size of a particle dictates its behavior in air [Hinds, 1999]. Usually, particle size refers to the particle diameter. In some circumstances, a particle might be spherical (or nearly so) as in the case of liquid particles. A solid particle, on the other hand, might have an irregular shape. For such a case, the aerodynamic diameter, $d_a$, is often used to describe the effective diameter of an irregular particle. The aerodynamic diameter is defined as the diameter of a spherical particle with a density of a water droplet that has the same settling velocity as the particle of interest [Hinds, 1999]. The settling velocity is the velocity at which the drag (resistance) force of the air affecting the particle equals the force of gravity. Settling times for different particle aerodynamic diameters are shown in Table 3. In some circumstances, a Stokes diameter, which is defined as the diameter of a sphere that has the same density and settling velocity as the particles of interest is used. As the particle size gets smaller, the force of gravity becomes less significant and the behavior of the particle is determined by diffusion. At this point, a mobility equivalent diameter is commonly used [Maynard and Kuempel, 2005]. The U.S. Environmental Protection Agency has classified particles based on their size as seen in Table 4.

The particulate generated by a process has a variety of different shapes and sizes, and as a result, statistical methods are needed to characterize size distributions. For example, if a sample of particulate is collected from the workspace air surrounding a process, the number of particles within each size range of interest may be recorded, and then a histogram may be prepared displaying the particle count as a function of diameter. The same approach could be followed to characterize the mass distribution as a function of particle size (see Figure 4). Several statistics may then be calculated from the data including the mean, median, and mode that can be used for further analysis [Hinds, 1999]. The **mean** is defined as the sum of all the particle sizes divided by the number of particles, the **median** is the midmost value if the data are organized in ascending order, and the **mode** is the size that is found most frequently in the data.

Other values are calculated when analyzing aerosols. Two of the most common are the **mass concentration** that is expressed in terms of mass per unit volume and **number concentration** that
is expressed in terms of number of particles per unit volume. It is the mass concentration that is most often used to evaluate aerosols in working environments to ensure regulatory compliance. More details about regulations, exposure limits, and standards will be provided shortly.

Particles will deposit in different parts of the respiratory system, with the particle size serving as a principal factor in determining the deposition location. Relative to deposition concerns, ISO [1995] uses the following particle size classifications:

- **Inhalable fraction** – the mass fraction of total airborne particles that is inhaled through the nose and mouth.
- **Thoracic fraction** – the mass fraction of inhaled particles penetrating beyond the larynx.
- **Respirable fraction** – the mass fraction of inhaled particles that reach the gas exchange region of the lungs.

At present, the cutoffs for these three fractions are 100, 10, and 4 micrometers respectively. Of course, in practice, it is difficult to create a sampling device that can take in only particles less than 100 µm (inhalable fraction) for example. With this in mind, sampling devices are created with collection efficiencies that range from 100% at low particle sizes to 0% at high particle sizes; generally, these devices are constructed to have a collection efficiency of 50% at the specific cutoff value of interest.

### 2.3. Composition

The chemical composition of aerosols will vary from process to process. The composition depends on the materials used to fabricate the desired product and composition of the material being processed. The scenario becomes more complex if there are chemical reactions within the aerosol (secondary aerosols). One of the primary reasons for performing chemical characterization is to identify the contaminants that are present in the working environment to allow industrial hygiene personnel to determine whether applicable standards relating to specific chemical constituents are being met.

Devices frequently used for identifying particle composition include:

- X-ray fluorescence spectrometry (XRF)
- Proton-induced X-ray emission spectrometry (PIXE)
- X-ray diffraction (XRD)
- Optical emission spectrometry and mass spectrometry

Jenkins and Eagar [2005] provide an excellent summary of techniques and devices to characterize particle chemical composition. As a reminder, in the case of low toxicity fine particles it has been shown that inflammatory activity is linked to the high surface area of the particles [Brown et al., 2001]. This suggests that the particle size is the characteristic that "promotes" toxic reactions and that chemical composition is of secondary significance [Donaldson et al., 1998].
2.4. Instrumentation

A variety of instruments are available for sampling and analyzing aerosols. Brandt [1947] defined four reasons for the collection of particles: (1) to assess the workers’ exposure, (2) to determine the average exposure of a worker that seems to have become ill, (3) to determine the type of controls that could be incorporated, and (4) to study the efficiency of particle control equipment. Another reason for sampling is to quantify the effect of process variables on the resulting particle size distribution. To learn more about sampling instruments the reader is referred to Cohen and McCammon [2001]. Table 5 lists some common aerosol measuring instruments and the size range in which they may be utilized.

3. Health Effects and Regulations

Air quality in manufacturing environments has been a social concern since the 1700s when Bernardino Ramazzini, in his work called “De Morbis Artificum Diatriba” (Diseases of Workers), reported diseases that resulted from exposure to dust and fumes [Patty, 1978]. The U.S. manufacturing industry experienced a “boom” increase after World War I and II, due to higher demands for products. Even though this increase marked an important stage in strengthening the U.S. economy, it gave “birth” to a new problem. The increase in production resulted in an unhealthy environment for workers – poor air quality – that immediately had a negative impact on the workers’ health; therefore representing a new challenge for employers and regulatory agencies. Epidemiological studies have linked air pollution to adverse health effects, including respiratory diseases and increased mortality and morbidity [Dockery and Pope, 1994; Oberdörster et al., 1995; HEI, 2001]. This section focuses on reviewing some of the most common occupational diseases caused by the inhalation of airborne particles.

3.1. Health Effects

In 2004 the manufacturing industry represented less than 14% of the private employment sector and accounted for 42% of the non-fatal work place illnesses as published by the U.S. Bureau of Labor Statistics [BSL, 2005]. A portion of work-related illnesses is lung diseases, which are associated with poor air quality conditions. Some statistics compiled in 2004 are: i) inhalation and accumulation of dust were responsible for 2,860 deaths in 2000, ii) about 20-30% of asthma cases in adults are caused by work-related exposure, and iii) the fourth national leading cause of death, chronic obstructive pulmonary disease, was estimated to be 15% related to workplace exposure [NIOSH, 2004]. It is evident that the manufacturing sector still has a significant impact on the health of workers. Inhaled particles have also been linked to increased lung cancer cases [Knaapen et al., 2004].

Once particles are inhaled they can “promote” adverse biological effects in the human body, leading to local or systemic reactions, e.g. impact the area of first contact or other organ(s) as the particles are transported through the body. The biological impacts have been reported to include allergenic and irritative reactions, as well as carcinogenic effects; these may lead to lung inflammation, respiratory diseases, and lung tumors [Oberdoster et al., 1994; Nikula et al., 1995; Dasenbrock et al., 1996; Knaapen et al, 2004]. Health effects will depend on different factors, including length and frequency of exposure, susceptibility of the workers, and type of chemicals present in the inhaled aerosol. Symptoms may be noticed in a short-term or in a long-term
period. Short-term exposures might lead to *acute* poisoning, while long term or repeated doses might lead to *chronic* poisoning depending on the toxicity of the inhaled material.

In the case of welding, short-term health effects might include irritation of the nose, chest, and eyes, coughing, bronchitis, edema, pneumonitis, nausea, and vomiting. Long-term health effects include diseases such as asthma, emphysema, silicosis, and cancer in the lungs, larynx, and urinary tract [UCLA, 2003]. A common disease found in welding workers is the *metal fume fever*. Welding has also been linked to Parkinsonism [Racette et al., 2001].

*Silicosis* is thought to be the oldest occupational disease [Peterson, 1977]. It is caused by the inhalation and accumulation of silica particles in the workplace. Symptoms include shortness of breath, fever, coughing, fatigue, and chest pain. *Fibrosis* is a disease caused by the accumulation of fibrous material in human tissue, e.g. the lungs, with symptoms including shortness of breath and cough. Other occupational diseases include chronic beryllium disease (CBD), asbestosis, and pneumoconiosis.

Occupational standards are established and enforced by government agencies to avoid or prevent adverse health effects. The following section provides a description of workplace standards and regulations in the United States.

### 3.2. Workplace Air Quality Regulations

Workers’ health has been impacted by work-related activities since the industrial revolution. However, it was not until the 1900’s that major actions (see Table 6) were taken by the government to address occupational health and safety issues. In 1936 the Walsh-Healy Public Contract Act was passed in the United States providing for basic labor standards and establishing maximum working hours, as well as health and safety standards.

In 1970, the U.S. Congress recognized that employees should be provided a healthy working environment with the enactment of the *Occupational Safety and Health Act of 1970* [Public Law 91-596], considered the most important legislation dealing with occupational issues. It created the Occupational Safety and Health Administration (OSHA) – under the Department of Labor – for the enforcement of safety and health regulation, and also established the National Institute of Occupational Safety and Health (NIOSH) – under the U.S. Department of Health and Human Services [NIOSH, 2006b]. The Act authorizes NIOSH to “develop and establish recommended occupational safety and health standards” to prevent work-related illness, disability, and death, and to conduct research to make recommendations for current and new standards. This agency is also responsible for educating and training in the occupational safety and health field. Under the Act, the Secretary of Labor is authorized to establish health and safety standards. The first standards were adopted from the Walsh-Healy Public Contract Act and from the American National Standards Institute [MacCormik, 1978]. In addition, the Institute has authority for coal and mine research under the *Federal Mine Safety and Health Amendments Act of 1977* [NIOSH, 2006b]. The States are given jurisdiction under section 18 of the Act to decide if they want to be in charge of the enforcement of health and safety standards.

For airborne particles, OSHA publishes standards called permissible exposure limits (PELs), aimed at protecting the workers against health effects that may arise from exposure to hazardous substances. The PELs are described as the amount or concentration of a substance in air, based
on an 8-hour time weighted average (TWA) exposure. For particles, the PELs are given in mass per unit volume (mg/m³). Up to 2003, 500 PELs had been established by OSHA. The airborne particulate standard (OSHA) is 5 mg/m³ for Particulates Not Otherwise Regulated (PNOR). In 1946 the American Conference of Governmental Industrial Hygienists (ACGIH) was created with the purpose of advancing the field of occupational health by educating, developing and disseminating technical and scientific knowledge. The ACGIH publishes recommended air quality standards called the Threshold Limit Values (TLV) and Biological Exposure Indices (BEI). These standards may be used by a company in addition to those required by law.

3.3. **Trends in standards and regulations (PM₁₀ to PM₂.₅)**

Since its creation, the EPA has established standards for particulate matter, which can be composed of small particles and liquid droplets suspended in air [EPA, 2006]. The EPA established that one of the characteristics of particulate associated with negative health impacts is the presence of particles smaller than 2.5 µm. Particles this small can be inhaled and may reach the gas exchange region of the lungs and even translocate to other organs, such as the olfactory bulb [Oberdörster et al., 2004]. In 1987 the EPA set a standard for particulate matter smaller than 10 µm (PM₁₀), and in 1997 the agency published a standard to include particles smaller than 2.5 µm (PM₂.₅). This decision was not well received by industry and other organizations, and establishment of the new standard was contested before the U.S. Court of Appeals for the D.C. Circuit. The EPA’s 1997 standard was rejected by the DC Circuit in 1999. The EPA, conjunction with the U.S. Department of Justice (DOJ), appealed the decision, and in the year 2002 the D.C. Circuit allowed the EPA to follow with implementation of the PM₂.₅ standard.

4. **Origin of Airborne Particles**

Airborne particulate in the workplace environment originates from a variety of sources. Particles can be generated directly by the manufacturing process as the product is been created or indirectly as a result of part cleaning, product packaging, part handling, etc. The airborne particulate that is generated varies with the type of manufacturing process and the associated particle formation mechanism. This section is aimed at describing the various mechanisms and modes that lead to the formation of aerosols and examines particle generation/formation for a variety of manufacturing processes.

4.1. **Welding**

There are a variety of different types of welding operations that serve to join two or more metal components. In welding operations, the workpieces are melted in the desired contact area to form a strong permanent joint as the melted material fusions and gets cooler. Common welding processes include: metal inert gas (MIG) arc welding, tungsten inert gas (TIG) arc welding, shielded metal arc welding (SMAW), gas metal arc welding (GMAW), plasma-arc welding (PAW), carbon-arc welding (CAW), submerged arc welding (SAW), electroslag welding (ESW), etc. [Schey, 2000]. During many welding operations, fumes are produced [Zimmer and Biswas, 2001; Chan et al. 2002; Spiegel-Ciobanu, 2003]. Fume constituents produced by welding operations include: Aluminum, Beryllium, Cadmium, Chromium, Copper, Iron, Lead, Manganese, Molybdenum, Nickel, Vanadium, Zinc, and oxides of various types. Welding fumes contain particles of various sizes, with a significant number of the particles lying within the
nanoscale regime (<0.1 µm). The number of particles, particle size, and specific chemical components of the fume depend on the process type, process conditions, and the materials being used. Welding particles can take on an assortment of morphologies, depending on the forces acting among them, which may lead to particle agglomeration and the final size of the airborne particulate. When analyzing the welding fumes, individual particles may be seen, as well as particle chains and agglomerates as a result of such forces. Spiegel-Ciobanu [2003] reports that for manually operated arc welding on Cr-Ni steel, particle sizes may be as small as 20 nm, with agglomerates on the order of 500 nm. For an automated version of the process, particle sizes were observed as small as 10 nm and agglomerates were approximately 100 nm in size.

The constituents within a welding fume depend on the i) base and filler metals, ii) electrode coating, iii) contaminants on the base metal, and iv) the reactions that occur during the welding process [Battelle, 1973]. Chan et al. [2003] found that for a shielded metal arc welding (SMAW) operation the particle size, composition, and generation rate depend on electrode type and diameter, welding current, welding speed, welding angle, and current type (AC or DC). For this case, the electrode was found to be the dominant factor in the chemical composition of the fume, and the fume generation rate was linked to the current type, with an AC current decreasing the fume generation rate. Similar studies for the characterization of SMAW emissions have been reported by Stephenson et al. [2003] and Hewett [1995].

4.2. Wet Machining

Some manufacturing processes, e.g., tapping, turning, drilling, and milling, incorporate metalworking fluids (MWF) in an effort to improve machined surface quality, enhance tool life, provide lubrication, and remove heat from the working zone [DeChiffre, 1988; El Baradie, 1996; Shen and Oberwalleney, 1997]. The interaction of the cutting fluid with the machine tool and the workpiece provides several mechanisms for the formation of mist. Figure 5 displays two potential mechanisms that may lead to the formation of fluid mist. When fluid is exposed to hot elements within the machining system (cutting tool, workpiece, etc.) some of the fluid may vaporize and subsequently condense to form mist. In the case of processes with high-speed rotating elements, mechanical energy may lead to fluid breakup via atomization. Gunter [1999] found that for a rotating cylindrical workpiece the dominant process variables for atomization are the spindle speed and the workpiece diameter. Other factors that affect the mist formation are the type of nozzle, distance of nozzle from point of application, and fluid application mode [Byers, 1994].

4.3. Dry Machining

In recent years, dry machining has been investigated as an option for the elimination of metalworking fluids [Granger, 1994; Aronson, 1995; Young et al., 1997; Popke, 1999; Adler, 2006]; thus, avoiding the environmental, health, and safety challenges associated with wet machining. In the absence of metalworking fluids, some workpiece materials have the propensity to form dusts; therefore, dry machining should also be given attention from an air quality standpoint. Sutherland et al. [2000] demonstrated that the speed, feed, and depth of cut were key variables in the formation of dust during the machining of cast iron. Research findings reported that aerosol concentration during dry machining were 12-80 times less than those
produced by wet machining operations. Particles sizes were found to be between 1-4 µm. In a similar study [Dasch et al., 2005], the particle distribution was found to have a MMAD of 10 µm.

### 4.4. Grinding

Several studies have been performed to characterize aerosols produced during grinding processes [Martyny et al., 2000; Rosenthal and Yeagy, 2001; Zimmer and Maynard, 2002; Dasch, 2005]. Zimmer and Maynard [2002] proposed three mechanisms/modes, or sources, for the formation/generation of aerosols from grinding: i) emission of particles from the motor of the machine tool itself, ii) combustion of the workpiece material, and iii) volatilization and subsequent condensation of grinding materials at the wheel/workpiece interface.

Dasch et al. [2005] considered a wet grinding operation performed on gray cast iron with a straight cutting fluid from Castrol. Temporal sampling plots revealed that particle concentration increased when the machine tool enclosures were periodically opened. The concentration of PM$_{10}$ was reported to be 2.5 times the concentration of PM$_{1.0}$. In terms of the particle distribution, the MMAD was reported to be 2.5 µm.

Zimmer and Maynard [2002] examined surface grinding of various substrates (granite, clay, ceramic, steel, Aluminum, polytetrafluoroethylene-PTFE, and oak hardwood) under dry conditions and characterized the particulate as having sizes ranging from 4.2 nm to 20.5 µm. In some instances it was possible to identify the particle mechanism of formation though the morphology of the particles, e.g., in the case of granite grinding, particles larger than 1 µm were attributed to the pullout of wheel abrasives. Grinding of PTFE produced a large number of nanoparticles (< 0.1 µm) with some nanoparticles also detected from the grinding of steel. The mechanism for aerosol generation for PTFE and steel were said to be through nucleation, since the temperature in the working zone was high enough for vaporization or combustion to occur. Aerosol from wood grinding was attributed to frictional heating. Transmission Electron Microscopy (TEM) was used to conclude that the source of nanoparticles in the grinding of PTFE was associated the workpiece material. The source of nanoparticles for the other workpiece materials was not identified due to technical limitations of chemically characterizing particles at the nanoscale.

### 4.5. Casting

Many components of products are created through casting processes. It is estimated that 13 million tons of castings are produced each year in the United States [EPA, 1998]. There are a number of different types of casting processes including: sand casting, investment casting, permanent mold casting, continuous casting, and lost foam casting. Each process has unique stages, but most of them share four basic steps: i) pattern making, ii) mold and core preparation and pouring, iii) furnace charge preparation and metal handling, and iv) shakeout, cooling, and sand handling [EPA, 1998]. While not technically associated with casting, other processes are often linked with it: quenching, finishing, cleaning, and coating. Stages producing particulate for a typical green sand foundry include: sand and binder mixing, core forming, mold making, sand preparation and treatment, metal melting, tapping, treatment, slag and dross removal, mold pouring and cooling, casting shakeout, and riser cutoff and gate removal [EPA, 1998].
Several studies have been performed to characterize the aerosol emissions from a casting process. Chang et al. [2005] characterized the particle (PM$_{2.5}$) number and mass distribution, and chemical composition of gray iron for single-pour/no-baked molds. Sampling was performed in several stages of the process including pouring, cooling, and shakeout. During the study, it was observed that particle number and mass increased during the pouring process and a rapid decrease occurred during the cooling period. Overall, the maximum emissions of particulate were seen in the shakeout process with particle sizes ranging between 1.5-2.6 µm.

Chang et al. [2005] observed a large number of ultrafine particles (< 0.1 µm) and attributed these to condensation and coagulation mechanisms. The melting of gray iron takes place around 1,500 °C. Chang et al. [2005] hypothesized that the interaction of the hot metal with the cold mold (21 °C) led to chemical reactions, vaporization, and combustion of some organic compounds that form particles through nucleation or condensation, depending on the changes in the medium, e.g., vapor pressure. It was also found that process changes such as different pouring and shakeout variables influence both the particle size and the chemical presence of elements. The sampled particulate mostly consisted of organic and elemental carbon, oxides of aluminum, silicon, calcium, and iron.

Lost foam casting (LFC) is an alternative method with advantages over the traditional casting process, such as the reuse of casting sand. However, as with other casting processes, significant amounts of airborne particulate can be produced, and with LFC there is also the concern about the decomposition of the foam pattern (often made of expanded polystyrene, EPS). Behm et al. [2003] investigated the generation of particulate matter from LFC using an EPS pattern with the variation of three process variables: pouring temperature, pattern coating, and pattern thickness using a 2$^3$ full factorial experiment. Many of the emissions appeared to be associated with the decomposition of the EPS pattern. Behm et al. [2003] concluded that process variables play a significant role in the generation of airborne particles.

An initiative to improve the air quality associated with the foundry industry started in 1994 with the establishment of the Casting Emissions Reduction Program (CERP). CERP is a collaborative effort between the U.S. government, the auto industry, and academia aimed at helping industry to meet air quality standards through R&D in a real-world foundry environment. CERP also pursues research for emission measurements and energy technologies that will advance the casting industry in compliance with environmental regulations [CERP, 2006].

### 4.6. **Powder Manufacture – Carbon Black**

Many industries (e.g., pharmaceutical and chemical industries) produce large quantities of powders that are used for medical products, cosmetics, paint pigments, etc. In many of these industries, there is a high probability that workers will be exposed to suspended powders. A powder that is produced in great quantities is carbon black. In fact, a million metric tons of carbon black was produced globally in 1999 [Poliski, 1999].

Carbon black (CB) has long been used by industry for many purposes. It is used as an additive in the manufacturing of tires, toners, reinforcement filler, and paint pigment. While carbon black
can result from incomplete combustion, this section only focuses on exposure to manufactured carbon black [Kuhlbusch et al., 2004; Gardiner, 1996].

Carbon black manufacturing usually consists of three steps: i) reactor processing, ii) pelletizing, and iii) packaging [Kuhlbusch et al., 2004; Poliski, 1999]. The reactor processing stage is used to fabricate the primary particles with size ranges in the 1-500 nm range, but due to the high concentration of particles, the individual particles aggregate to form larger particles that are the primary entity of CB. The pelletizing stage is used to make very large clumps of particles. Once the particles are dried following pelletizing, particles are packaged in different bag sizes and shipped.

Kuhlbush et al. [2004] conducted an investigation to characterize aerosols during the packaging of carbon black in three European plants, concentrating on ultrafine particles. Ultrafine particles (<0.10 µm) were only detected in plants 2 and 3, and were attributed to the use of diesel or propane fork lift machines and to the heaters used in plant 3. Emissions from heaters have also been reported by Stephenson et al. [2003] in a welding facility. On the other hand, elevated mass concentrations found in the filling area were linked to carbon black. CB particles in the bagging area had a lower size limit of 0.4 µm.

The propensity and mechanisms of powders (in the nanoscale) to become airborne are not clearly understood. Attempts have been undertaken to determine the propensity of powders to become airborne, known as dustiness [Hinds, 1999]. The dustiness of CB was investigated by Lyons and Mark [1994].

5. Traditional Control Technologies

A majority of the air quality control technologies that are classified as traditional were initially implemented upon identification of the existence of an airborne hazard. The sole objective of these technologies is to control the identified airborne particulate to the level specified in the relevant regulations. The type of traditional control technology employed depends primarily on three factors: (i) the type of particulate to be controlled, (ii) the process by which the particulate is produced, and (iii) the interaction of the worker with the manufacturing process. The latter consideration can include the possibility of worker exposure, as well as the level of worker intervention in the process. Brandt [1947] described a hierarchy of principles that are used for particle control (Table 7). Several broad categories of traditional control technologies are discussed in this section.

5.1. Ventilation Systems

Ventilation systems are used to control particulate that can be easily transported by the movement of air in the workplace. This includes smoke, dust, fumes, and fine mists but not larger droplets or metal particles. Ventilation systems range in configuration from typical building HVAC units to more specialized ducted configurations dedicated to a single piece of equipment. Regardless of the configuration, ventilation systems employ a collection mechanism specific to the particulate being removed from the workers’ environment. Collections systems may or may not include filters. The adaptability of ventilation systems makes them suitable for a wide range of manufacturing operations and worker interaction levels.
Ventilation systems remove particulate from the workplace air to a location where the particulate is trapped or collected. Such equipment often functions by drawing particulate-laden air through HEPA (high efficiency particulate air) filters and/or by using centrifugal air flow to force particles to side walls to be collected and possibly recycled (collected MWF mist can be returned to the sump). The location of the ventilation system within the workspace is critical. The system must remove particulate from the workspace without drawing it closer to the worker. Therefore, systems that create a downdraft are considered more effective than those that create an updraft, which can draw particulate into the workers’ breathing space.

While such methods can be effective in substantially reducing particulate concentrations, they do not eliminate all the related health risks. Strong air flow induced by ventilation fans can force fine liquid particles to break away from liquid pools and saturated filter elements, thereby increasing the particulate concentration in the work environment. Evaporation or vaporization of a collected liquid can lead to increased amounts of fluid vapor, which can easily pass through collectors and air filters. This vapor may condense to form mist if it is recirculated from a warm duct to a cooler workroom [Cooper and Leith, 1998]. Therefore, even in the presence of a 100% efficient particulate collector, hazardous particulates in the form of vapor may still pass through removal systems and recondense to form fluid mist [Raynor et al., 1996].

Another important issue regarding ventilation systems is the implementation of a routine maintenance program. A study conducted to analyze the performance of industrial mist collectors indicated that performance of individual collections stages, as well as assembled collectors, varied substantially. A protocol was developed to evaluate the systems that filter the mist produced by MWFs that suggested overall mist collector efficiency may be somewhat suspect [Leith et al., 1994]. Although filter efficiency increased with solid loading, efficiency decreased with liquid loading. In some cases, it was found that mist-loaded filters developed negative efficiencies and became generators of submicrometer droplets. In addition, the inability of liquid saturated filters to fully drain under normal continuous operation was reported by Cozzen [1985]. The recommendation is to enforce a rigorous maintenance program with implementation of air cleaner or air filter rotation. In closing, while they can be effective, collectors within ventilation systems are expensive to purchase, install, operate, and maintain.

5.2. Enclosures

Maintaining the appropriate air quality in the workplace can be accomplished by containing the particulate with the use of an enclosure. A wide variety of enclosures, including OEM (original equipment manufacture) and retrofit types, are used in manufacturing processes that require minimal worker interaction. It is not uncommon for a ventilation system to be used in combination with an enclosure. Enclosures can control a wide variety of airborne particulate provided they are properly designed.

The purpose of an enclosure is to contain the particulate, which may be released into the workers’ environment if the enclosure is opened. Hands et al. [1996] investigated the efficacy of machining enclosures, in which exposure from three different control methods used for MWF aerosols were compared. It indicated that OEM enclosures equipped with exhaust ventilation provided significantly lower exposures as compared to retrofit enclosures or no enclosure. It was
also found that operations with retrofit enclosures have exposures that are not significantly different from those with no enclosure at all. Furthermore, retrofit enclosures were twice as costly to fabricate and install as OEM enclosures, as they were inherently difficult to design due to operation and maintenance requirements and their efficacy may degrade over time.

Enclosures are most effective in manufacturing environments in which all processes can be enclosed. This is not always the case, as illustrated by a study conducted to assess the exposure to MWFs in a typical automotive manufacturing facility. Of the 295 machines studied, 35% had no enclosures, 45% were partially enclosures, and 20% were completely enclosed [Woskie et al., 1996]. Furthermore, 88% of the machines had no local exhaust in place. Heitbrink et al. [1997] found that non-ventilated machine operations appeared to disperse mist concentrations throughout the particular machining plant they investigated. Half of the worker exposure was attributed to the machine operation, while the other half was attributed to this background concentration of mist.

5.3. Chemical Treatment

The use of chemicals as a control technology for airborne hazards is limited to manufacturing processes that produce MWF mists. These can be used in any process that utilizes MWF without consideration of the level of worker input to the process.

A method developed for reducing the amount of suspended mist in machining operations involves the use of chemical additives called mist suppressants. It was found that the addition of high molecular weight polymer polyisobutylene (PIB) increased the elongational viscosity of the MWF, thus increasing the size and settling rate of the mist drops that are created and reducing the quantity of suspended mist. This particular mist suppressant has not been found to be as effective in reducing mists generated from water-based MWFs [Marano et al., 1997; Gluari et al., 1995]. Therefore, studies have been conducted to investigate the use of high molecular weight polymer polyethylene oxide (PEO) as a mist suppressant for water-based MWFs [Marano et al., 1997; Kalhan et al., 1997]. The physical theory behind mist suppressants is based on the atomization mechanism of mist formation, and, as a result, such methods may have little effect on reducing mist practices generated via vaporization/condensation.

5.4. Personal Protection Systems

Under the Occupational Health and Safety Act of 1970 employers are required to provide a healthy working environment, i.e., free of substances that might impact workers’ health. Personal protection equipment is required after efforts have been undertaken to control the sources of particulate and the elimination of particulate generation has not been accomplished. Respirators serve two purposes: (i) filter airborne particles and (ii) supply clean air to the worker [NIOSH, 2006a].

6. Environmentally Responsible Particulate Mitigation/Elimination

The airborne emissions from several manufacturing processes have been examined along with traditional control methods. Attention now turns to identifying environmentally responsible actions that may be employed to improve the performance of these operations. As opposed to
the control actions presented in the previous section, these efforts are not focused on simply
containing or capturing the emissions, but rather on reducing or eliminating the emissions at their
source. Of course, as Figure 6 suggests, it is desirable to establish environmentally responsible
mitigation/eradication technologies early in product/process design. The earlier these
technologies can be considered, the more options will be available and the more effective the
resulting technology development effort. In addition, developments early in the design activity
typically cost much less to implement than developments that are introduced later. These facts
have been reported elsewhere [DeVor et al., 1992] for characteristics such as quality and ease of
manufacture.

From a manufacturing standpoint, there are at least three general actions that can be taken to
address emissions in an environmentally responsible manner. These approaches are (i)
alternative process plan, (ii) alternative process sequence, and (iii) process change. Additional
detail pertaining to each action is described below. Furthermore, specific examples are given for
each environmentally responsible manufacturing approach.

6.1. Alternative Process Plan

The set of operations to be employed in producing a manufactured product can be identified once
sufficient product specification detail is available. There is generally significant flexibility in
deciding the operations to employ (and their order) in creating a product. This process-planning
task has historically been based primarily on the economics and cycle times associated with the
various operations. Product designers have traditionally developed product designs based on
product use considerations but nowadays must also consider the downstream impacts on
manufacturing. The objective of environmentally responsible manufacturing requires that all
product and process decision makers consider new metrics in addition to the traditional ones.

As noted, process planners generally have some flexibility in deciding the manner by which a
product is to be created. It is quite possible that one candidate process sequence could be
preferable to another in terms of airborne emissions. Figure 7 illustrates this point with two
candidate process plans. Assuming that both plans are comparable in terms of cost, cycle time,
quality, etc., the figure indicates that Plan 2 is preferable to Plan 1 because it is more
environmentally responsible, i.e., it produces less harmful aerosols. In general, process plans can
involve completely different sets of operations, or they may be the same except for a single
operation. Eliminating an operation from a process plan would be considered equivalent to
creating a new process plan (this could involve changing the settings of the remaining
operations).

Examples that illustrate this approach to ERM include: (i) avoiding the emissions from a painting
operation by employing a grinding operation that produces an aesthetically pleasing product
surface appearance; (ii) avoiding cutting fluid mist by creating the desired feature via a casting
operation; or (iii) utilization of hard turning to eliminate a grinding operation and its concomitant
dust. It is worth noting that a more environmentally responsible process plan may also produce
parts at lower cost or reduced cycle times.
6.2. Alternative Process Sequence

In addition to specifying the operations within a plan, process planners may also have some discretion in varying the order of said operations. In the context of a plan, such as that of Plan 2 in Figure 7, this may mean that the process order is switched from D-E-F to D-F-E. While such a switch would mean that the same operations are performed, it does not necessarily follow that the aerosol emissions of the resulting plan would be the same. For example, consider a product that is presently laser welded following a machining operation. MWFs remain on the part after machining can be vaporized during welding and subsequently condense to form a mist that represents a risk to worker health. It may be possible to consider switching the cutting and welding operations to avoid this problem completely.

6.3. Process Change

The previous approaches have focused on the set of operations (and their sequence) that are used to manufacture a given product. With the process plan specified, decision-making degrees of freedom are reduced to the point that environmental improvement must be sought within an operation. The problem at hand is the reduction/elimination of process aerosols given the degrees of freedom available only at the process level. This means that a critical examination of such operation characteristics as process settings, inputs, and process procedure are required.

6.3.1. Process Method and Inputs

Even though a given process has been specified, this does not mean that there is no latitude in the performance of the operation. Certainly, those methods and equipment types that provide for reduced aerosol emission should be favored, assuming they still affect the same desired change to the product being operated upon. For example, Hands et al. [1996] reported that machine tools with original equipment manufacture (OEM) installed enclosures are better than retro-fitted structures at containing fluid mist. As another example, researchers have reported some success with an innovative dry drilling approach [Ackroyd et al., 1998; Toews et al., 1998; McCabe, 2002; Filipovic and Sutherland, 2005] – and in the absence of a cutting fluid, fluid mist will not be produced. With this approach, the drill is subjected to axial modulations to produce chips that can be easily channeled out of the drill flute in the absence of a cutting fluid. Another innovative approach to address cutting fluid mist employs kinematic coagulation, the capture of smaller particles by larger collector droplets [Kinare et al., 2004].

Manufacturing operations take some input component and modify it in a particular way to accomplish an objective. Often, other materials (apart from the product material itself) are used to achieve this goal. The mission of environmentally responsible manufacturing requires that these materials be selected and used wisely.

An example of a well known material substitution is of chlorofluorocarbons (CFC). CFCs were used as refrigerants and banned in the 1970s due to their role in depleting the ozone layer. Nowadays, solvents are still used in the auto, electronic, chemical, and pulps industries as process inputs, cleaning agents, and dispersants [DeSimone, 2002]. Additional concerns of solvents include the emission of volatile organic compounds (VOCs) and flammability. To avoid these, some efforts have been undertaken to mitigate or reduce the environmental impacts
of solvents [DeSimone, 2002]. An example taken from the auto industry is the use of water-based paint, which has proven to reduce the use of solvent, therefore minimizing their impacts.

6.3.2. Processing Conditions
This refers to such characteristics as machine settings and the ambient conditions under which an operation is performed. Again, conditions should be selected with consideration for aerosol emissions along with attention to other factors such as cost, cycle time, and quality. As suggested above, dry machining may require a significant process change to be successful; however, for some situations, few substantive changes may be required, and dry machining can be implemented by simply turning off the fluid. When compared to wet machining, the aerosol concentration generated by dry machining in turning was reported to be 12 to 80 times less than that generated from wet machining [Sutherland et al, 2000]. However, dry machining is still a research topic as many challenges need to be overcome, e.g., product quality. If some fluid is needed for machining, minimum quantity lubrication (MQL) represents a strategy that can offer technological and economic advantages over traditional fluid applications in machining [Weinert et al., 2004; Klocke et al., 1996]. As the name implies, MQL seeks to reduce the amount of cutting fluid used in an operation, and with less fluid, less MWF mist may be generated.

7. Manufacturing Trends and Potential Particulate Concerns
Thus far, this chapter has focused on air quality issues associated with traditional manufacturing processes. Recently, there has been a growth in interest in such emerging manufacturing trends as nanotechnology and biotechnology within industry and academia. In the case of nanotechnology, the focus has been to exploit the improved properties that materials show at the nanoscale in contrast to their bulk counterparts. Manufacturing-related biotech applications include drug development, biomaterials, and tissue engineering. A review of the literature reveals that air quality research related to these emerging technologies has been limited. With this in mind, this section focuses on exposure to carbon nanotubes and microorganisms.

7.1. Nanoparticles
In the last decade we have experienced a boom in nanotechnology research. Nanotechnology has been defined “as the science and technology that will enable the understanding, measurement, manipulation, and manufacturing at the atomic, molecular, and supra-molecular levels, with the aim of creating materials, devices, and systems with fundamentally new molecular organization, properties, and functions” [U.S., 2003]. The emerging field of nanotechnology is leading to unprecedented understanding and control over the composition of all physical things. Nanotechnology is expected to change the way in which products are designed and manufactured [NSTC, 1999].

When reviewing the literature associated with nanotechnology, the case is often made that this technology will positively affect society. On the other hand, it is unclear at this point, the effects that the creation of these nanoscale products will have on the environment and society. Of course, the manufacturing of nanomaterials such as carbon nanotubes, nanowires, and quantum dots should raise concerns about worker exposure. Currently, there are no standards regarding
exposure to nanomaterials in the United States, and in addition, the literature related to the toxic effects of nanomaterials is limited and much research needs to be performed.

Manufacturing of nanomaterials may give rise to new sources of nanoscale airborne particles. During the manufacturing of nanomaterials, possible stages during which workers could be exposed to nanomaterials include: synthesis, material handling, equipment cleaning (e.g., reactor), and facility maintenance [HSE, 2004]. The level of exposure will vary by process as the synthesis methods change. Common commercial processes include: (i) vapor-phase, (ii) colloidal, (iii) gas-phase, and (iv) attrition. Table 8 provides a comprehensive description of the exposure that might result from each of these processes.

As can be seen in Table 8, it is unlikely that there will be a concentration of nanoparticles during the manufacturing of the nanomaterials. During synthesis, exposure might result if there are leaks from the reactor [HSE, 2004]. Therefore, reactor design will play an important role in ensuring that the synthesis process limits the exposure of the worker to nanoparticles. It is important to mention that if the product becomes airborne, it may start to agglomerate and the exposure could be less significant since the particles may no longer be in the nano-regime. At this moment, it is unclear if agglomerated particles would have the same toxicity as individual particles. However, it is believed that the particles will be disaggregated following inhalation, thus causing the same possible effects on worker health.

7.1.1. Exposure to Carbon Nanotubes
Nanoparticles could become airborne, and therefore may threaten worker health if inhaled. Figure 8 depicts confirmed and potential exposure routes for nanomaterials. Maynard et al. [2004] conducted the first assessment of exposure to carbon nanotubes (CNTs) by two different production processes: (i) laser ablation, and (ii) high pressure carbon monoxide (HiPCO®). This project investigated the propensity of carbon nanotubes to become airborne when agitated in a laboratory environment. CNT material from laser ablation did not lead to a significant amount of airborne CNT and detectable particles were bigger than 100 nm. For the case of HiPCO® there were a number of nanoscale particles (<100 nm). In both cases, the concentration of particles in air decreased very quickly with time and measured concentrations never exceeded the OSHA mandated personal exposure limit currently set at 5 mg/m³ (for Particulates Not Otherwise Regulated, PNOR). Maynard et al. [2004] also reported on experiments to investigate the propensity of carbon nanotubes to become airborne during material removal/handling at four facilities, but the results from these experiments were not conclusive.

7.2. Bioaerosols
Bioaerosols are aerosols of biological origin. Different types of aerosols can be found in the occupational environment including: viruses, bacteria, fungal spores, and pollen. Common settings for exposure to viruses and bacteria are hospitals and health clinics. Tuberculosis is an example of an occupational related disease cause by the bacterium mycobacterium tuberculosis. Bioaerosols can contain very small components; for example, viruses exist at the nanometer scale. In manufacturing environments, bioaerosols might originate from HVAC systems, machining operations that use metalworking fluids (MWF), or manufacturing biotech applications. Table 9 provides the size range for several bioaerosols. A comprehensive list of the origin/source of bioaerosols in addition to bioaerosols related diseases is given in Table 10.
It has long been known that MWFs contain diverse microbial populations [Awoskia-Olumo et al., 2003; van der Gast et al., 2001; Wallace et al., 2002]. Some of these bacteria are believed to cause respiratory problems in humans, including MWF-associated non-tuberculosis mycobacteria (NTM). Endotoxin levels can also be significant due to the relatively high levels of gram-negative bacteria [Lewis et al., 2001; Simpson et al., 2003]; a recent review has concluded that bacterial endotoxin is a primary component of MWF toxicity [Gordon, 2004]. There are no regulations or recommendations regarding worker exposure to microorganisms, and it is not apparent that the current air quality recommendations adequately protect worker health, as evidenced in 2001 at a TRW automotive plant in Mount Vernon, Ohio. Despite an OSHA inspection of the plant that found the level of exposure to MWF to be within “acceptable” limits, 107 workers were placed on medical restrictions due to respiratory problems, and 37 suffered long-term disability.

In the last decade, the biotechnology industry has experienced an increase in production as biotechnology finds its way into the development of innovative new products such as pharmaceuticals, non-chemical pesticides, and useful microorganisms (e.g., for waste biodegradation). Fungal enzymes play an important role in the production of these products [MacIntosh and Spengler, 2000]. With the growing use of these microorganisms within industrial applications, it is likely that they (or some component or by-product of the microorganism) will become aerosolized within the working environment.

8. Summary & Conclusions

This chapter has focused on air quality (aerosols) issues in manufacturing environments. It has covered a variety of topics such as the importance of occupational health, regulations, and aerosol characterization. The chapter has also reviewed common industrial processes in terms of relevant aerosol generation mechanisms, particle mass concentration, particle size, etc. Finally, particulate control technologies have been examined, and efforts to mitigate/eliminate particulate in a more environmentally responsible manner have been studied. The chapter has concluded with an examination of air quality concerns for innovative new manufacturing technologies. A large number of references have been cited in the chapter and the reader is encouraged to consult these works for further details.

The emphasis of this chapter on manufacturing process aerosols is driven by concerns for human health as a result of exposure to airborne particles. Given this statement, it must be noted that all the manufacturing studies that have been cited in the chapter reported compliance with applicable U.S. health/safety standards. However, as has been noted, there is some concern that current standards might not be protective of human health, especially from exposure to ultrafine particles. The authors believe that as more knowledge is accumulated regarding the potential health effects of workplace aerosols, in particular for novel processing methods that are of growing importance, emphasis on air quality will increase. New/improved standards will be developed and many manufacturers will be forced to scramble to react to these changes; such reactionary approaches are usually not cost effective and may be counterproductive. Since traditional particulate control approaches often only seek to contain or mask process generated aerosols, more and more emphasis will need to be placed on innovative techniques to
avoid/eliminate airborne particulate from manufacturing processes. The development of such techniques will likely require an understanding of the relevant mechanisms associated with the creation of process aerosols that is vastly improved over the knowledge that exists today.

9. Acknowledgments

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Figures and tables

Figure 1: Product Life Cycle, Adapted from Haapala et al. [2006]

```
Raw Material Extraction → Material Processing → Manufacturing → Use → End-of-Life

Reuse
Remanufacturing
Recycling
Disposal
```

Inputs
- Energy
- Tooling
- Fixturing
- Lubricants
- Raw materials, Etc.

Outputs
- Solid waste
- Waste water
- Desired product
- Liquid effluents
- Airborne particles, Etc.

Figure 2: Input-Output Description of a Manufacturing Process

Figure 3: Parts of the Respiratory System [UMHS, 2005]
Figure 4: Sample Mass Distribution of Particles, Published with Permission [Dasch et al., 2005]

Figure 5: Mist Formation from MWF in Machining Process, Adapted from Yue et al. [1996].
Figure 6: Degrees of Freedom and Change Costs at Various Points in the Design of the Product and Process, Adapted from Gunter and Sutherland [2001]

Figure 7: Alternative Process Plans Producing Different Performance, Adapted from Gunter and Sutherland [2001]
Figure 8: Exposure routes of nanoparticles, Reproduced with Permission from Environmental Health Perspectives, Oberdörster et al. [2005]

Table 1: Size and Fate of Particles [Lu and Kacew, 2002]

<table>
<thead>
<tr>
<th>Size (µm)</th>
<th>Fate of particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 10</td>
<td>Deposited in the nose</td>
</tr>
<tr>
<td>5-10</td>
<td>Trapped in the nasal pharynx</td>
</tr>
<tr>
<td>2-5</td>
<td>Removed by mucociliary escalator in the tracheobronchial area</td>
</tr>
<tr>
<td>0.01-2</td>
<td>Alveolar deposition in the lung</td>
</tr>
<tr>
<td>&lt; 0.01</td>
<td>Exhaled</td>
</tr>
</tbody>
</table>

Table 2: Description of Airborne Particles, Adapted from [NAS, 1979]

<table>
<thead>
<tr>
<th>Name</th>
<th>Origin</th>
<th>Usual Size Range (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dust</td>
<td>Mechanical dispersion</td>
<td>&gt;2</td>
</tr>
<tr>
<td>Fumes</td>
<td>Condensation</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Smoke</td>
<td>Condensation</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Mists</td>
<td>Condensation or atomization</td>
<td>5-1,000</td>
</tr>
<tr>
<td>Sprays</td>
<td>Breakup of a droplet</td>
<td>&gt;1&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>2</sup> Source: Hinds [1999]
Table 3: Time Required for a Particle to Settle 5 Feet in Still Air [Baron, 2006]

<table>
<thead>
<tr>
<th>Particle Size (d&lt;sub&gt;a&lt;/sub&gt; in µm)</th>
<th>Settling time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>41 hours</td>
</tr>
<tr>
<td>1</td>
<td>12 hours</td>
</tr>
<tr>
<td>3</td>
<td>1.5 hours</td>
</tr>
<tr>
<td>10</td>
<td>8.2 seconds</td>
</tr>
<tr>
<td>100</td>
<td>5.8 seconds</td>
</tr>
</tbody>
</table>

Table 4: Particle Size Categories, Adapted from [EPA, 2006a]

<table>
<thead>
<tr>
<th>Name</th>
<th>Particle size (aerodynamic diameter, d&lt;sub&gt;a&lt;/sub&gt;) (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super coarse</td>
<td>&gt; 10</td>
</tr>
<tr>
<td>Coarse</td>
<td>2.5 &lt; d&lt;sub&gt;a&lt;/sub&gt; &lt; 10</td>
</tr>
<tr>
<td>Fine</td>
<td>0.1 &lt; d&lt;sub&gt;a&lt;/sub&gt; &lt; 2.5</td>
</tr>
<tr>
<td>Ultrafine</td>
<td>&lt; 0.1</td>
</tr>
</tbody>
</table>

Table 5: Common Sampling Instrumentation

<table>
<thead>
<tr>
<th>Air Sampling Device</th>
<th>Average Size Range (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scanning Mobility Particle Sizers (SMPS)</td>
<td>0.015-0.7</td>
</tr>
<tr>
<td>Aerodynamic Particle Sizer (APS)</td>
<td>0.2-20</td>
</tr>
<tr>
<td>TSI DustTrak</td>
<td>0.3-1.0</td>
</tr>
<tr>
<td>Micro-Orifice Uniform Deposit Impactors (MOUDI)</td>
<td>0.06-20</td>
</tr>
<tr>
<td>Electric aerosol analyzer (EAA)</td>
<td>0.01-1</td>
</tr>
<tr>
<td>Microscopy Device</td>
<td></td>
</tr>
<tr>
<td>Scanning electron microscope (SEM)</td>
<td>0.5-50</td>
</tr>
<tr>
<td>High resolution SEM (HRSEM)</td>
<td>0.002-1</td>
</tr>
<tr>
<td>Electron probe microanalysis (EPMA)</td>
<td>0.5-50</td>
</tr>
<tr>
<td>Transmission electron microscope (TEM)</td>
<td>0.001-1</td>
</tr>
<tr>
<td>Light microscopy</td>
<td>1-400</td>
</tr>
</tbody>
</table>
Table 6: Occupational Related Action in U.S., Adapted from [McCormick, 1978]

<table>
<thead>
<tr>
<th>Date</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1852</td>
<td>First safety law in the state of Massachusetts</td>
</tr>
<tr>
<td>1908</td>
<td>Congress passed a law to compensate work-related injured workers</td>
</tr>
<tr>
<td>1910</td>
<td>First national conference in occupational diseases</td>
</tr>
<tr>
<td>1913</td>
<td>Creation of the Department of Labor</td>
</tr>
<tr>
<td>1934</td>
<td>Labor standards established by the Dept. of Labor</td>
</tr>
<tr>
<td>1936</td>
<td>Walsh-Healy Public Contract Act</td>
</tr>
<tr>
<td>1941</td>
<td>Federal Mine Inspection Act</td>
</tr>
<tr>
<td>1946</td>
<td>American Conference of Governmental Industrial Hygienists (ACGIH)</td>
</tr>
<tr>
<td>1966</td>
<td>The Metal and Nonmetallic Mine Safety Act of 1966</td>
</tr>
<tr>
<td>1977</td>
<td>Federal Mine Safety and Health Amendments Act of 1977</td>
</tr>
</tbody>
</table>

Table 7: Traditional Approach for Particle Control

<table>
<thead>
<tr>
<th>Prevention of contaminant dispersion</th>
<th>Selection of “less toxic” materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eliminating the source of aerosols</td>
<td>Adjusting the process parameters</td>
</tr>
<tr>
<td></td>
<td>Housekeeping</td>
</tr>
<tr>
<td>Prevention of contaminant dispersion</td>
<td>Incorporation of Enclosures</td>
</tr>
<tr>
<td></td>
<td>Local exhaust ventilation</td>
</tr>
<tr>
<td></td>
<td>Maintenance of equipment</td>
</tr>
<tr>
<td></td>
<td>Education of employees</td>
</tr>
<tr>
<td>Protection of employees</td>
<td>Use of general ventilation</td>
</tr>
<tr>
<td></td>
<td>Personal protection equipment</td>
</tr>
</tbody>
</table>

Table 8: Possible Route of Exposure to Nanoparticles by Process and Type [HSE, 2004]

<table>
<thead>
<tr>
<th>Synthesis process</th>
<th>Particle formation</th>
<th>Inhalation risk</th>
<th>Dermal/ingestion risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas phase</td>
<td>In air</td>
<td>Leakage from reactor</td>
<td>Air contamination</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Product recovery</td>
<td>Handling of product</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Packaging</td>
<td>Cleaning/maintenance</td>
</tr>
<tr>
<td>Vapor phase</td>
<td>On substrate</td>
<td>Product recovery</td>
<td>Dry contamination</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Packaging</td>
<td>Handling of product</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cleaning/maintenance</td>
</tr>
<tr>
<td>Colloidal</td>
<td>Liquid suspension</td>
<td>Drying of product</td>
<td>Spillage of workplace</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Handling of product</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cleaning/maintenance</td>
</tr>
<tr>
<td>Attrition</td>
<td>Liquid suspension</td>
<td>Drying of product</td>
<td>Spillage</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Handling of product</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cleaning/maintenance</td>
</tr>
</tbody>
</table>
### Table 9: Type and Size of Bioaerosols [Hinds, 1999]

<table>
<thead>
<tr>
<th>Type of bioaerosol</th>
<th>Size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viruses</td>
<td>0.02-0.3</td>
</tr>
<tr>
<td>Bacteria</td>
<td>0.3-10</td>
</tr>
<tr>
<td>Fungal Spores</td>
<td>0.5-30</td>
</tr>
<tr>
<td>Pollen</td>
<td>10-100</td>
</tr>
</tbody>
</table>

### Table 10: Common Bioaerosols, Related Diseases and Typical Sources, Adapted from MacIntosh and Spengler [2000]

<table>
<thead>
<tr>
<th>Bioaerosol</th>
<th>Examples of diseases</th>
<th>Common sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pollen, spores, plant parts</td>
<td>Hay fever, allergic rhinoconjunctivitis, asthma, upper airway irritation</td>
<td>Plants, trees, grasses, ferns harvesting, cutting, shiploading</td>
</tr>
<tr>
<td>Fungi</td>
<td>Asthma, allergic diseases, infection, toxicosis, tumors</td>
<td>Plant material, skin, leather, oils; bird, bat and animal droppings; feathers, soil nutrients, glues, wool</td>
</tr>
<tr>
<td>Bacteria</td>
<td>Endotoxicosis, tuberculosis, pneumonia, respiratory and wound, infections, legionellosis, Q and pontiac fever</td>
<td>Humans, birds, and animals (e.g., saliva, blood, dental secretions, skin, vomit, urine, feces); water sprays and surf, humidifiers, hot tubs, pools, drinking water, cooling towers</td>
</tr>
<tr>
<td>Other allergen sources, arthropods, Vertebrates</td>
<td>Asthma, dermatitis, hypersensitivity, pneumonitic</td>
<td>Mite excreta, insect parts (cockroach, spiders, moths, midge), dander and saliva from cats, dogs, rabbits mice and rats, bird serum, farm animal dander</td>
</tr>
<tr>
<td>Viruses</td>
<td>Respiratory infections, colds, measles, mumps, hepatitis A, influenza, chicken pox, Hanta virus</td>
<td>Infected humans, animal excreta, insect vectors, protozoa</td>
</tr>
</tbody>
</table>