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By Beauregard Middaugh

Entitled Assessment of Cut-Off Saw Control Methods for Respirable Particulate and Crystalline Silica during Highway Construction Applications

For the degree of Master of Science

Is approved by the final examining committee:

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ASSESSMENT OF CUT-OFF SAW CONTROL METHODS FOR RESPIRABLE PARTICULATE AND CRYSTALLINE SILICA DURING HIGHWAY CONSTRUCTION APPLICATIONS

A Thesis

Submitted to the Faculty

of

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by

Beauregard Middaugh

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science

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West Lafayette, Indiana

I dedicate this thesis

to my future wife Sarah,

and to my entire family.

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ABSTRACT

Middaugh, Beauregard. M.S., Purdue University, August 2009. Assessment of Cut-off Saw Control Methods for Respirable Particulate and Crystalline Silica during Highway Construction Applications. Major Professor: Neil J. Zimmerman.

The purpose of the study was to investigate the dust reduction capabilities of currently available wet suppression and local exhaust ventilation (LEV) methods for gas-powered cut-off saws during the sawing of concrete curb on highway construction worksites. Dust control efficiency (e.g. concrete displacement rate) and weather conditions (e.g. wind) were also monitored to determine their effects on dust reduction. Personal filter cassette sampling revealed a median percent reduction in respirable (RSP) dust concentrations of 87.7 percent for the wet sawing method (WSM) and 87.0 percent for the LEV sawing method (LSM) compared to the traditional dry sawing method (DSM). A statistically significant difference ($p<0.001$) was seen between both the WSM and LSM compared to the DSM; however, no significant difference ($p=0.118$) was seen between the WSM and LSM. Based on estimated values of percent quartz, the RSP quartz reduction was approximately 84.4 percent for the WSM and 77.1 for the LSM. If workers are only exposed to RSP silica during the normal two hour cutting duration, the WSM and LSM would reduce RSP silica concentrations below the National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limit (REL).

Concrete displacement rates revealed a 63.1 percent reduction in productivity for the WSM and 40.0 percent reduction in productivity for the LSM compared to the DSM. After adjusting the traditional two hour cutting time for reductions in productivity, exposure was shown to increase by 33 percent for the WSM and 29 percent for the LSM. Although both the WSM and LSM were still below the Occupational Safety and Health Administration (OSHA) Permissible Exposure Limit (PEL), they were no longer below the NIOSH REL after this adjustment. A combination of wind speed and wind direction was also shown to be a significant predictor (p=0.02) of exposure during the DSM. Video exposure monitoring revealed the WSM was more consistent in reducing peak RSP dust concentrations, but overall reductions were still similar between the WSM and LSM. Based on these findings, standardized methods of quantifying dust control effectiveness should be implemented by manufacturers to ensure proper use and appropriate comparisons between engineering controls.

INTRODUCTION

General Study Introduction

Construction workers frequently utilize hand-held cut-off saws for cutting concrete and other hard materials. Without methods of dust control, concrete sawing produces elevated concentrations of ambient respirable (RSP) particulate, a portion of which is composed of crystalline silica (i.e. quartz) (Thorpe, Ritchie, Gibson, & Brown, 1999). Breathing elevated concentrations of RSP quartz is associated with multiple diseases and disorders including silicosis, a progressive lung fibrosis (NIOSH, 2002). Controlling quartz exposure within roadway construction has proved to be an arduous undertaking due to the mobile and unpredictable nature of the work. In 1996, the National Institute for Occupational Safety and Health (NIOSH) issued an alert requesting assistance to prevent silica exposure in construction, specifically during applications such as dry cutting concrete (NIOSH, 1996).

In 2002, NIOSH requested further research to improve and test the feasibility of two primary means of dust suppression: wet suppression methods and local exhaust ventilation (LEV) methods (NIOSH, 2002). A recent study of concrete surface grinders demonstrated that both wet and LEV methods of dust suppression are capable of reducing exposure to silica by greater than 97 percent (Akbar-Khanzadeh, et al., 2007). Regardless of capability, utilization and application of these methods in construction has not been as successful.

Although most cut-off saws are now manufactured with wet suppression attachments, there are significant drawbacks preventing widespread implementation: a water source is needed close by for operation, the worker often becomes wet and uncomfortable after use, and the water needed for operation can freeze during winter months. Conversely, very few cut-off saws are manufactured with LEV capabilities. Even fewer LEV systems are capable of operating without an electrical power source, a power source not commonly available to roadway workers using hand-held tools. Many of the current cut-off saw LEV systems consist of an add-on, aftermarket shroud connected to an electric vacuum as the exhaust source. Although these systems can be effective, many still cause unwanted obstruction of the work area or limit the range of saw motion.

For both wet methods and LEV methods, performance data or guidance on the proper operation of these controls is not usually provided by the manufacturer (Croteau, Guffey, Flanagan, & Seixas, 2002). Even in cases where the dust control system is operated correctly, the effectiveness of the control can be overestimated by the worker. As a result of these shortcomings, many construction contractors have chosen not use such controls (Nij, et al., 2003). Consequently, the latest National Occupational Research Agenda (NORA) has requested research to "Reduce silica exposures and future silicosis risks among construction workers by increasing the availability and use of silica dust controls and practices for tasks associated with important exposures" (NIOSH, 2007). Sawing of concrete is currently listed under these important exposures.

Statement of Research Purpose

The purpose of this study was to evaluate the dust reduction capabilities of cut-off saw dust control methods currently available and feasible for roadway construction use. In addition, the study was completed during actual field conditions to investigate dust control characteristics and outdoor conditions that may either reduce exposure control effectiveness or reduce utilization of dust controls.

Specific Research Objectives

The specific research objectives of the study were: 1) to develop an exposure baseline for RSP dust and RSP quartz during the use of three methods of concrete curb cutting: a dry sawing method (DSM), a wet sawing method (WSM), and a LEV sawing method (LSM), 2) to determine if current gas-powered LEV sawing technology is comparable in dust reduction capabilities to that of wet sawing methods compatible for roadway construction use, and 3) to characterize the effect of additional factors such as weather conditions and productivity that may help improve dust control design and use in roadway construction.

BACKGROUND

Crystalline Silica

Silicon dioxide (SiO_2), more commonly known as silica, can occur in two structural forms: crystalline and amorphous (NIOSH, 2002; Castranova, Vallyathan, & Wallace, 1996). The crystalline form of silica can assume multiple polymorphs including alpha quartz, cristobalite, and tridymite (NIOSH, 2002). Crystalline silica, specifically alpha quartz, is the most abundant mineral in the earth's crust, a universal component of sand, clay, and stone materials (OSHA, 2008; NIOSH, 2002; Castranova, Vallyathan, & Wallace, 1996).

History of Silica

Silica dust was one of first substances documented as an occupation-specific, disease-causing agent (OSHA, 2008). Dust-induced lung disease was reported over 2,000 years ago among miners in ancient Greece (OSHA, 2008; Castranova, Vallyathan, & Wallace, 1996). In 1556, Georgius Agricola published "De Re Metallica", which provides accurate accounts of working conditions which intensify disease and dust penetration into the lungs (Agricola, Translation by Hoover, & Hoover, 1950). By the 1800's, deceased individuals from many different occupations including stonecutters, masons, potters, and miners were found to have small deposits of sand-like material in their lungs (Castranova, Vallyathan, & Wallace, 1996). At the time, each occupation had its own disease taxonomy (i.e. potter's rot and stonecutter's lung); however, exposure to airborne silica particulate was the common factor (OSHA, 2008).

This disease outcome was later termed silicosis, and did not emerge as a major public health concern until the 1920's and 1930's in the United States (OSHA, 2008; Castranova, Vallyathan, & Wallace, 1996). Silicosis is an incurable and debilitating disease of the lungs, triggered by excessive inhalation of fine crystalline silica particulate (Valiante, Schill, Rosenman, & Socie, 2004; NIOSH, 2002). In 1936, the most infamous silica-related catastrophe in the United States occurred at the Hawk's Nest Tunnel in West Virginia (Castranova, Vallyathan, & Wallace, 1996). Almost 2,000 workers suffered acute respiratory damage or death in less than a two year period during its construction (Castranova, Vallyathan, & Wallace, 1996). Following the disaster, silica was perceived as an immediate occupational health threat, driving improvement in conditions and regulation in the mining industry (OSHA, 2008; Castranova, Vallyathan, & Wallace, 1996).

Exposure Guidelines

After silica exposure and acute disease in the mining industry diminished, attention to exposure regulation of silica within other trades also diminished until the institution of the Occupational Safety and Health Administration (OSHA) in 1970 (OSHA, 2008). OSHA formally adopted enforceable permissible exposure limits (PELs) for both respirable nuisance dust and RSP quartz dust in 1971 (OSHA, 2009; Castranova, Vallyathan, & Wallace, 1996). RSP is a term used to describe the size of dust particles. RSP particles are defined by OSHA as having an approximate median aerodynamic diameter (a function of particle diameter and density) of 3.5 micrometers (µm), and more recently by the American Conference of Governmental Industrial Hygienists (ACGIH) as having a median aerodynamic diameter of 4 µm (ACGIH, 2009; OSHA, 2008). Contraction of silicosis is dependent on the dose of particles reaching the alveolar region of the lungs; therefore, exposure limits are designed to prevent respiration of these small particles into the deep reaches of the lung (OSHA, 2008).

In the 1970's, OSHA PELs were designed for the collection and analytical techniques used at the time, which involved the counting of individual particles using a light-field microscope (OSHA, 2009). Therefore, the eight hour time-weighted average (TWA) PEL was expressed in millions of particles per cubic foot (mppcf) (OSHA, 1997). The particle counting method is now outdated, with new methods utilizing particulate mass as a measure of exposure (OSHA, 2009; OSHA, 2008). The OSHA General Industry (OSHA 29 CFR 1910) exposure limits have accounted for this, adopting PELs in milligrams per cubic meter (mg/m^3) of air sampled; however, the OSHA Construction Industry (OSHA 29 CFR 1926) exposure limits for silica dust are still expressed in mppcf (OSHA, 2006; OSHA, 1997). To complicate matters, general industry and construction industry exposure limits do not always coincide. Table 1 provides a summary of the current OSHA PELs for RSP dust with and without quartz.

Table 1. Existing OSHA 8-hour TWA PELs (OSHA, 2006; OSHA, 1997).

General		Industry	Construction	
	OSHA 29 CFR 1910		OSHA 29 CFR 1926	
Substance mppcf		mg/m^3	mppcf mg/	m^3
RSP Dust (<1% SiO_2)[A]	15 5		50	15
RSP Dust (>1% SiO_2)	$=\frac{250}{\%SiO_2+5}$	$=\frac{10}{\%SiO_2+2}$	$=\frac{250}{\%SiO_2+5}$	-

Notes: %SiO_2 refers to the percent quartz within the total RSP dust fraction.
[A] Defined as inert or nuisance dust.

In the case of the regulation of RSP dust with greater than one percent quartz, simple conversions cannot be made from mg/m^3 to mppcf for the construction exposure limit; therefore, OSHA accepted a recommended conversion factor developed by NIOSH (OSHA, 2008). NIOSH proposed that 0.1 mg/m^3 of RSP dust was approximately equivalent to 1 mppcf (Occupational Safety and Health Administration, 2008). Based on this accepted recommendation, the resulting construction PELs for RSP dust with and without quartz are less stringent than general industry regulations (OSHA, 2009).

In addition to regulatory standards, other exposure guidelines have been suggested by OSHA, NIOSH and the ACGIH. Most recently, guidance from OSHA suggested a straightforward limit of 0.1 mg/m^3 be used as a benchmark for RSP quartz when comparing dust control measures in construction (OSHA, 2009). NIOSH suggests a more stringent recommended exposure limit (REL) for quartz: 0.05 mg/m^3 for a ten hour TWA (NIOSH, 2005). ACGIH, a non-governmental recommendatory organization, suggests a threshold limit value (TLV) of 3 mg/m^3 for RSP inert dust and 0.025 mg/m^3 for RSP crystalline silica for an 8- hour TWA (ACGIH, 2009). The current NIOSH REL and ACGIH TLV are limited by the accuracy of methods used to measure small airborne concentrations of silica; therefore, until new methods are developed, these current exposure limits will remain fixed (NIOSH, 2002). Unfortunately, there is significant epidemiological evidence that these levels may not be sufficiently protective for preventing silicosis (NIOSH, 2002).

Occupational Exposure and Risk

RSP crystalline silica is one of history's most persistent and well characterized occupational health hazards (Steenland K. , 2005). Traditionally, inhalation of RSP silica was singularly thought of as a disease-causing agent for the lung disease, silicosis; however, in recent decades, it has been identified with multiple health conditions and diseases. In addition to silicosis, crystalline silica has been implicated as a potential causal agent or risk factor for lung cancer, tuberculosis, renal disease, and various autoimmune disorders (NIOSH, 2002; Valiante, Schill, Rosenman, & Socie, 2004). However, regardless of the disease outcome, avoiding silica exposure is the most obvious resolution.

Silicosis

Silicosis is classified into three major categories defined by the latency period in which the disease develops following exposure: acute, accelerated, and chronic (NIOSH, 1996). Acute silicosis develops within a few weeks to a few years after exposure, while accelerated silicosis has a latency of five to ten years (NIOSH, 1996). Both emerge as a result of inhalation to varying high concentrations of RSP crystalline silica. Today, acute and accelerated forms of silicosis are uncommon, but are still associated with very high mortality rates (Mannetje, et al., 2002; Greaves, 2000). Chronic silicosis is the most prevalent form of the disease, with latency often greater than twenty years (OSHA, 2008; Valiante, Schill, Rosenman, & Socie, 2004).

Chronic silicosis, a form of pneumoconiosis, results from long-term inhalation of relatively low concentrations of RSP-size crystalline silica particles (OSHA, 2008; Greaves, 2000; NIOSH, 2002). Deposition of these small particles in the lung leads to the formation of fibrotic nodules (Mannetje, et al., 2002; OSHA, 2008). Initially, silicotics experience little or no respiratory symptoms; however, as fibrosis spreads, symptoms such as cough, shortness of breath, and wheezing become more serious (Mannetje, et al., 2002; Valiante, Schill, Rosenman, & Socie, 2004). Disease progression is marked by increasingly larger and coalesced nodules, eventually leading to progressive massive fibrosis (Greaves, 2000). Consequently, fibrosis may continue after silica exposure has ceased, and in its final stages, can lead to respiratory failure and death (Greaves, 2000; OSHA, 2008).

Despite the well-known association between crystalline silica exposure and chronic silicosis, the causal pathways leading to the disease are still being disputed (Greaves, 2000; NIOSH, 2002). Altrec-Williams et al. (2002) suggests that the pathogenic nature of silica simply rests with its ability to persist in the alveolar region of the lung for many years. Regardless of the pathogenic processes, many epidemiological studies have assessed the risk of silica-related diseases based on cumulative exposure data (NIOSH, 2002).

In 2002, NIOSH concluded that previous epidemiological studies demonstrate a significant risk of developing radiographic, identifiable silicosis over a 45 year working lifetime at concentrations as low as the NIOSH REL (NIOSH, 2002). NIOSH estimated that the probability of developing the disease was at least 1 in 100 at these concentrations (NIOSH, 2002). In reviews, specifically of epidemiological studies with follow-up after employment, Greaves (2000) and Steenland (2005) independently estimated that the risk of developing radiographic silicosis at a RSP quartz concentration of 0.1 mg/m^3 over a working lifetime was between 40 to 90 percent and 47 to 77 percent respectively. Both estimates suggest that the current regulatory standards are insufficient for preventing chronic silicosis. In a pooled analysis of six cohorts, Mannetje et al. (2002) estimated that the risk of direct mortality from silicosis over a working lifetime of exposure to a concentration of 0.1 mg/m^3 is approximately 1.3 percent.

Lung Cancer

In 1997, the International Agency for Research on Cancer (IARC) classified RSP quartz as a Group 1, known human carcinogen (IARC, 1997). Like silicosis, the cellular pathways leading to the silica-related lung cancer are still being debated, sparking continued toxicological and epidemiological research (NIOSH, 2002). Recent epidemiological meta and pooled analyses (i.e. ones accounting for bias and limiting inclusion to studies that account for confounders such as smoking and exposure to other carcinogens) have investigated the relationship between lifetime exposure to silica, silicosis, and lung cancer.

In a meta-analysis of 17 cohort and 13 case-control studies, Kurihara and Wada (2004) found a mildly significant association between lung cancer and individuals exposed to silica over a working lifetime that may or may not have silicosis: pooled relative risk of 1.32 (95% Confidence Interval (CI) 1.24-1.41). A meta-analysis of sixteen studies examining the relationship between lung cancer and silicosis yielded a much more significant association: pooled relative risk 2.37 (95% CI 1.98-2.84)

(Kurihara & Wada, 2004). This association was also confirmed by a meta-analysis of 31 studies by Lacasse et al. (2005). Conversely, a non-significant pooled relative risk of 0.96 (95% CI .81-1.15) was found when the association between lung cancer and non-silicotic subjects was investigated (Kurihara & Wada, 2004). Evidence from these meta-analyses supports the theory that silica may induce lung cancer indirectly, with silicosis acting as the risk factor for lung cancer; however, the strong correlation between lifetime silica exposure and silicosis makes this hypothesis difficult to prove (Kurihara & Wada, 2004; Checkoway & Franzblau, 2000).

Kurihara and Wada (2004) also addressed the effect of smoking on development of lung cancer among silicotics. A meta-analysis of eight studies revealed a pooled relative risk of 4.47 (95% CI, 3.17-6.30) for smokers, and a pooled relative risk of 2.24 (95% CI, 1.46-3.43) for non-smokers, supporting the theory that silicotics with a history of smoking are much more likely to develop lung cancer (Kurihara & Wada, 2004).

Other Related Health Effects

Inherently, inhalation of RSP crystalline silica is harmful to the respiratory system, causing other conditions such as bronchitis and emphysema. In addition, silicotics are predisposed to the contraction of severe respiratory infections such as tuberculosis (NIOSH, 2002; Valiante, Schill, Rosenman, & Socie, 2004). Furthermore, studies have also investigated the relationship between silica and autoimmune disorders, demonstrating that effects of exposure are not confined to the lungs. A multitude of case reports have identified disorders such as rheumatoid arthritis, scleroderma, systemic lupus, and renal disease among individuals chronically exposed to silica (Parks, Conrad, & Cooper, 1999).

In a pooled analysis of three cohorts, Steenland et al. (2002) revealed a weak, non-significant excess lifetime risk of 1.8 (95% CI .8-9.7) for renal disease mortality at a RSP quartz concentration of 0.1 mg/m^3 over a working lifetime. Steenland (2005) later reported a highly significant excess lifetime risk of 5.1 (95% CI 3.3-7.3) for end-stage renal disease itself at the same exposure levels. The latter study offers highly significant evidence of multi-disease risk when exposed to crystalline silica near the OSHA PEL for a working lifetime (Steenland K. , 2005)

Construction

In 1996, NIOSH issued a health alert requesting assistance in reducing silica-related deaths and illness among construction workers (NIOSH, 1996). According to a 2002 surveillance report by NIOSH, silica exposures obtained during regulatory inspections between 1990 and 1999 were higher for the construction industry than any other industry classification (NIOSH, 2003). For the same time period, census data indicated that the construction industry was recorded most frequently on death certificates of silicotics (NIOSH, 2003). The universal use and disturbance of materials containing crystalline silica such as clay, asphalt, and concrete leads to widespread exposure across the industry (NIOSH, 2002).

According to the U.S. Bureau of Labor Statistics (BLS), almost 7.7 million individuals are employed in the construction industry (United States Department of Labor, 2006). Construction is often organized along trade lines, which involve similar skill sets such as in building construction or heavy and civil engineering construction (Woskie, Kalil, Bello, & Virji, 2002; United States Department of Labor, 2006). Within the heavy and civil engineering trades, there are 983,000 workers employed in the U.S. (United States Department of Labor, 2006). Based on an ACGIH compilation project of silica exposure in the construction industry, the geometric mean (GM) quartz exposure was .13 $mg/m^3$for highway and bridge construction, far over the REL and TLV for RSP silica (Flanagan M. , Seixas, Becker, Takacs, & Camp, 2006).

In addition to stratification by trade, workers are designated occupational titles based on the specific tasks associated with their vocation (e.g. construction laborer). Within highway, street, and bridge construction, construction laborers make up the largest percentage of the workforce (United States Department of Labor, 2008). These workers perform the majority of “hand” work on the jobsite, utilizing hand tools and power tools such as shovels, jack-hammers, and hand-held saws to execute precision tasks beyond the capabilities of large equipment. Other, less well-represented occupations in roadway construction, such as concrete finishers, also complete related tasks.

Nature of Roadway Work

Crystalline silica, specifically alpha-quartz, is a principal health hazard within the roadway construction industry (Flanagan M. , Seixas, Majar, Camp, & Morgan, 2003). Quartz exposure can occur during almost every step of road construction: from the excavation and placement of underground drains until the final sweep of the roadway after its completion (Lumens & Spee, 2001). In addition to road construction, new methods of road repair and maintenance also present significant risk for exposure.

Because roadway construction is a mobile industry, worksites change frequently and worker turnover rates are high (Flanagan M. , Seixas, Majar, Camp, & Morgan, 2003). Individuals composing a working crew can change on a daily basis as the distance between consecutive worksites is not always convenient or economical for workers. Constantly changing worksites and outdoor conditions yield large inconsistencies in working environments. Occupational classifications, like the construction laborer, also perform a diverse assortment of tasks during a work day. The duration of these work tasks may vary considerably based on the construction phase and requirements of the jobsite. Historically, these variables have made roadway construction exposures very difficult to quantify (Flanagan M. , Seixas, Majar, Camp, & Morgan, 2003; Woskie, Kalil, Bello, & Virji, 2002).

Cutting, grinding, drilling and chipping activities yield some of the highest silica exposures in construction (Flanagan M. , Seixas, Becker, Takacs, & Camp, 2006). For roadway construction, these activities are primarily used to manipulate silica-containing materials such as concrete and asphalt, concrete being the more versatile of the two materials. Concrete can be used in conjunction with steel reinforcement for bridge, runoff, sewer, and road paving applications as well as in free form for sidewalk and curb applications. The composition of concrete can vary among both application and region. Strength, speed of cure, density, and workability requirements of jobsite plans often define the exact "add mixture" of substances used within the concrete, and thus the percentage of crystalline silica within the concrete.

The primary components of concrete are aggregates (35-90%), Portland cement (10-20%), fly ash (0-5%), slag cement (0-10%), and reinforcing additives (0-2%), all of which may contain varying amounts of crystalline silica (Shepherd, Woskie, & Ellenbecker, 2009; Linch, 2002; Flanagan M. , Seixas, Becker, Takacs, & Camp, 2006). The amount of crystalline silica within these materials is often defined by geographic availability (e.g. surrounding geological characteristics). A regional, concrete ready mix supplier estimated that the percent crystalline silica within concrete ranges between 3 to10 percent in the area of the study, depending on the "add mixture" (Thapr, 2007). It is also important to note that even though concrete mixtures are approximately homogeneous in new material, the continued maintenance of concrete often leads to varying quantities of crystalline silica throughout the roadway infrastructure. Maintenance, demolition, and removal of existing roadway structures and materials can often lead to highly unpredictable levels of silica content.

General Dust Control in Construction

The clearest way to prevent silica-related disease is to decrease crystalline silica exposure to less harmful levels within industry (OSHA, 2008). Industrial hygiene practices specify the order in which control systems should be prioritized: 1) engineering control, 2) administrative control, and 3) personal protective equipment (AIHA, 2003). It may be necessary, however, to use multiple control methods to reduce exposures to an acceptable level (Nij, et al., 2003).

Engineering Controls

Engineering controls include: 1) substitution to a less hazardous material, 2) isolation of the worker from the exposure, and 3) ventilation or source management (AIHA, 2003). Substitution of materials with lower silica content, especially in the case of concrete, is not feasible because of the overall need for the naturally abundant, silica-containing materials used as its constituents (Croteau, Guffey, Flanagan, & Seixas, 2002; Lahiri, Levenstein, Nelson, & Rosenberg, 2005). Hand and power tools must also remain: 1) small and easily movable by an individual, 2) adaptable for use in many environments, and 3) capable of precise and unsystematic manipulations of material. These criteria eliminate almost all options for isolation and enclosure during these handheld operations.

The most common engineering controls used for dust suppression in the construction industry are local exhaust ventilation (LEV) and wet suppression methods (Nij, et al., 2003). Nij et al. (2003) estimated that 26 percent of concrete workers use wet suppression methods, with only 11 percent using LEV methods. Based on these estimates, more than 63 percent of concrete workers are not using any engineering controls for dust suppression. A principal reason for the lack of use may relate directly to portability and operational capacity in field conditions. Particularly in the case of hand-held tools used in roadway construction, electrical and water sources are not readily available. In addition, there is still appreciable uncertainty in the degree of dust control that these methods provide, because manufacturers do not usually provide performance data related to dust reduction (Thorpe, Ritchie, Gibson, & Brown, 1999).

Wet Suppression Methods

According to OSHA, wet suppression methods are the most effective and consistent means for reducing silica dust levels (OSHA, 2009). There are two primary practices used in roadway construction to supply water to the dust source: a constant flow source (e.g. tanker truck with water pump) and a variable flow source (e.g.

pressurized spray canister). Constant flow sources are not readily available to hand-held tool operators within a roadway work zone. Constant flow sources usually provide higher, steadier flow in comparison to that of pressurized spray canisters. Therefore, it is possible that studies with constant flow sources may slightly overestimate the effectiveness of dust control methods for a roadway setting.

In a study of hand-held grinders by Akbar-Khanzadeh et al. (2007), a RSP crystalline silica reduction of 98 percent was found at a constant water flow rate of 3 liters per minute (LPM). A study of hand-held cut-off saws by Thorpe et al. (1999) also showed a 98 percent RSP dust reduction for a similar constant flow source (e.g. garden hose). Thorpe et al. (1999) also examined the use of a portable pressurized water source: using an 8.5 liter pressurized hand sprayer. A 92.5 percent RSP dust reduction was found for the portable water source; however, the canister required multiple pumps during the sampling period to sustain adequate flow to the source (Thorpe, Ritchie, Gibson, & Brown, 1999).

Additionally, Thorpe et al. (2009) investigated various water flow rates to determine the amount of flow necessary to sustain adequate dust control. In a laboratory setting it was determined that a water flow rate of 0.5 LPM resulted in considerable dust reduction; however, there appeared to be no marked improvement at water flow rates above 1 LPM (Thorpe, Ritchie, Gibson, & Brown, 1999). It was also noted that small pressurized canisters cannot sustain a flow rate above 0.5 LPM unless they are pumped throughout the sawing period (Thorpe, Ritchie, Gibson, & Brown, 1999). In addition to these findings, there is very limited published data on the use of portable, pressurized canisters; therefore, there may be a large variation in the flow rates necessary for other control designs and applications.

Although wet suppression techniques have been demonstrated as an effective dust control, there are a wide variety of disadvantages associated with the use of water. A significant amount of water runoff can be created during these operations. In the case of roadway construction, concrete slurry material from concrete can overflow onto private residences, discolor nearby materials such as black asphalt, and cause slipping and electrocution hazards for workers (Croteau, Flanagan, Camp, & Seixas, 2004).

Wet suppression methods also create significant spray and splatter. As a result, workers are often uncomfortable and wet for extended periods of time, and can suffer from abrasive and caustic burns from grainy concrete slurry. During colder months, these conditions can also lead to potential hypothermia (Croteau, Guffey, Flanagan, & Seixas, 2002). In addition, most water suppression systems are simply not usable during freezing temperatures. This is significant because in northern regions of the United States, wet suppression methods cannot be used for as many as four months out of the year for outdoor applications.

LEV Methods

According to OSHA, LEV methods can be an effective means for reducing dust; however, they are generally less consistent than wet methods (OSHA, 2009). Most hand-held LEV systems consist of a partial or total shroud enclosure with a separate vacuum source. In a study of hand-held concrete grinders by Akbar-Khanzadeh (2007), a RSP crystalline silica reduction of 99.8 percent was found for the LEV method when compared to the uncontrolled method. Furthermore, no significant difference ($p=0.999$) was found between the dust reductions of the wet and LEV methods investigated. Variation in airborne concentrations for the LEV method was also lower than that of the wet methods (Akbar-Khanzadeh, et al., 2007).

Evidence presented by Akbar-Khanzadeh (2007) supports the theory that LEV methods can be as effective as wet suppression and even more consistent than wet suppression. However, multiple studies have shown that this is entirely contingent upon the effectiveness of the collection design. Nash and Williams (2002) evaluated the use of LEV during tuck pointing, and initially found only a 37 to 47 percent reduction in silica exposure; however, after small alterations by the manufacturer to the collection equipment, silica reduction was increased to 94 percent.

Similar results have also been noted among other construction applications. Croteau et al. (2002) reported that no dust reduction was seen when LEV was used in conjunction with a vacuum port on the side of the back guard of a cut-off saw. Conversely, Thorpe et al. (1999) found a 90 percent dust reduction when a custom guard was made for a cut-off saw to ensure maximum containment. The effectiveness of a shroud design is dependent on many factors including shroud configuration and its distance from the farthest point of release (X), the ejection velocity of the particles (v_p), the flow the of the vacuum source (Q), and the capture velocity (v_c) at point X (Croteau, Guffey, Flanagan, & Seixas, 2002). To achieve adequate capture velocity (v_c) and containment around the saw blade, an adequate exhaust system must be implemented.

Electrical power, even by generator, is not commonly available or feasible for use with hand-held tools, and based on a review of current LEV dust control studies, LEV was provided almost exclusively by electrically-powered, vacuum sources (Akbar-Khanzadeh, et al., 2007; Shepherd, Woskie, & Ellenbecker, 2009; Croteau, Guffey, Flanagan, & Seixas, 2002; Croteau, Flanagan, Camp, & Seixas, 2004; Thorpe, Ritchie, Gibson, & Brown, 1999). For these vacuum systems, OSHA recommends the use of high-efficiency particulate (HEPA) filters in conjunction with a pre-filter or cyclonic separator to enhance collection results (OSHA, 2009). Published data could not be identified documenting exposure reduction differences due to filter selection for outdoor applications.

For surface grinders, ACGIH recommends an exhaust flow rate of at least 25-60 cubic feet per minute (cfm) per inch of grinder diameter (ACGIH, 2004). In the study by Akbar-Khanzadeh et al. (2007), approximately 17 cfm per inch of grinder diameter, slightly below the ACGIH recommendation, yielded almost a 99.8 percent reduction. Nonetheless, specific ACGIH recommendations for other construction applications are limited. Croteau et al. (2002) suggests that an exhaust flow of 75 cfm provides an 80-95 percent dust reduction for angle grinders, surface grinders, and stationary masonry saws; however, the higher blade velocity and larger distance to the source for hand-held cut-off saws resulted in no reduction. A later study by Flynn and Susi (2003) suggested that 20 cfm per inch diameter of a saw blade should be used with hand-held cut-offs.

Croteau et al. (2002) also suggests that flow can be decreased by almost 20 percent over a fifteen minute working period due to HEPA-type filter overload. Therefore, filter cleaning and maintenance may be required frequently to ensure proper function. Other noted drawbacks include reduced functionality due to the shroud configuration (Nash & Williams, 2000; NIOSH, 2002). Regardless of these drawbacks, the effectiveness of LEV is encouraging, but evidence for applicability within the roadway setting is limited due to lack of research on non-electrical vacuum systems.

Administrative Controls

Administrative control is a broad term used to describe action taken by management to reduce exposure, including training for proper use and maintenance of equipment (AIHA, 2003). Job rotation is also a common exposure reduction method used by management to prevent exposure above regulatory limits; however, dividing exposure duration between two workers not only decreases risk of one worker, but it increases the risk of another worker. When exposure is initially above the OSHA PEL for a single worker, dividing the work equally between two workers will still result in exposures above the NIOSH REL for both workers. Therefore, job rotation alone proves to be an ineffective solution for many construction tasks.

Personal Protective Equipment

Lastly, respiratory protection, a form of personal protective equipment, is the most widely used preventive dust measure (Nij, et al., 2003). According to Nij et al. (2003), 42 percent of concrete workers wear varying levels of respiratory protection. In an earlier study by Lumens and Spee (2001), respiratory protection was seen on only 30 percent of jobsites, the most prevalent forms being paper dust masks (i.e. comfort masks) and half-mask respirators (Lumens & Spee, 2001; Rappaport, Goldberg, Susi, & Herrick, 2003).

Each respirator type is given an Assigned Protection Factor (APF) by NIOSH (AIHA, 2003). Under optimal conditions, a maximum use concentration (MUC) can be calculated for each exposure guideline. The MUC defines the maximum concentration in which the respirator is effective for reducing exposure to below the corresponding exposure guideline (See Equation 1). A half-mask respirator has an APF of ten, while paper dust masks are not considered respirators and do not have a true APF (NIOSH, 2005). However, Lahiri et al. (2005) suggests that paper dust masks reduce exposure by 30 percent, which is approximately equivalent to a protection factor of 1.4. Given these protection factors, MUCs can be calculated for various forms of respiratory protection (See Appendix A, Table A-1).

$$MUC\ (mg/m^3) = [APF]\ X [\ Exposure\ Guideline\ (mg/m^3)] \qquad (1)$$

Regardless of exposures above the theoretical MUC, working conditions in construction can lead to less than optimal conditions for respiratory use. Assessing respiratory protection by only its APF can lead to a false sense of safety. The effectiveness of respirator protection is often a byproduct of the efficacy of management training and control (AIHA, 2003). Implementation of a proper respiratory protection program (RPP) can decrease the risk of misuse or potential health complications; however, the mobility of construction operations and the high turnover rates do not foster widespread adoption (Nash & Williams, 2000; AIHA, 2003; Flanagan M. , Seixas, Majar, Camp, & Morgan, 2003; Lahiri, Levenstein, Nelson, & Rosenberg, 2005). Components of a RPP, such as respirator fit testing and respirator maintenance training are vital to ensuring optimal performance.

Even with a proper RPP, use within the construction industry comes with significant drawbacks. Roadway workers often perform heavy physical labor and are exposed to a wide range of weather conditions, including high temperature and humidity.

Even among fit individuals, this can still result in negative physiological effects such as heat exhaustion (Shepherd, Woskie, & Ellenbecker, 2009). There is also a level of inconvenience and risk involved with the donning of this protection. For example, half-mask dust respirators often cause safety glasses to fog up, resulting in reduced vision and impeded work. Despite these disadvantages, until widespread use of engineering controls are accepted, workers will continue to rely heavily on this form of protection (Nash & Williams, 2000).

Other Influential Dust Control Factors

Under normal outdoor operating conditions, a variety of factors can affect a worker's exposure for the same dust control system. Three main sources for these influences are: 1) the worker, 2) the task, and 3) the environment. A worker's technique, posture, working speed, and endurance can all result in variations of exposure. The activity also defines other influential factors such as duration, how the work is applied, frequency, where it is performed, and the source of exposure (e.g. asphalt or concrete) (Croteau, Guffey, Flanagan, & Seixas, 2002). In addition, especially for outdoor settings, environmental conditions such as weather and surrounding objects can have a profound effect on exposure as well (Thorpe, Ritchie, Gibson, & Brown, 1999).

Temperature, relative humidity, and wind direction potentially affect exposure because of their ability to influence particle motion. Changes in temperature can affect particle motion by changing the viscosity of air, and changes in relative humidity can affect the adhesion of particles to surfaces and each other; however, these forces are often negligible to those forces created by wind under normal outdoor conditions (Hinds, 1999; Akbar-Khanzadeh & Brillhart, 2002). Thorpe et al. (1999) reported that certain wind directions and wind speeds can cause a worker to be enveloped in a cloud of dust.

In a study by Akbar-Khanzadeh et al. (2002) of concrete surface grinding, there were found to be no significant differences in concentrations based on if the worker was categorized as upwind or downwind; however, there were significant differences

($p<0.01$) in the concentrations of RSP dust when wind speeds were greater than 1 meter per second (m/s) compared to wind speeds below 1 m/s (Akbar-Khanzadeh & Brillhart, 2002). The concentration of RSP dust was also significantly correlated with wind velocity alone for grinders with and without LEV dust controls (Akbar-Khanzadeh & Brillhart, 2002). This study provides evidence that wind speed alone is a predictor for exposure; however, concrete surface grinding creates disperse ejection of particles around the worker. In cases like hand-held cut-off saws, dust ejection is directed behind the worker. As mentioned by Thorpe (1999), wind direction may be a more significant factor for these applications.

Hand-held Cut-off Saws

Hand-held cut-off saws are used in almost every facet of construction and demolition to perform a very wide variety of tasks. Cut-off saws are operated by a single individual and are found in electric, pneumatic and gas-powered forms; however, the gas-powered form is used almost exclusively during roadway construction. They are used to cut very hard surfaces including materials such as metals, stone, concrete, asphalt, etc. and are a much more versatile tool than their larger counterparts, the walk-behind saw. An adjustable guard allows the saw to cut flat and irregular surfaces with both vertical and horizontal planes. The saws are often used with diamond embedded blades to cut concrete materials during construction including barrier divider walls, bridge sidewalls, sewer inlet boxes, sound barrier walls, road surfaces, sidewalk surfaces, bridge decks, and curb. Depending on the application, sawing can be performed for a whole working day or for only a few minutes a day.

Concrete Curb Cutting

Concrete sawing is performed for two primary reasons: 1) to remove unwanted material and 2) to create expansion joints. Expansion joints are created to prevent uncontrolled cracking throughout the concrete. During hardening and fluctuation in temperature, expansion joints allow the concrete to expand and contract at defined intervals. Concrete curb paving is a common application that requires these expansion joints. To create these expansion joints, a cut-off saw is used to cut grooves at defined depths for intervals of five to ten feet.

Long stretches of curb are usually placed by a curb paving machine (See Figure 1). The curb paving machine places the concrete using a slipping form. As the paver continues along the roadway, the paver deposits concrete behind the machine in the shape of the form, the desired curb shape. Chair back and extruded are names that refer to different form types. After the curb is placed, a curing compound is sprayed on the surface, and it is allowed to harden for approximately six to eighteen hours, depending on the weather conditions. When the concrete is sufficiently hardened, the concrete joints are then sawed into the top surface of the curb at variable depths. Expansion joint sawing normally occurs for approximately 1 to 2 hours a working day. Workers will then perform other concrete-related activities with potential for silica exposure.

Figure 1. Concrete Curb Paving Operation.

Cut-Off Saw Dust Control Studies

Thorpe et al. (1999) stated that cut-off saws were generally used without dust control, and ten years later this statement still holds true in roadway construction. Even though multiple cut-off saw manufacturers produce a water attachment built onto to the saw; water suppression is not frequently used. A discussion with many regional contractors found that LEV methods were not used among any of the contractors (ICA, 2007). To support these findings, among the 65 hand-held saw personal air samples submitted to the ACGIH compilation project, Flannagan et al. (2006) noted a geometric mean (GM) concentration of RSP crystalline silica of 0.13 mg/m3, exceeding the OSHA General Industry PEL. Therefore, this provides additional evidence that current dust control methods are inadequate or being under-utilized.

A few key points can be derived from two prior studies that investigated both uncontrolled (i.e. no dust control) and a dust control method for cut-off saws (See Appendix B, Table B-1). Thorpe et al. (1999) has shown that water is an effective control method for cut-off saws, and a pressurized water pump can be an effective supply system for wet suppression. The portability of the pressurized pump system is a key component needed for applicability in road construction. Thorpe et al. (1999) also demonstrated that LEV can be an effective dust control system for cut-off saws; however, Croteau et al. (2002) identified the pitfalls of poorly designed systems. Both studies used electrically-powered vacuum systems, a dust control method not feasible during roadway construction.

MATERIALS AND METHODS

General Research Design

Personal air monitoring was completed during the sawing of concrete expansion joints in both chair back and extruded curb along roadway and parking lot systems (See Figure 2). Curb cutting was selected because it allows for reproducible cuts along a multi-faceted surface, rigorously testing the functionality of particulate control methods. Sawing was performed by a professional volunteer using one of three saw methods. All curb had been freshly placed, and was sawed within 18 hours of placement.

Figure 2. Chair Back Curb (on left) and Extruded Curb (on right).

Saw Methods

Three different sawing methods were investigated during the study: 1) the traditional dry sawing method, 2) a wet sawing method, and 3) a local exhaust ventilation (LEV) sawing method. For all sawing methods, a 14 inch diamond cutting blade (model Green D307P; Archer), a saw blade specifically designed for cutting green or freshly hardened concrete, was employed. The latter two sawing methods, wet and LEV, utilized particulate control technology currently available to contractors, whereas the dry sawing method acted as a control for normal practices. All particulate control technology needed to be easily transportable in a small compact vehicle and completely operational without external power or water sources during a sampling period. The reason for these constraints was to mirror environments frequently encountered by workers in this application.

Dry Sawing Method

The dry sawing method (DSM) was performed using a cut-off saw (model TS 420; STIHL) with a 14 inch cutting wheel (See Figure 3). The cut-off saw weighs approximately 21.2 lbs and operates with a maximum spindle rotation speed of 5,350 rpm (STIHL, 2008). Dust production is not modified for the DSM; therefore, the DSM is considered a baseline for the other particulate suppression methods.

Figure 3. Cut-off Saw Used with DSM.

Wet Sawing Method

The wet sawing method (WSM) utilized the same cut-off saw as the DSM; however, the manufacturer's integrated water attachment system was employed. The attachment was connected with a quick disconnect coupler to approximately 8 feet of 0.25 inch diameter rubber tubing, and then sequentially attached to a 3.5 gallon industrial pressurized sprayer (model 1949; Chapin). The sprayer was then mounted directly to a two-wheel collapsible mobile cart (See Figure 4).

Figure 4. Cut-off Saw with Water Supply System for WSM.

To maintain adequate water flow to the saw, the tank handle is manually pumped by the operator during the sawing process. If this is not done consistently, the pressure within the canister becomes insufficient for supplying water to the saw (Thorpe, Ritchie, Gibson, & Brown, 1999). The time, quantity, and speed of the manual hand pumps affect the water flow to the saw. Because of unavoidable operator and field condition variability, these variables were not specified during the study. Due to the nature of the work and water supply system, water flow was determined by the operator's discretion and experience.

As mentioned previously, water flow rates above 0.5 LPM were noted to have an appreciable effect on reducing dust, but water flow above 1 LPM was not considerably more effective (Thorpe, Ritchie, Gibson, & Brown, 1999). Therefore, the water attachment valve was used to adjust the stream of water reaching the saw blade during preliminary testing. Adjustments to the valve allowed the 3.5 gallon tank to be emptied over an approximately 16 minute span of continuous sawing. During the preliminary testing, the valve was opened three quarters of the way and the operator stopped twice to pump the canister five times. An estimated mean water flow of 0.22 gallons per minute (0.83 LPM) was estimated for the system at these settings. Based on this preliminary testing, the attachment valve was adjusted to the three-quarters open setting for each sampling period.

Local Exhaust Ventilation Sawing Method

The LEV sawing method (LSM) utilized a cut-off saw (model HC510-DV; RedMax) with 14 inch cutting wheel (See Figure 5). A different saw was employed for the LSM because currently available saws do not come adapted for both water and LEV use. The saw weighs approximately 28.9 pounds and operates with a maximum spindle rotation speed of 3,100 rpm (RedMax, 2002), which was slower than the saw used for the other methods due to the power needed to operate the LEV system. The slow spindle speed will likely result in decreased v_p, which in theory, would increase worker exposure if the LEV saw could be operated similar to the DSM; therefore, a slow spindle speed itself is an unlikely source of dust reduction bias.

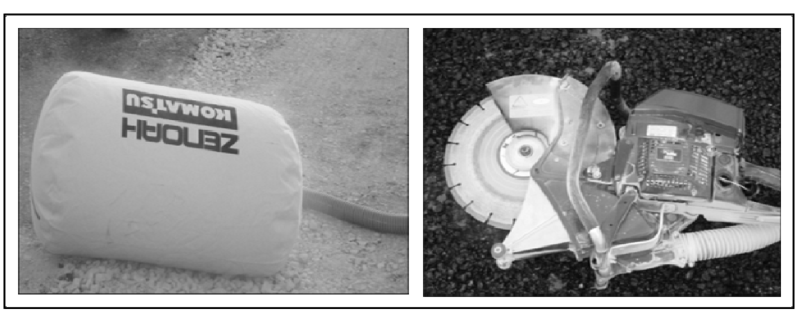

Figure 5. Dust Collection Bag (on left) and Cut-off Saw (on right) for LSM.

The dust collection system consists of a spring-loaded, movable guard that diverts dust into a belt driven impellor system located below the saw. The impellor draws the dust into a two inch flexible vacuum hose connected to an approximately five gallon filtering dust collection bag. The flow of the LEV system and the collection efficiency of the dust bag were not specified or available from the manufacturer; therefore, the flow rate was measured experimentally using a thermal anemometer. The area of the face was estimated to be approximately 8 in^2, and an average of three centerline measurements at full throttle was approximately 1890 feet per minute (fpm). The flow rate was subsequently determined to be approximately 105 cfm; however, it is important to note that the blade had to be removed and the spring-loaded guard pulled back to make the measurement, and only a rough measurement of the true face area could be made. Full traverse velocity measurements of the face area were also not possible; therefore, multiple measurements were taken at the center of the face area.

Recruitment and Protection of Human Subjects

The research protocol was approved by the Institutional Review Board for Human Subjects Research at Purdue University. The targeted enrollment population included Laborer's Union members required to perform cut-off sawing during their normal job duties. The age of all workers exceeded age eighteen as a condition of employment. The rationale for selecting these individuals was their familiarity with the cut-off saw equipment as well as the processes necessary for their operation. In addition, to ensure proper fit of respiratory protection, only individuals lacking obstructive facial hair were allowed to participate.

Potential volunteers did not report to a base office or headquarters; therefore, an advertisement was displayed at mobile construction sites. A recruitment advertisement was delivered to crew foremen on each applicable construction crew for display (See Appendix C). The purpose of the research and the specific procedures required of the subjects were explained prior to subject signature of a consent form (See Appendix D).

Saw Operators

A saw operator was selected from the volunteer population when they were 1) available on a measurement site and 2) previously designated by the contractor to perform cut-off sawing for that site. The number of subjects selected from the volunteer population was directly related to volunteer availability during site visits. Four total saw operators were utilized throughout the study.

Field Measurement Sites

The field measurement sites were selected based on three primary criteria: 1) the site contained a substantial volume of homogeneous, continuous lengths of applicable curb, 2) qualifying volunteers were present on the site and responsible for sawing of this curb, and 3) research equipment would not interrupt other operations or violate traffic control plans of the construction site.

Exposure Evaluation Methods

During the study, two exposure evaluation methods were used: personal air sampling by filter cassette and video exposure monitoring (VEM). Personal air sampling by filter cassette was used to determine the RSP dust and quartz air concentrations for each saw method over a sampling period. VEM was then used to visualize specific risk factors for each saw method and to compare personal RSP dust peak concentrations.

Personal Air Sampling by Filter Cassette

The goal of the research for the first evaluation method was to determine the RSP dust and quartz exposure of workers operating a cut-off saw during normal contractor processes. Personal air sampling was conducted for ten days on five different jobsites. A total of 44 air samples were taken; 17 DSM, 14 WSM, and 13 LSM samples. Samples were completed during a four to sixteen minute operating period of the saw, and did not include long-term rest breaks or operating tasks such as refueling. The duration of the sawing period was partially determined by the LOD parameters of the RSP dust laboratory analysis as well as the operational constraints of the experimental methods. Therefore, a lower duration limit (LDL) was set by the LOD parameters of RSP dust, and an upper duration limit (UDL) was determined by constraints of the sawing methods.

The sixteen minute UDL was established by the duration in which the water supply system could provide water to the saw without refilling. The four minute LDL was determined by the time interval which would provide a RSP dust LOD-based concentration below the current ACGIH TLV for RSP dust (See equation 2). The LDL was calculated using the current TLV for RSP dust (3 mg/m^3), the LOD mass of RSP dust for the NIOSH 0600 analytical method (0.03 mg), and the flow rate required by the sampling equipment (2.5 LPM) (ACGIH, 2009; NIOSH, 1998).

$$LDL = 0.03mg \times 1/3mg/m^3 \times 1000\,L/m^3 \times 1/2.5LPM = 4\min \qquad (2)$$

In addition to RSP dust and quartz air monitoring, supplementary data was recorded to explain potential differences in air concentrations between saw methods as well as within the same saw method due to varying field conditions. Concrete displacement and real-time onsite weather conditions were documented for each sampling period. Weather data included temperature, relative humidity, wind speed, and wind direction relative to worker heading. In addition, bulk material samples of the curb were collected for each site and sampling day to confirm the percent quartz within air samples. Video monitoring was also performed during the air filter samples, and was used to verify sampling duration, the number of saw cuts taken, and wind direction relative to worker heading.

Air Monitoring Protocol

Personal RSP dust and quartz air samples were collected using one sampling pump (model 224-52; SKC, Inc.) connected with tygon tubing to an aluminum cyclone (SKC, Inc.) with cassette. The cyclone was consistently placed on the left lapel of each subject. Air samples were collected on 5 µm pore size polyvinyl chloride (PVC) filters, loaded in three-piece 37 millimeter (mm) cassettes. Each filter was pre-weighed by an American Industrial Hygiene Association (AIHA) accredited laboratory. The sampling train was pre-calibrated to approximately 2.5 LPM using a primary calibrator (model Dry Cal Lite-M; BIOS International), and post calibrated after each sampling period.

Air Monitoring Field Blanks

One field blank was taken for every ten samples gathered during the course of the project. The field blank cassettes were stored in the same conditions as the cassettes used for air sampling. The protocol used for acquiring field blanks consisted of: 1) opening the cassette, 2) attaching the cassette to the cyclone and sequentially to the sampling train, 3) allowing the cassette to collect dust passively (i.e. no pump operation) for sixteen minutes during a sampling period in the onsite sample and worker preparation area, and 4) returning the cassette to the sealed shipment bag with the other air samples. Therefore, the field blanks acted as quality control against potential contamination during preparation for sampling and shipment, as well as extended cassette exposure to ambient field conditions.

Concrete Displacement Rate

The concrete displacement rate was determined for each sampling period to help describe differences in cut depths and the number of cuts performed over that sampling period. Because slipping forms were used to pour the curb at continuous standard sizes, the dimensions of the curb were approximately constant. The depth of cuts made by the worker was variable and measured with a ruler in inches. The displaced area is represented by the area above the dotted line in Figure 6 for both chair back and extruded curb applications.

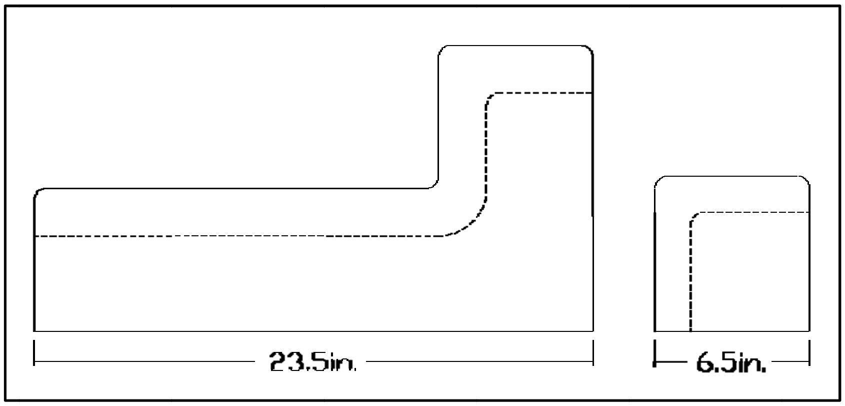

Figure 6. Displaced Area of Chair Back Curb (on left) and Extruded Curb (on right).

The average concrete displacement in cubic inches for a single saw cut was determined by measuring the displaced area of five random saw cuts per sample, taking the average of these cuts, and then multiplying this area by the saw blade width (BW) (See Equation 3). The total displacement in cubic inches was established by multiplying the average displaced area times the total number of saw cuts performed during the sampling period (See Equation 4). The number of saw cuts were recorded by researchers during the sampling period and verified by video analysis. Finally, a concrete displacement rate (CDR) was calculated by dividing the total displacement by the sampling period duration (T) in minutes (See Equation 5). The CDR gives the volume of concrete in cubic inches removed per minute over the sampling period.

$$\textit{Concrete Displacement} = BW \times \left(\sum_{i=1}^{5} \textit{DisplacedArea} \right) / 5 \qquad (3)$$

$$\textit{Total Displacement} = [\textit{Concrete Displacement}]\ X\ [\textit{Number of Cuts}] \qquad (4)$$

$$\textit{CDR} = [\textit{Total Displacement}]\ X\ [T] \qquad (5)$$

Weather Conditions

Real-time weather conditions were also recorded to assist in understanding exposure potential for a worker during a sampling period. Weather was monitored onsite using a Pocket Weather Tracker (model 4500, Kestrel, Inc.) in conjunction with a portable wind vane mount (Kestrel, Inc.). Temperature, relative humidity, wind speed, and wind direction were logged every five seconds for the duration of the sampling period.

Wind Direction Relative to Worker Heading

The wind direction relative to the direction the working is facing is an important factor when explaining the relationship between wind and exposure potential. When wind is blowing particulate back into the worker's breathing zone, the worker's exposure potential increases. Therefore, a relative wind direction was calculated by combining the general wind direction and the worker heading for each sampling period.

To categorize the wind direction, a compass rose of cardinal and intermediate directions was divided into eight equal categories labeled one through eight. Each sample was assigned a wind direction category (WDC) corresponding to the direction in which the wind was blowing particulate. Microsoft Excel spreadsheet statements were used to stratify individual wind direction measurements into wind direction categories, and the category with the majority of measurements for a sampling period was determined to be the sample's WDC. For example, if the majority of the wind direction measurements fell between 0 degrees north and 45 degrees northwest, the sample was assigned a WDC of one (See Figure 7).

In addition, for each sample, personal, real-time global positioning information was collected. A small global positioning system (GPS) data logger (model DG-100; GlobalSat) was attached to the sampling pump of each subject. The data logger gathered real-time longitude and latitude coordinates every five seconds for the worker during a sampling period. Utilizing the PC Data Logger Utility, the coordinates of these GPS points were plotted on an aerial map view of the measurement site. Based on the worker's path and the orientation of the curb, it was then possible to determine the worker's orientation during cutting in relation to true north (See Figure 8). When the GPS data logger lost satellite signal due to shaking or weather complications, a general orientation could still be determined using noted visible landmarks from video monitoring and the aerial map view of the site.

To categorize the worker's heading, an additional compass rose of cardinal and intermediate directions was divided into eight equal categories labeled one through eight. The worker heading found using the GPS points was then overlaid onto this figure. For example, if the saw operator was facing between 0 degrees north and 45 degrees northwest, the sample was assigned a worker heading category (WHC) of one (See Figure 9).

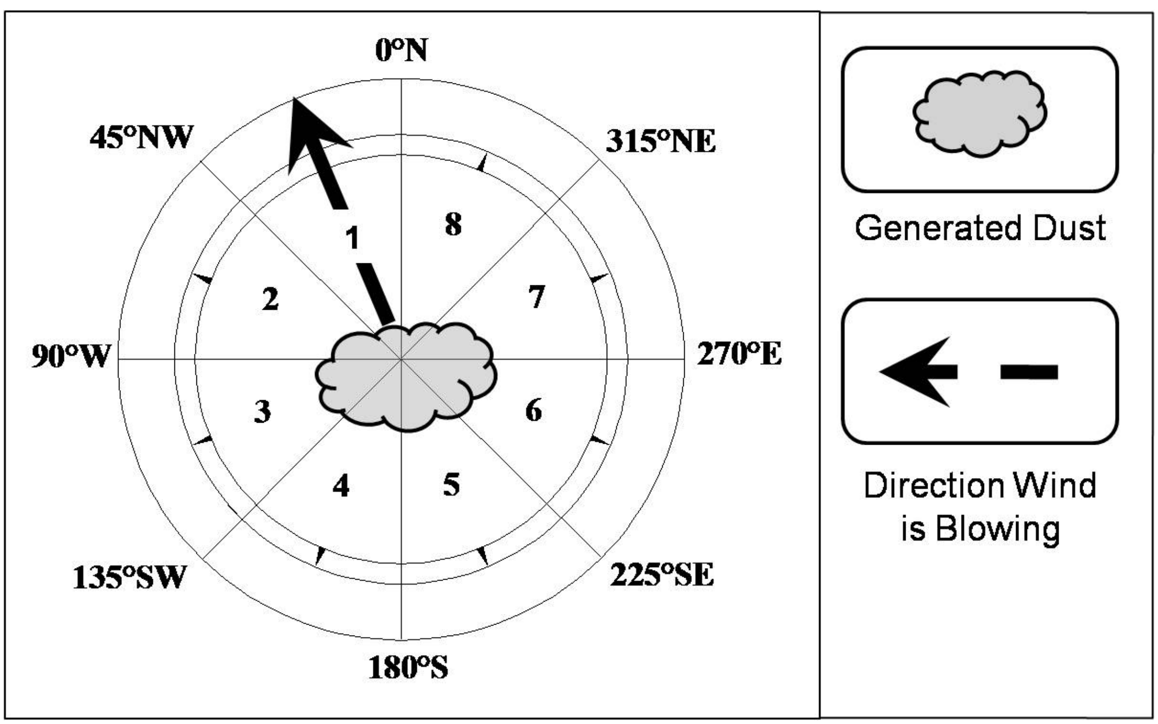

Figure 7. Wind Direction Category (WDC) Methodology.

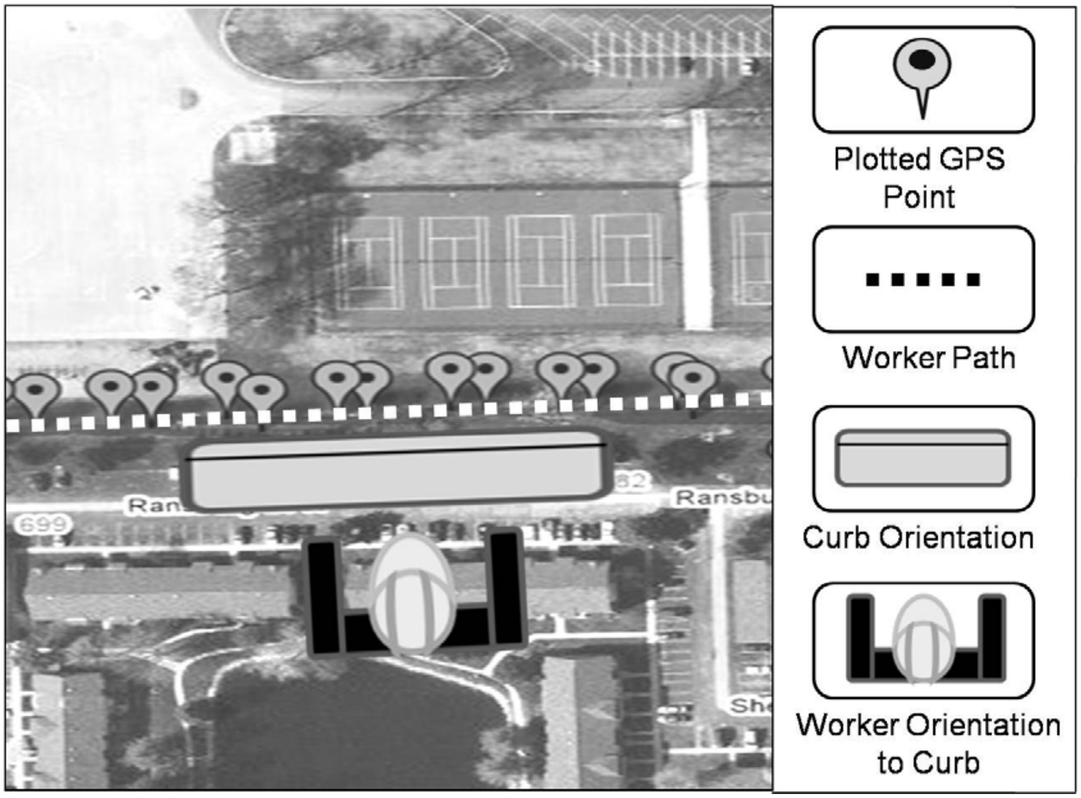

Figure 8. Illustration of Worker Path and Orientation to Curb during Cutting.

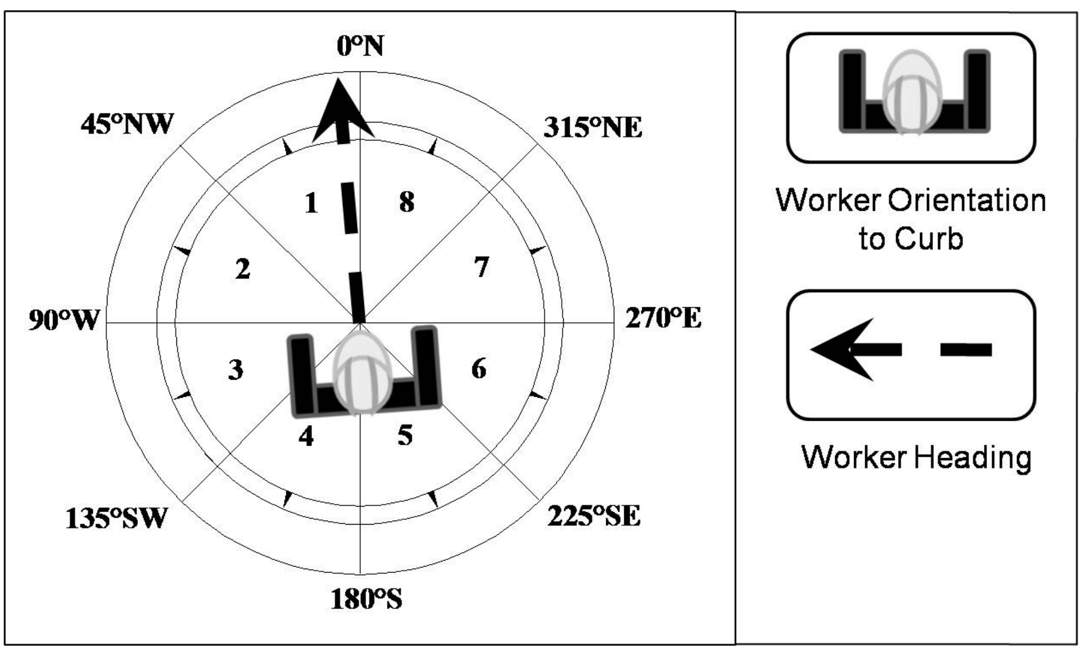

Figure 9. Worker Heading Category (WHC) Methodology.

Finally, the WDC and WHC were collectively used to categorize wind direction using the worker as a relative reference point. For the study, the combined category was designated as the relative wind direction (RWD). The RWD specifically describes where the wind is blowing relative to the direction the worker is facing: front, right front, right, right rear, back, left rear, left, and left front. The WDC and WHC were combined and then stratified into these categories using a Microsoft Excel spreadsheet statement, with each RWD assigned a value of one through eight (See Equation 6).

$$RWD = if\,(WHC - WDC \leq -1, WHC - WDC + 8, WHC - WDC) \qquad (6)$$

If the WDC was equal to one (between N and NW), and the WHC was equal to one (between N and NW), the RWD would be assigned a category of eight (see Figure 10). A category of eight in Figure 10 corresponds to the front category, or the 45 degree range directly in front of the worker. For these conditions, if a majority of the dust is being ejected by the saw behind the worker, then these weather conditions would be favorable for higher dust exposure. A fraction of the airborne particulate would be blown back into the worker's breathing zone.

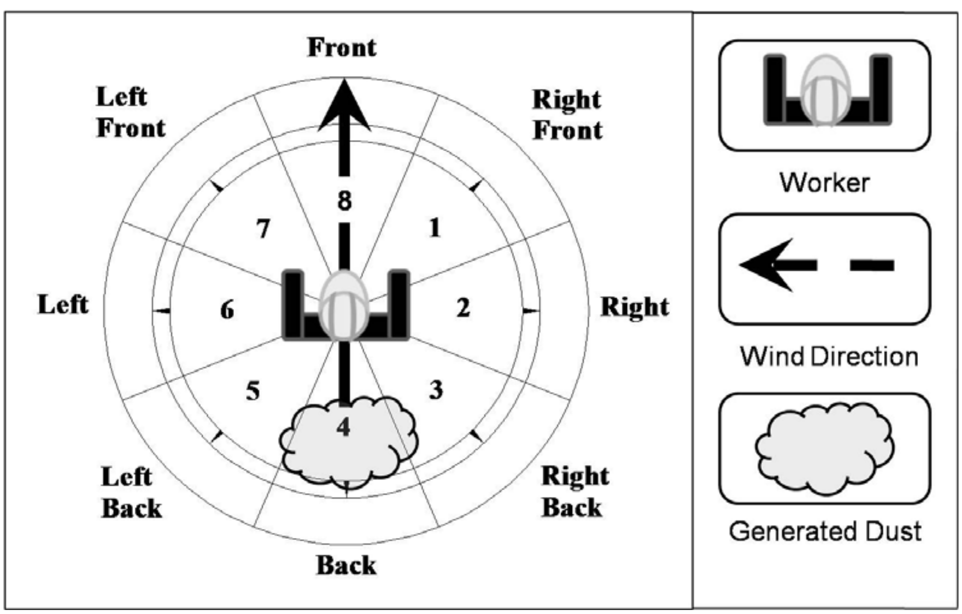

Figure 10. Relative Wind Direction (RWD).

Bulk Sample Collection

For each site, the curb was an identical "add" mixture of aggregate materials defined by the requirements of each jobsite, and was distributed from the same production facility. Because of this, it was assumed that the composition of the curb would be approximately homogeneous. Two samples were collected from one joint for each site and sampling day using two different collection methods; bulk filter and bulk fracture. Both collection methods were used to identify the percent quartz within the curb material.

Bulk filter samples were collected from freshly sawed curb joints. Dust deposited on the surface of the curb during sawing was impacted onto a filter using a sampling pump (model 224-52; SKC, Inc.) connected to a two-piece 37 mm, closed-face filter cassette. Dust was collected by placing the cassette face down approximately three inches from the curb joint. The bulk samples were collected on 5µm pore size, PVC filters. Each filter was pre-weighed by an AIHA accredited laboratory. The sampling train was pre-calibrated to approximately 3 LPM using a primary calibrator (model Dry Cal Lite-M; BIOS International). A higher flow rate was used to improve collection of the dust on the filter. Three field blanks were also collected using similar protocol as outlined under the air monitoring field blank section. For the bulk fracture collection method, a fracture of concrete was obtained by using a rock chisel to break off a small piece of curb from the upper part of the curb joint. The fracture size collected was greater than 2 mg for each sample. After an adequate size fracture was acquired, each fracture was placed in a sealable bag for analysis.

Laboratory Analysis

Three separate laboratory analysis protocols were used for the air monitoring filter samples, the bulk filter samples, and the bulk fracture samples. All analyses were performed by an AIHA accredited laboratory, and a laboratory blank was included with each set of samples analyzed.

Air Monitoring Filters

All air filter samples were analyzed for RSP dust gravimetrically in accordance to the NIOSH 0600 method (NIOSH, 1998). In addition, all samples obtained during the DSM were expected to exceed the LOD for RSP dust; therefore, each DSM sample was automatically analyzed for quartz by x-ray diffraction spectrometry via the NIOSH 7500 method (NIOSH, 1998). The experimental saw methods, WSM and LSM, were expected to result in very low dust masses, either less than the RSP dust LOD or close to the RSP dust LOD. Therefore, filters with dust masses greater than the LOD for RSP dust were combined to increase the probability of measuring at least a collective quartz mass greater than the quartz LOD (Rice, 2008).

As previously stated, if the RSP dust mass exceeded its LOD, then the filter was combined with all other filters exceeding the LOD for that saw method. However, any filters for which the RSP dust mass did not exceed the LOD were grouped with all other filters below the LOD for that saw method. Once the filters were assembled into these four different groups, the filters were combined and analyzed for quartz using the modified NIOSH 7500 method (NIOSH, 1998). The combined filter groups with individual RSP dust masses below the LOD were only used to ensure detectable quartz masses were not present on these filters.

Bulk Sample Analysis

The bulk filters were analyzed for total weight gravimetrically in accordance with the NIOSH 0600 method of analysis. The filters were then analyzed for quartz by x-ray diffraction using the NIOSH 7500 method. The RSP quartz weight on the filter was then divided by the total RSP dust weight to determine the percent quartz in the bulk material.

The bulk fractures were ground up by the laboratory using a mortar and pestle. Approximately 2 mg of the resulting material was isolated from the total material. The isolated material was analyzed for quartz using the NIOSH 7500 method. The RSP quartz weight was then divided by the RSP dust weight, approximately 2 mg, to determine the percent quartz in the fracture material.

Estimation of Quartz Concentrations for Experimental Saw Methods

The 16 minute UDL was pre-determined by operational constraints of the WSM. As a result, obtaining a LOD-based concentration value for quartz above the current TLV was not possible with individual filters. The LDL for quartz needed to obtain this value would be 80 minutes. The LDL for quartz was calculated using the current TLV for RSP silica (0.025 mg/m^3), the LOD mass of RSP silica for the NIOSH 7500 analytical method (0.005 mg), and the flow rate required by the sampling equipment (2.5 LPM) (ACGIH, 2009; NIOSH, 1998) (See Equation 7) (ACGIH, 2009; NIOSH, 1998). In addition, the majority of the RSP dust masses for the WSM and LSM were already expected to be below the LOD for RSP dust, a mass much higher than the LOD for quartz.

$$LDL\ for\ Quartz = 0.005mg \times 1/0.025mg/m^3 \times 1000L/m^3 \times 1/2.5LPM = 80\min \quad (7)$$

To provide an approximation of quartz concentrations for the WSM and LSM, four methods were used to estimate the average percent quartz: 1) using the GM percent quartz from the DSM samples, 2) utilizing the percent quartz from the combined filters with detectable dust masses for the LSM and WSM, 3) using the GM percent quartz from the bulk filter samples, and 4) using the GM percent quartz from the bulk fracture samples. These percent quartz values were then used to determine an estimate of the quartz air concentrations from the previously determined RSP dust concentrations (See Equation 8).

$$Quartz(mg/m^3) = RSPDust(mg/m^3) \times \%Quartz/100 \quad (8)$$

Video Exposure Monitoring

Video exposure monitoring (VEM) was conducted to assist in the visualization and comparison of the cutting process between saw methods by using a task-based approach. VEM can help “discern exposure sources and the interaction between normal work practices and engineering controls such as LEV. Pinpointing exposure sources can lead to cost effective controls and the development of an effective feedback mechanism for showing workers and management where they had exposures and where they could be controlled” (McGlothlin, 2005). Therefore, three saw joints were cut consecutively by one operator to allow quantification of potential differences in dust concentrations as the process progressed. A real-time photometric particulate monitor was paired with camera footage for the duration of each sample. All cutting was performed on the same length of curb within a two hour time span. Three samples were taken for each sawing method.

Real-Time RSP Dust Monitoring

Personal real-time RSP dust monitoring was accomplished using one DustTrak real-time aerosol monitor (model 8520; TSI, Inc.) in conjunction with the 10 µm inlet adapter connected to a 10 mm nylon Dorr-Oliver cyclone. The aerosol monitor was zeroed before calibration, and pre-calibrated to a flow rate of 1.7 LPM. The operator wore the monitor on his lower back with the cyclone placed on the left lapel (See Figure 11). Concentrations were logged every second for the duration of each sampling period. Before the sampling period, the DustTrak was synchronized with the time of a laptop which had been previously coordinated with the National Institute of Standards and Technology (NIST) Internet Time Service (Rosen, et al., 2005).

Figure 11. Real-Time RSP Dust Monitoring.

Determination of Calibration Factor

According to the DustTrak operating manual, the photometric aerosol monitor is most accurate when calibrated for a specific aerosol (TSI Incorporated, 2005). Factory calibration for the DustTrak is achieved using RSP ISO 12103-1, A1 test dust, a dust with specific optical properties (TSI Incorporated, 2005). Although the monitor is still useful in determining relative concentration changes over time, the magnitude of these concentrations may vary by a factor depending on the optical properties of the aerosol being sampled (TSI Incorporated, 2005). To determine a calibration factor for the DustTrak, it is recommended that the average RSP dust concentration of the real-time monitor be compared to a side-by-side gravimetric analysis of the aerosol (TSI Incorporated, 2005). Due to restrictions within the accepted human subject protocol, the real-time instrument could not be worn by saw operators in conjunction with gravimetric sampling pumps.

Therefore, area samples were taken in close proximity to the dry sawing operation for approximately four minutes. The DustTrak was zeroed, calibrated at 1.7 LPM, and set with a logging interval of one second. The DustTrak, 10 mm nylon Dorr-Oliver cyclone was clipped on a stand approximately four feet from the ground. This cyclone was placed side-by-side with one separate aluminum cyclone (SKC, Inc.) The aluminum cyclone was used to collect gravimetric samples on pre-weighed 5µm pore size PVC filters, loaded in three-piece 37 mm cassettes. The sampling media was connected to a sampling pump (model 224-52; SKC, Inc.). Each gravimetric sampling train was pre-calibrated to approximately 2.5 LPM, and post-calibrated at the end of the sampling period.

The DustTrak and gravimetric sampling pump was started and stopped simultaneously for the sampling period. Filters from gravimetric sampling were analyzed by an AIHA accredited laboratory according the NIOSH 0600 analytical method. The average real-time RSP dust concentration and the average gravimetric RSP dust concentration were used to calculate a calibration factor (CF) (See Equation 9). The resulting calibration factor can then be multiplied to DustTrak concentrations to reveal a newly adjusted approximation of RSP dust concentrations, comparable to gravimetric values of RSP dust (See Equation 10).

All data displayed will remain unadjusted because it is unclear whether a CF determined from dust at a nearby position will have the same optical properties, specifically the size distribution, of escaping particles for all samples. The CF will be reported for comparative purposes, and unadjusted values will be used for magnitude comparisons between saw methods.

$$CF = [Gravimetric\ Concentration] / [DustTrak\ Concentration] \quad (9)$$

$$Adjusted\ RSP\ Dust\ (mg/m^3) = [DustTrak\ Output\ (mg/m^3)]\ X\ CF \quad (10)$$

Video Synchronization and Task-Based Analysis

At the commencement of each video, the laptop time was filmed with the camcorder. After the data was collected, the camera footage was combined with the real-time concentration data using the reference time at the beginning of each video. Each sample was further analyzed by breaking the process into 10 subparts or tasks. Appendix E, Table E-1 provides an overview of each task description.

Video from one sample of each saw method was manually rendered with real-time concentration data. These exposure monitoring videos combine a scrolling real-time concentration graph with each sample video (See Figure 12). The exposure monitoring videos allow an in-depth visual analysis of worker actions and dust control attributes that may increase or decrease exposure potential for the worker. A fourth exposure monitoring video was created with all three saw method videos in a side-by-side comparison using the same concentration scale for each graph (See Appendix F, Figure F-1).

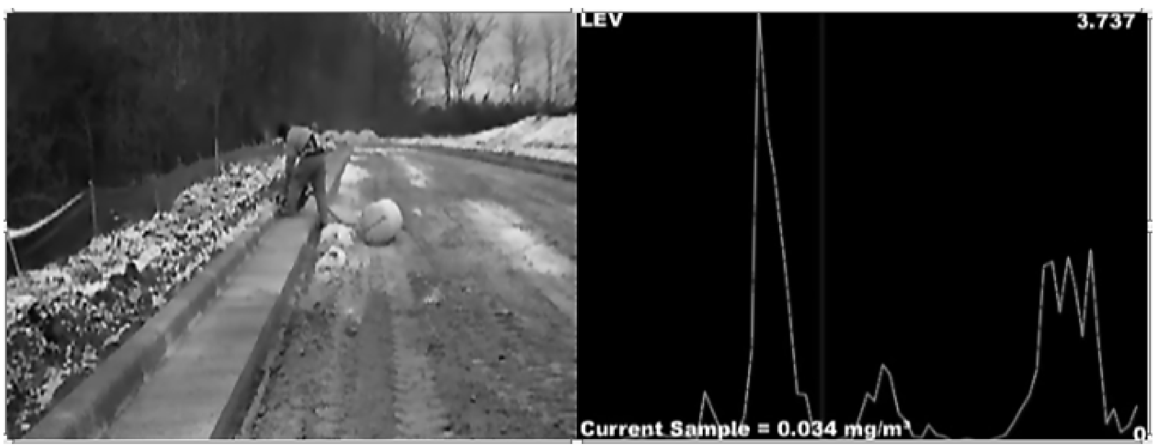

Figure 12. Video Exposure Monitoring Screenshot.

Statistical Analysis

Descriptive statistics were used to describe air concentrations and percent quartz, as well as variables such as weather conditions and concrete displacement. Non-normal distributions occurred throughout the study, and in many cases, it was not possible to generate a normal distribution by simple transformations (e.g. lognormal). Therefore, instead of transforming the distribution for use in a parametric statistical comparison such as the t-test, a non-parametric statistical comparison was performed.

The Wilcoxon signed rank test, a non-parametric test, was used for all statistical comparisons. The relative power of the Wilcoxon signed rank test for non-normal distributions is greater than the t-test, and under normal distributions, the advantages of the t-test over the Wilcoxon are very small (Sawilowsky, 2005). An analysis of covariates (ANCOVA) was used to explain differences in concentration values within the same saw method. Descriptive statistics were performed in Microsoft Excel, and verified in SAS (version 9.0). All ANCOVA and statistical comparisons were performed using SAS.

RESULTS AND DISCUSSION

Personal Air Sampling by Filter Cassette

The following section provides an analysis of data gathered during the personal filter cassette sampling periods including RSP dust concentrations, RSP quartz concentrations, and other supplementary variables such as concrete displacement and weather conditions.

RSP Dust

Table 2 provides descriptive statistics of RSP dust concentrations acquired from filter cassette sampling. The central tendency of this data is described by both the GM and the median. The GM is commonly used to describe the central tendency of lognormal distributions, a commonly encountered distribution for particulate samples. The DSM concentrations do follow this lognormal distribution; therefore, the GM is the most the appropriate measure of central tendency. However, the LSM and WSM do not follow the lognormal distribution because of the large number of concentration values below the LOD for RSP dust; therefore, the median was also used because of its ability to resist outliers. Nonetheless, both the median and the GM values were very comparable within each method.

Twelve out of fourteen dust samples were below the LOD for the WSM, and nine out of twelve dust samples were below the LOD for the LSM. The DSM samples had a median RSP dust concentration of 15.9 mg/m^3, the WSM had a median concentration of 2.55 mg/m^3, and the LSM had a median concentration of 2.97 mg/m^3. Figure 13 depicts the reduction in RSP dust for both the WSM and LSM. The WSM provided a median

RSP dust reduction of 87.7 percent and the LSM provided an 87.0 percent median RSP dust reduction (See Table 3). A non-parametic statistical comparison (Wilcoxon Signed Rank, 2-sided) shows a statistically significant difference between the DSM and both the WSM ($p<0.001$) and LSM ($p<0.001$). There was no significant difference seen between the WSM and the LSM ($p=0.118$). Based on this analysis, the LSM appears to be very similar to the WSM in its dust reduction abilities; however, differences may have been masked because of the large percentage of samples below the LOD.

Table 2. Gravimetric Air Filter Analysis of RSP Dust[A].

			TWA RSP Dust Concentration (mg/m^3)[B]		
Saw Method	N	n	GM (GSD)	Median	Min-Max
DSM	17	0	16.4 (1.89)	15.9	5.22-48.6
WSM	14	12	2.55 (2.14)	1.96	1.40-16.9
LSM	12	9	2.97 (2.00)	2.07	1.71-13.8

Notes: TWA= time-weighted average over sampling periods, N=number of samples, n=number samples with concentrations below the LOD for RSP dust, GM=geometric mean, GSD=geometric standard deviation.
[A] When individual concentrations were below the LOD for RSP dust, one-half the LOD was substituted for the concentration (Hornung & Reed, 1990).
[B] $Concentration\,(mg/m^3) = mass\,(mg) \times 1000\,L/m^3 \times 1/Volume\,(L)$

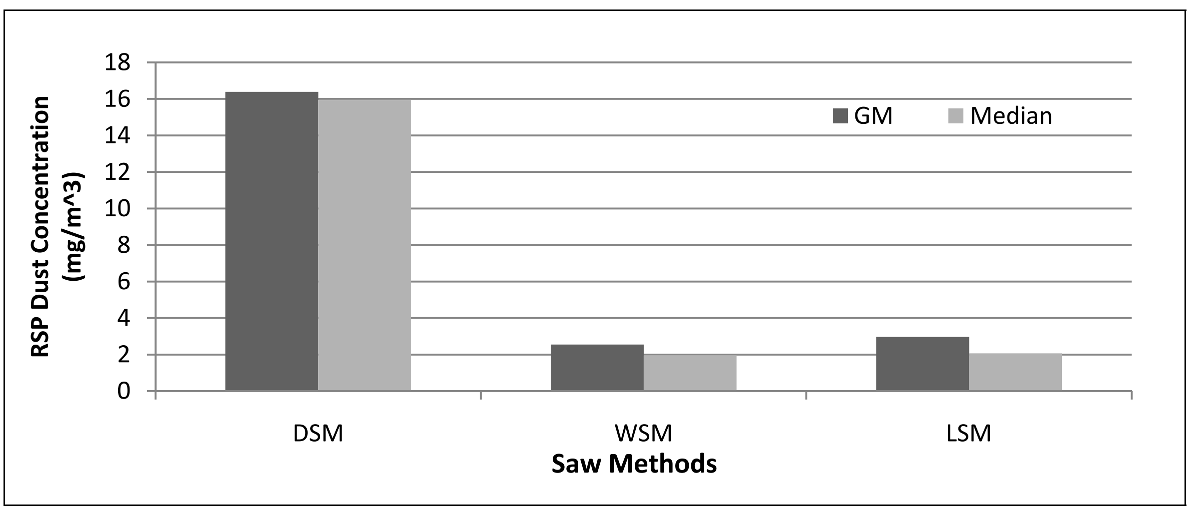

Figure 13. GM and Median RSP Dust Concentrations for Saw Methods.

Table 3. RSP Dust Reduction from Gravimetric Analysis.

Saw Method	RSP Dust Reduction (%) GM[A]	RSP Dust Reduction (%) Median[B]
WSM	84.5	87.7
LSM	81.9	87.0

Notes: GM=geometric mean.
[A] $\% = \left(GM_{DSM} - GM_{Control}\right)/\,GM_{DSM} \times 100$
[B] $\% = \left(Median_{DSM} - Median_{Control}\right)/\,Median_{DSM} \times 100$

The RSP dust reduction for the LSM was 87 percent greater than the nonexistent reduction seen in the study by Croteau et al. (2002) (See Appendix B, Table B-1). Although some of this can be attributed to natural ventilation, it is most likely a result of better shroud design and higher exhaust rates. The exhaust flow for the LSM was 105 cfm compared to that of 75 cfm used in the Croteau et al. (2002) study. A marked improvement among designs available for commercial use resulted in a reduction three percent less than that reported by Thorpe et al. (1999) for a custom built system. This may simply be due to the small (N=1) sample size reported in that study.

Compared to Thorpe et al. (1999), the WSM had a 10.3 percent smaller dust reduction than the system supplied by a garden hose, and the hand pressurized tank system demonstrated a 4.8 percent smaller dust reduction than the WSM. It was expected that the WSM would be less effective than the garden hose supply because of the steady flow rate of water to the saw blade. The hand pressurized tank requires hand pumping to maintain an adequate flow rate. For WSM, the worker depended solely on the creation of visible dust to determine when to pump the canister. If the flow dropped below an adequate level during a saw cut, the worker often continued until the cut was completed. This resulted in peak levels of dust exposure during particular saw cuts. This could account for the lower reduction seen in our study; however, it may also be due to the small sample size (N=1) utilized by Thorpe (1999).

RSP Quartz

Table 4 provides an estimate of quartz concentrations based on the percent quartz derived from four estimating methods. The individual DSM filter estimate, the combined LSM and WSM filter estimate, and the bulk fracture quartz estimate revealed very comparable estimations of percent quartz. The range of these three estimations was only 1.7 percent quartz. The fourth estimation from the bulk filter analysis, however, displayed a much lower quartz percentage.

This low estimation is likely due to the collection process used for the bulk filters. When the cassettes were placed on the curb surface to collect dust, it was not possible to discern how much dust was being collected on the filter. In some cases, the filter was overloaded by more than two times (i.e. >4 mg dust), resulting in multiple dilutions by the laboratory. These inconsistencies may have resulted in much lower quartz percentages, and provides evidence that the collection protocol used for the bulk filters is not an appropriate measure for determining percent quartz.

Regardless of the bulk filter results, the other three estimation methods did provide very similar estimations of the quartz concentration. The range of estimated quartz concentrations for the WSM was 0.01 mg/m^3, and the LSM was 0.05 mg/m^3. Although these estimation methods are no substitute for actual quartz measurements, they provide important insight into a worker's quartz exposure when a majority of control method samples are below the LOD for RSP dust. It is also important to note that the homogeneity of the source substance was vital to the consistency of the quartz fractions among samples, and these estimation methods may not be effective for applications where the material or mixture of materials is heterogeneous.

Using only the air filter cassette results, the actual GM quartz concentration for the DSM was 0.96 mg/m^3, compared to the combined filter estimate of 0.15 mg/m^3 for the WSM and 0.22 mg/m^3 for the LSM. Table 5 provides the quartz reductions for the LSM and WSM based on these estimated values. The WSM provided an 84.4 percent reduction, and the LSM provided a 77.1 percent reduction. Figure 14 illustrates these corresponding percent quartz reductions. The RSP quartz reductions were within ten percent of that seen by RSP dust; however, as a whole, quartz reductions appear to be somewhat smaller than RSP dust reductions. This appears to be generally consistent with other dust control studies (Thorpe, Ritchie, Gibson, & Brown, 1999; Akbar-Khanzadeh, et al., 2007).

Table 4. RSP Quartz Concentrations Determined from Four Estimating Methods.

			Saw Methods TWA Estimated Quartz (mg/m^3)[D,E]	
Estimate Method	N	Quartz (%)	WSM	LSM
1) Individual DSM Filters	17	5.8 (1.2)[B]	0.15	0.17
2) Combined WSM Filters	2[A]	5.8[C]	0.15	-
2) Combined LSM Filters	3[A]	7.5[C]	-	0.22
3) Bulk Fractures	10	6.8 (1.4)[B]	0.16	0.19
4) Bulk Filters	10[F]	.90 (1.5)[B]	0.02	0.02

Notes: TWA=Time-weighted average over sampling periods. N=number of samples.
[A] Number of filters combined during analysis.
[B] GM percent quartz (GSD percent quartz).
[C] Point value percent quartz from combined filter analysis.
[D] $Quartz(mg/m^3) = RSPDust(mg/m^3) \times \%Quartz/100$
[E] Calculated from Table 3 RSP dust concentrations.
[F] Nine filters were overloaded and required dilution by the laboratory.

Table 5. RSP Quartz Reduction from Air Filter Analysis for Sampling Periods.

Saw Method	RSP Quartz Reduction (%)[A]
WSM	84.4
LSM	77.1

[A] $\% = \left(GM_{DSM} - Combined_{Control}\right)/GM_{DSM} * 100$

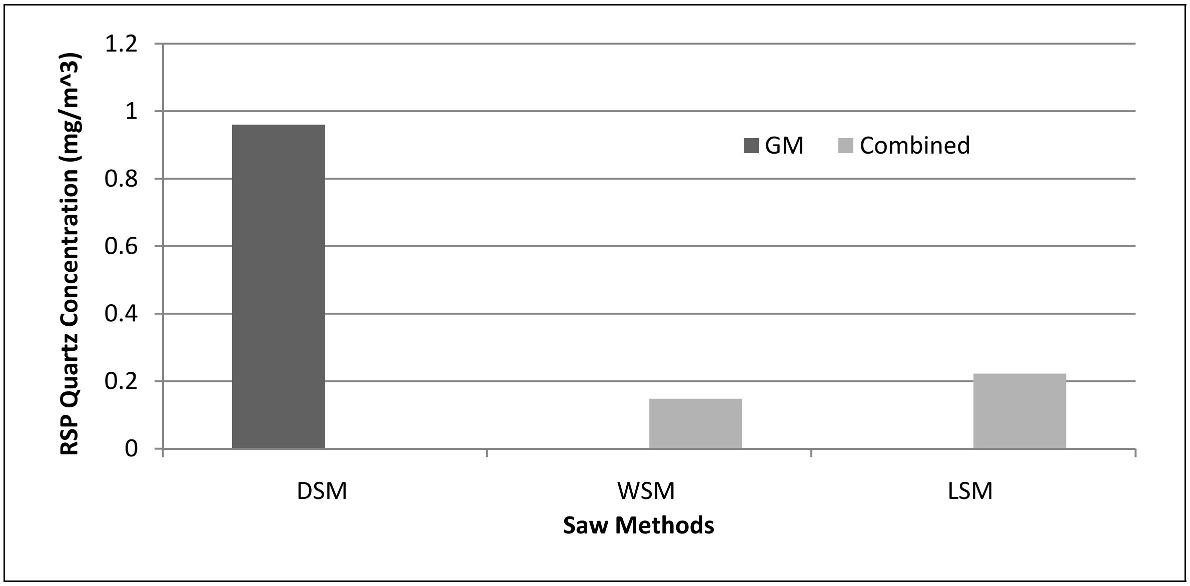

Figure 14. RSP Quartz Concentrations based on Air Filter Analysis.

Based on the TWA quartz concentration values, the DSM would exceed the General Industry PEL by almost 10 times (See Table 6). The WSM and LSM also exceed the PEL by 1.5 times and 2.2 times respectively. According to the MUCs, even with the engineering controls implemented, workers would still need to be enrolled in a respiratory protection program. To meet OSHA, NIOSH, and ACGIH exposure guidelines, workers would need to wear at least a half-mask respirator (APF=10).

Table 6. Severity Ratio of Quartz Concentrations for Sampling Periods.

	Severity Ratio [A]		
Method	PEL[B]	REL	TLV
1) Individual DSM Filters	9.6	19	38
2) Combined WSM Filters	1.5	3.0	6.0
2) Combined LSM Filters	2.2	4.4	8.8

[A] $Severity\ Ratio = Concentration / ExposureLimit$
[B] OSHA General Industry PEL.

Even though some applications require sawing for an entire 8 to 10 hour workday, curb sawing is usually performed for 1 to 2 hours per day. An equivalent 8-hour and 10-

hour TWA was also calculated for each method using 2 hours as the full exposure duration (See Table 7). This, however, will not take into account other potential exposures that a worker could incur during a workday. Based on these time-weighted concentrations, the DSM would still exceed the OSHA PEL by almost 2.4 times, but both the WSM and LSM would be reduced below the NIOSH REL (See Table 8). The DSM would still require the donning of half-mask respirators (APF=10), but the WSM and LSM would not require respirators by law. However, to ensure exposures were below the TLV, respirators would still be needed.

Table 7. Estimated 8-hour and 10-hour TWA RSP Quartz Concentrations.

	Estimated 8h-TWA[A] and 10h-TWA[B] Quartz Concentrations (mg/m^3)		
Method	DSM	WSM	LSM
1) Individual DSM Filters	0.24 (0.19)	-	-
2) Combined WSM Filters	-	0.04 (0.03)	-
2) Combined LSM Filters	-	-	0.05 (0.04)

Notes: Values= 8h-TWA Concentration (10h-TWA Concentration)

[A] $\textit{Estimated 8-h TWA for Work Shift} = (\textit{Concentration} \times 120\ \text{min}) / 480\ \text{min}$

[B] $\textit{Estimated 10-h TWA for Work Shift} = (\textit{Concentration} \times 120\ \text{min}) / 600\ \text{min}$

Table 8. Severity Ratio of 8-hour or 10-hour TWA RSP Quartz Concentrations.

	Severity Ratio [A]		
Method	PEL[B]	REL	TLV
1) Individual DSM Filters	2.4	3.8	9.6
2) Combined WSM Filters	0.4	0.6	1.6
2) Combined LSM Filters	0.5	0.8	2.0

[A] $\textit{Severity Ratio} = \textit{Concentration} / \textit{ExposureLimit}$

[B] OSHA General Industry PEL.

Supplementary Data

The supplementary data section includes an analysis of concrete displacement rates and weather conditions for the filter cassette sampling periods. Data for each sampling period is summarized in Appendix G.

Concrete Displacement Rate

The concrete displacement rate quantifies the amount of work completed during each saw method. The arithmetic mean (AM) concrete displacement rate for the DSM method was 14.2 cubic inches per minute (in^3/min), 6.62 in^3/min for the WSM, and 8.52 in^3/min for the LSM (See Table 9). A non-parametic statistical comparison (Wilcoxon Signed Rank, 2-sided) shows a statistically significant difference between the DSM and both the WSM ($p<.001$) and LSM ($p<.001$). There was also a significant difference between the WSM and the LSM ($p=.022$); however, the difference was not as profound.

Table 9. Concrete Displacement Rates for Saw Methods.

		Concrete Displacement Rate (in^3/min)		
Saw Method	N	AM (SD)	Median	Min-Max
DSM	17	14.2 (2.51)	14.2	9.50-18.3
WSM	14	6.62 (3.15)	5.24	3.94-15.2
LSM	12	8.52 (1.62)	8.46	6.48-12.3

Notes: N = number of samples, AM (SD) = arithmetic mean (standard deviation).

Table 10. Concrete Displacement Percent Reduction (DR)

Saw Method	Displacement Reduction (%)[A]
WSM	63.1
LSM	40.0

[A] $\% = \left(AM_{DSM} - AM_{Control}\right) / AM_{DSM} * 100$

The concrete displacement rate was 63.1 percent lower for the WSM and 40.0 percent lower for the LSM compared to the DSM (See Table 10). The difference is illustrated in Figure 15. The data supports the theory that both experimental methods (i.e. WSM and LSM) require the saw operator to work longer to accomplish the same amount of work. Differences can be attributed to the time needed to move the equipment, the time needed to make cuts, and tasks necessary to keep equipment operational (i.e. hand-pumping). Not only does this have implications for reduced productivity among engineering controls, but it also suggests that it may extend the exposure time of an individual using the engineering controls.

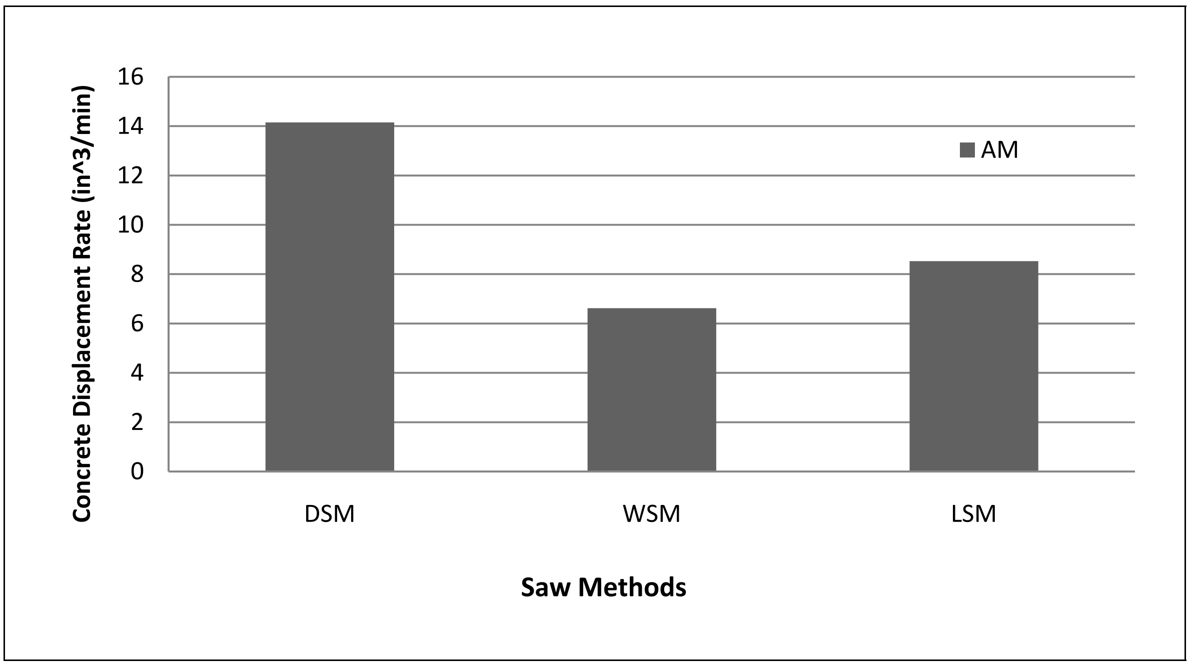

Figure 15. AM Concrete Displacement Rates for Saw Methods.

As reported by workers, the time needed to complete curb sawing usually takes 1 to 2 hours for the DSM; therefore, this time would be extended for the WSM and LSM to complete an equivalent amount of sawing. Table 11 gives the displacement-adjusted 8-hour TWA and 10-hour TWA concentrations for both the WSM and LSM. Although the concentrations are still below the PEL, the WSM 10-hour TWA concentration is now equivalent to the NIOSH REL, and the LSM 10-hour TWA exceeds the REL by 1.2 times (See Table 12). A comparison of the 8-hour TWA concentrations before and after the adjustment is displayed in Figure 16. Displacement adjustments created a 33 percent increase in the concentration for the WSM and a 29 percent increase in concentration for the LSM.

This provides additional evidence that engineering control efficiency is not only an important part of productivity, but also an important factor in terms of exposure. For many construction occupations, instead of one similar activity, many different activities of varying durations are completed throughout a work day. Therefore, the duration of a singular activity is not defined by eight hours, but by how long it takes to complete the required activity. Because of these conditions, an engineering control has the ability to slow work and increase the duration in which the worker performs the task. When manufacturers create engineering controls, an efficient and easy-to-use design should be a priority to reduce both operational costs and exposure time for the worker.

Table 11. Estimated 8-hour and 10-hour TWA RSP Quartz Concentrations Adjusted for Concrete Displacement Reductions.

	Estimated 8h-TWA[A] and 10h-TWA[B] Quartz Concentrations (mg/m^3)	
Method	WSM	LSM
2) Combined WSM Filters	0.06 (0.05)	-
2) Combined LSM Filters	-	0.07 (0.06)

Notes: Values= 8h-TWA Concentration (10h-TWA Concentration)

[A] *Estimated 8-h TWA for Work Shift=*
$(Concentration \times (120\min + \%DR \times 120\min/100)/480\min$

[B] *Estimated 10-h TWA for Work Shift=*
$(Concentration \times (120\min + \%DR \times 120\min/100)/600\min$

Table 12. Severity Ratio of 8-hour or 10-hour TWA RSP Quartz Concentrations Adjusted for Concrete Displacement Reductions.

Method	Severity Ratio [A] PEL[B]	REL	TLV
1) Individual DSM Filters	2.4	3.8	9.6
2) Combined WSM Filters	0.6	1.0	2.4
2) Combined LSM Filters	0.7	1.2	2.8

[A] $Severity\ Ratio = Concentration / Exposure Limit$
[B] OSHA General Industry PEL.

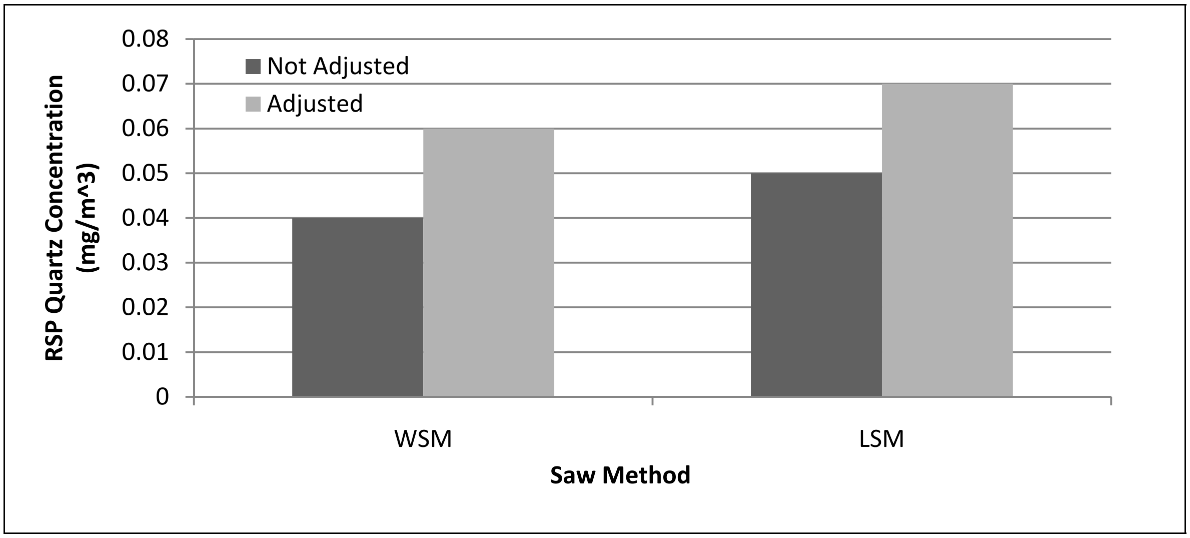

Figure 16. 8-hour TWA Quartz Concentrations before and after Adjustment to Displacement Reduction.

<u>Weather Conditions</u>

As expected, outdoor weather conditions varied considerably through the course of data collection. The mean temperature, relative humidity, and wind speed for each saw method is illustrated in Figure 17. Because sampling began early in the morning before sunrise, the ranges of temperature and relative humidity experienced for a single sampling day was sometimes as great as 20 °F and 25 percent, respectively. The arithmetic mean temperature was 60.1 °F for the DSM, 43.1 °F for the WSM, and 57.5 °F for the LSM (See Appendix H, Table H-1). The range of average temperature measurements for all methods was less than 20 °F, a difference that would have very little effect on the velocity of particles in air (Hinds, 1999). The range of mean percent relative humidity between methods was almost 35 percent; however, the effect of adhesive forces for suspended particles of this size is also relatively small (Hinds, 1999). Many of these differences were created due to the order in which control methods were sampled.

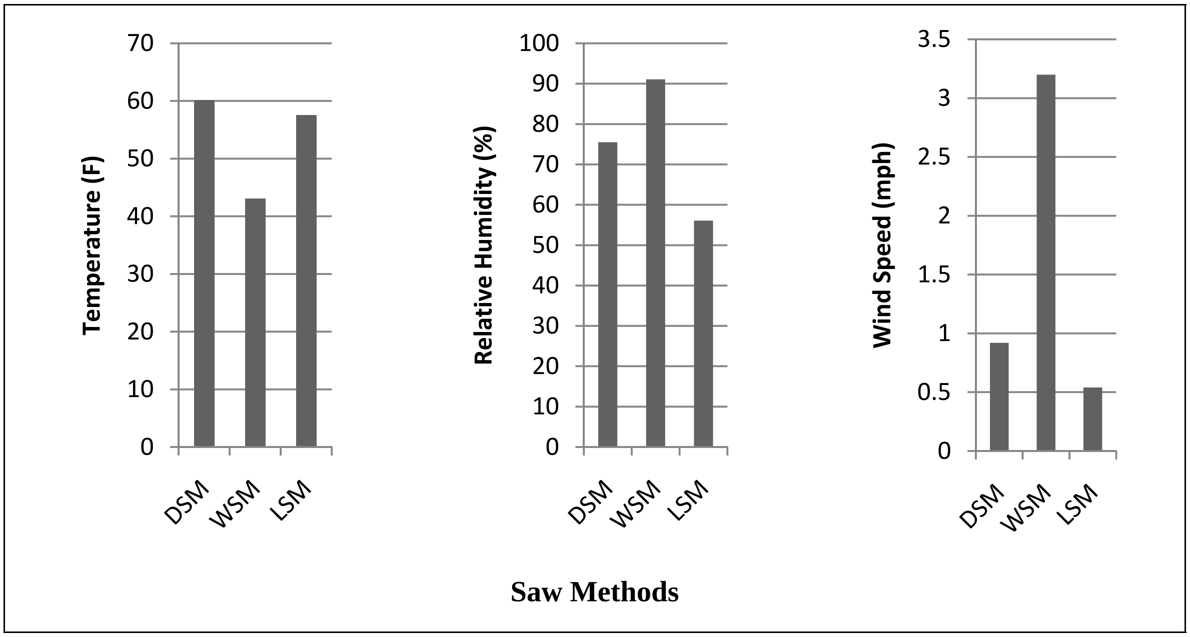

Figure 17. AM Temperature, Relative Humidity, and Wind Speed for Saw Methods.

Conversely, the wind speed, a factor shown to have an appreciable effect at low levels, was significantly different (Wilcoxon Signed Rank, 2-sided) for the WSM than both the DSM (p=0.025) and LSM (p=0.002) (See Appendix H, Table H-2) (Akbar-Khanzadeh & Brillhart, 2002). There was no difference (p=0.402) seen between the LSM and DSM. Therefore, an additional statistical comparison was made within the WSM samples.

To evaluate whether these higher wind speeds alone caused an increase in exposure for the WSM, a non-parametric comparison of the values greater than or equal to 0.5 mph was compared to the values below 0.5 mph. A value of 0.5 mph was chosen because it was the mean of the LSM, the method with the greatest significant difference in wind speed. The statistical comparison revealed no significant difference (p=0.835) in RSP dust concentrations for these two groups within the WSM samples. This provides evidence that wind speed alone did not explain an increase in RSP dust concentrations for the WSM.

The same statistical test for the DSM (p=0.17) and the LSM (p=0.37) also revealed no significant difference for these grouped wind speeds. Although a lack of significance for wind speed may be attributed to very small sample sizes, it may provide evidence that wind direction is also an important factor for this application. Because a majority of the material is ejected behind the worker, it is expected that concentrations may have increased when the wind direction was coming from the worker's back; however, the small sample sizes within each saw method does not allow for simple comparisons of the eight relative wind categories. In addition, it is suspected that different combinations of wind speed and wind direction may also result in different exposures.

Analysis of Covariance

To investigate the effect of the supplementary variables on RSP dust concentrations, an ANCOVA analysis was performed for the DSM. The WSM and LSM were not analyzed because data could not be adjusted to fit the assumptions of the ANCOVA model (i.e. due to the large number of values below the LOD). Concrete displacement, temperature, relative humidity, RWD, wind speed, and a wind speed, RWD interaction term was included in the initial analysis. The final model (p=0.02) included wind speed (p=0.007), RWD (p=0.074), and the wind speed, RWD interaction term (p=0.015) (See Equation 11). The natural log of the observed RSP dust concentrations were then plotted against the natural log of the RSP dust concentrations predicted by the model (See Appendix I, Figure I-1).

$$LN(P) = \mu + \alpha \times WS + \beta_j + (\alpha\beta)_j \times WS \qquad (11)$$

Notes: LN(P)=the natural log of the predicted RSP dust concentration, μ=intercept, α=Wind speed regression coefficient, WS=wind speed, β=RWD regression coefficient, j=RWD, (αβ)=interaction regression coefficient.

Even with a small sample size, the coefficient of determination was 0.8 and the model appeared to fit the data well. Validation of this model with a much larger sample size (i.e. more combinations of wind direction and wind speed) would need to be completed before predictions of RSP dust concentrations could be made for the DSM. However, more importantly, the model demonstrates that wind speed and wind direction play a significant role in a worker's exposure. When designing a dust control for outdoor activities, the role of these variables should be considered when assessing whether a control is adequate. The effect of various wind speeds and wind directions should become a part of the evaluation process for engineering controls intended for outdoor use.

Video Exposure Monitoring

The following section provides an analysis of data gathered during the VEM sampling periods, including an evaluation of RSP dust peak concentrations, a task-based analysis of real-time RSP dust concentrations, and a visual interpretation of the effectiveness of each engineering control.

Calibration Factor

Using two area side-by-side comparisons of average gravimetric and real-time concentrations, the real-time particulate calibration factor for the concrete dust was determined to be (8.1). Multiplying the real-time concentration data by the calibration factor reveals a concentration comparable to that of the gravimetric measurements. The calibration factor is reasonable because it falls within the range (i.e. 1- 18) for similar concrete measurements taken by Echt et al. (2003) during jack hammering. Nonetheless, because the measurements could not be taken side-by-side during personal sampling, all values have been left unadjusted. This will still allow for an appropriate comparison of concentration magnitude between saw methods and tasks.

Real-Time Overview

Appendix J, Table J-1 provides a summary of three real-time trials completed for each saw method. As in the gravimetric analysis, the percent RSP dust reduction was very similar between the WSM (80.9 percent) and the LSM (78.6 percent). The reductions for both the WSM and LSM were somewhat smaller for the real-time samples compared to the gravimetric samples. Some of this variation could be attributed to smaller real-time sample sizes and larger variations in environmental conditions for the gravimetric samples.

The WSM proved to be more effective in reducing peak concentrations (See Figure 18). The median peak reduction was almost 70 percent less for the WSM and only 54.6 percent less for the LSM. The wet method also appears to be more consistent in reducing peak levels of dust throughout the saw process (See Appendix K, Figure K-1). This supports statements made my OSHA in a guidance report to control silica in construction (OSHA, 2009). Regardless of reduction in RSP dust peak levels, the LSM still appears to be similar in its overall dust reduction capabilities.

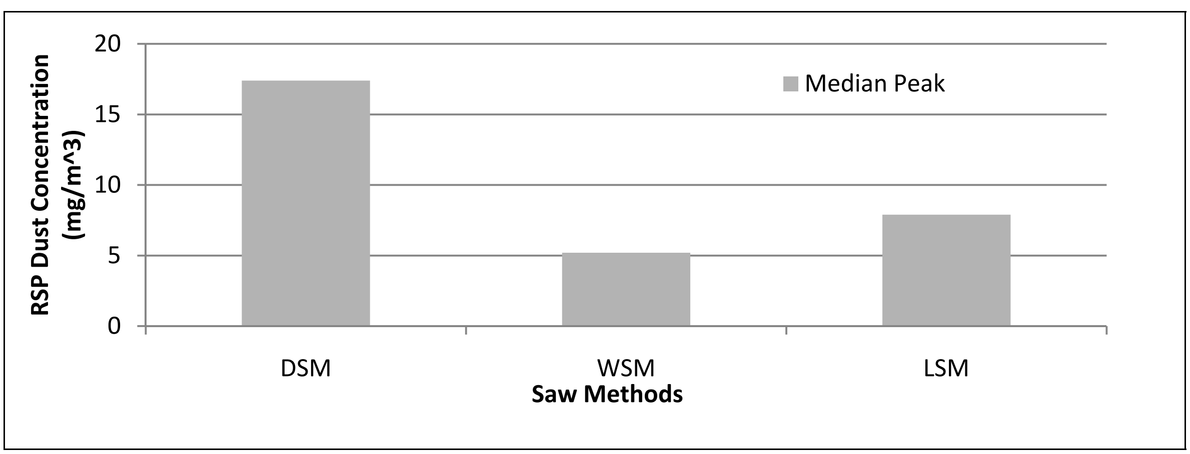

Figure 18. Median Peak Concentrations of Saw Methods.

Task-Based Analysis of Saw Process

A detailed, task-based analysis of the saw process provided additional knowledge regarding when the highest exposures were occurring during cutting. Appendix L provides an in depth summary of RSP dust concentrations for each task. In Appendix M, data from the individual trials were merged to illustrate the magnitude of concentrations seen during each individual task. For the DSM, both the median peak concentrations and the grand mean concentrations appeared to be much higher during the head cuts and the walk time following the head cut (See Appendix M, Figure M-1). Like the DSM, the WSM displayed the highest median peak and grand mean concentrations during either the head cut or the walk time following the head cut (See Appendix M, Figure M-2). The LSM also revealed similar results with the exception of the third flat cut (See Appendix M, Figure M-3).

Rendered with the real-time concentration streaming below the video, the video recordings allowed a further in-depth examination of these tasks to determine the potential risk factors during and immediately after the head cut. Although visible dust may not always relate directly to airborne RSP particulate, the videos show an appreciable amount of dust in the air during these noted tasks. Common to all saw methods, the worker was required to bend closer to the curb during the head cut. When the head cut was made, the dust was not ejected cleanly behind the worker, but was deflected off the ground and the worker. This resulted in a more concentrated cloud of dust around the worker. As the worker turned to walk, the dust appeared to be present in the air for at least half of the distance between cuts; therefore, the worker was exposed to the deflected particulate as they walked to the next cut as well.

A visible point source of dust creation could not be identified for the WSM; however, the LSM appeared to have identifiable weaknesses. As the LSM approached the 90 degree angle between the flat cut and the head cut, the spring-loaded guard did not meet closely with the curb face. During this short time, the saw ejected a steady flow of material under the worker. This was also observed at the very beginning of the flat cut, but for a shorter period of time. In addition, the collection bag also appeared to leak slightly at the zipper if the worker pulled on the bag too quickly. Eliminating these weaknesses may have a profound effect on local exhaust effectiveness and consistency.

Limitations for Roadway Construction

The saw water attachment, a feature that is present on most new gas-powered cut-off saws, provides workers with the ability to use wet suppression as an engineering control; however, less than 26 percent of concrete workers use this option (Nij, et al., 2003). Particularly in roadway construction, there are many drawbacks associated with the use of wet methods. As mentioned earlier, these include the worker getting wet, runoff onto residences, and discoloration of nearby materials (Croteau, Flanagan, Camp, & Seixas, 2004). Perhaps most importantly, is the fact that workers simply cannot use this dust control during the winter months, which can span a four month period in the upper United States. Worker and contractor habit of not using wet suppression in the winter months often downplays the necessity of preventing worker exposure. Another important drawback includes having a nearby water source. If water is not available onsite, the pressurized water canister can only hold enough water for approximately 15 minutes of effective dust suppression, greatly decreasing overall worker productivity.

On the other hand, less than 1 percent of concrete workers have access to LEV dust controls (Nij, et al., 2003). In addition, there are far less LEV dust controls that are gas-powered. Therefore, utilization of LEV in roadway construction is almost nonexistent. The advantages of gas-powered LEV systems include portability, year-round usability, lower operational costs, and improved comfort of the worker. Operators also reported only slight restrictions due to shroud design, and suggested that simple changes would fix these limitations. Drawbacks of the current LEV system include a 7 pound increase in the weight of the saw, with potential ergonomic repercussions, and a significant decrease in blade speed; however, utilizing a portable, external gas-powered vacuum system would reduce most of this weight and would increase power available to the saw blade. This would also give workers the ability to use a HEPA type filtering system, and eliminate dragging of a collection bag.

CONCLUSIONS

Personal cassette sampling revealed that the WSM and LSM method were capable of reducing RSP dust concentrations by 87 percent. In addition, statistical comparisons did not reveal significant differences in dust reduction capability between the LSM and WSM. Based on this data, LEV technology appears to have improved markedly in contrast to the absent reductions seen in the study by Croteau et al. (2002). The LEV system was also independent of electrical power, and well-adapted for roadway construction applications. Saw operators can perform cutting for almost 2 hours of work before emptying the collection bag. Roadway use of the WSM revealed smaller dust reductions than seen by Thorpe et al. (1999); however, use of a pressurized hand pump and placement on a two-wheeled cart also improved the ability of hand-held tool users to utilize water. Regardless of improved portability, the system was still not appropriate during cold weather conditions and workers were required to replenish water at least every sixteen minutes of sawing.

Based on an 8-hour period of continuous sawing, a worker would exceed the current quartz PEL by 9.6 times without dust suppression. Estimates of percent quartz determined from the individual DSM filter analysis, the combined filter analysis for both the WSM and LSM, and the bulk fracture analysis revealed similar results. Utilizing the combined filter estimates, a worker performing cutting for eight hours continuously would exceed the quartz PEL by 1.5 times for the WSM and 2.3 times for the LSM. For these circumstances, all methods would still prescribe the use of half-mask respirators. However, if exposure only occurred during the normal two hour cutting period, both the WSM and the LSM would reduce exposures to below the current NIOSH REL for quartz. Although respiratory protection would still be needed to reduce exposure below the TLV for quartz, with the implementation of these dust controls, the burden of exposure reduction would weigh less heavily on the proper implementation of respiratory protection programs.

Concrete displacement rates for the dust control methods revealed that the WSM reduced the rate of sawing by 63.1 percent and the LSM reduced the rate of sawing by 40.0 percent compared to the DSM. These rates suggest that exposure time would be extended due to reduced productivity. Adjusting the normal sawing period of two hours for these corresponding reductions in productivity, resulted in a 33 percent increase in concentration for the WSM and 29 percent increase in concentration for the LSM. Although the WSM and LSM were still below the OSHA PEL for this time period, they were equivalent or exceeded the NIOSH REL when the reduction in productivity was accounted for. The additional time needed for the WSM appears to be a rigid necessity when using a hand-pumped, pressurized canister; however, simply increasing the spindle speed of the LSM saw may reduce the additional exposure time for this method. Regardless of the solution, productivity was shown to be an important factor when assessing dust control reduction. In addition, wind direction and wind speed were determined to be significant predictors of RSP dust concentrations for outdoor sawing. For manufacturers to ensure methods designed for outdoor use will have consistent dust reductions, they must be evaluated under different degrees of wind speed and directions.

Real-time sampling revealed that over a period of three saw cuts, the WSM was more consistent in reducing peak concentrations of RSP dust than that of the LSM; however, the overall concentrations seemed to be very similar between the two methods. Although apparent weaknesses were not seen for the WSM, VEM revealed that the LSM had distinct point source weaknesses when maneuvering between sharp angles. The task-based analysis confirmed these findings, and provided evidence that exposure was highest for all methods during and immediately after such cuts.

With current overall LSM reductions approximately equivalent to the WSM, visible point source releases provides evidence that the dust reduction capabilities of the LEV methods can be improved, providing additional promise for even more effective designs in the future. In addition to dust reduction, the gas-powered LEV design appears to overcome many of the drawbacks associated with using water: workers being exposed to wet and caustic conditions, electrical hazards, and slipping hazards. Most significantly, workers would be protected year round through the winter months. Based on these findings, the LSM is the most appropriate solution for roadway construction; however, results have shown that the LSM may still need to be accompanied by respiratory protection, and further improvement of LEV system designs should be pursued by manufacturers.

Finally, it has been suggested by many studies that manufacturers provide performance data and instructions on proper use of particulate control methods (Croteau, Guffey, Flanagan, & Seixas, 2002; NIOSH, 2002; Thorpe, Ritchie, Gibson, & Brown, 1999). However, due to liability of false claims, a standardized method of testing these particulate control methods must be developed. For dust controls designed for outdoor applications, laboratory testing methods should include a baseline dust concentration for uncontrolled methods, a standardized material (e.g. concrete), a defined application (e.g. flat surface), a defined test of functionality (e.g. range of operating motion), flow rate measurements (e.g. water or air), productivity measurements, and a final determination of dust reduction at a defined distance from the source under different degrees of wind speed and directions. Reducing the liability of manufacturers would ultimately allow these companies to make legitimate claims of dust reduction and disease prevention. It is vital that manufacturers present this data to improve employer awareness and purchase knowledge.

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APPENDICES

Appendix A: Maximum Use Concentrations.

Table A-1. MUCs for Selected PPE and Exposure Guidelines.

		Maximum Use Concentration (mg/m^3)			
		OSHA	NIOSH	ACGIH	ACGIH
Various PPE	APF	PEL (Quartz)[B]	REL (Quartz)	TLV (Quartz)	TLV (RSP Dust)
Paper Dust Mask	≈1.4[A]	0.14	0.07	0.035	4.2
Half-Mask Respirator	10	1.0	0.50	0.250	30
Powered, Air Purifying with HEPA filter	25	2.5	1.25	0.625	75

[A] Estimated from values presented by Lahiri et al (2005).
[B] OSHA General Industry exposure limit.

Appendix B: Prior Dust Control Studies.

Table B-1. Comparison of TWA RSP Dust Concentrations for Hand-held Cut-off Saw Dust Control Studies.

Research Study	Control Method	Flow rate (Q)	RSP Dust (mg/m^3)	Dust Reduction (%)[E]
Thorpe et al. (1999)[A,B]	None		0.40	
	Hand Pump Supply (Wet)	NR	0.03	92.5
None			0.50	
	Garden Hose Supply (Wet)	NR	0.01	98.0
None			0.20	
	Vacuum Supply (LEV)	NR	0.02	90.0
Croteau et al. (2002)[C,D]	None		2.4	
	Vacuum Supply (LEV)	70 cfm	2.4	0.0

Notes: NR=not reported.
[A] Outdoor cutting of concrete slabs and curb.
[B] Concentrations are an arithmetic mean of the paired left and right personal air samples when using a diamond saw blade.
[C] Indoor cutting of concrete blocks.
[D] Concentration values are displayed as a geometric mean of six personal air samples.
[E] $\% = \left(Concentration_{NoCpntrol} - Concentration_{Control}\right) / Concentration_{NoControl} \times 100$

Appendix C: Recruitment Advertisement.

Call for Volunteer Subjects

Project Title: “Evaluation and Development of a Silica Scavenging System for Highway Construction Cut-Off Saws”

Contact Information (Principal Investigator):

Dr. Bryan J. Hubbard
[redacted]

Project Description:

The purpose of this study is to develop and evaluate a new application of existing ventilation technology to decrease exposure to respirable crystalline silica for cut-offing sawing while conforming to specific construction needs.

Specific Procedures:

You will operate a cut-off saw during normal work conditions. You will be assigned to one of three groups. The first group will not use engineering controls with the cut-off saw. The second group will use water as a dust control, which is attached to the cut-off saw directly by hose. The third group will use a local exhaust ventilation system as a dust control, which requires a vacuum pack to be worn. For all groups, you will be required to wear a sampling pump or real- time instrument on your belt in order to monitor particulate concentrations in the breathing zone. The sampling pump or real time instrument will be attached by tygon tubing to a cyclone and cassette, which will be clipped to the lapel. You must wear safety glasses, hearing protection, and a dust mask for the duration of the study. In addition, to ensure proper fit of the paper dust masks, you may not display facial hair that interferes with the efficiency of the dust mask. Pictures and/or video will be taken to correlate work practices with analysis results.

Appendix D: Consent Form.

For IRB Office Use Only
APPROVED
AUG 09 2008
EXPIRES 8/8/09
PURDUE UNIVERSITY
INSTITUTIONAL REVIEW BOARD

Research Project Number 0806007011

RESEARCH PARTICIPANT CONSENT FORM

Evaluation and Development of a Silica Scavenging System for Highway Construction Cut-Off Saw

Bryan Hubbard
College of Technology
Purdue University

Beauregard Middaugh
School of Health Sciences
Purdue University

Purpose of Research
The purpose of this study is to develop and evaluate a new application of existing ventilation technology to decrease exposure to respirable crystalline silica for cut-offing sawing while conforming to specific construction needs.

Specific Procedures
You will operate a cut-off saw during normal work conditions. You will be assigned to one of three groups. The first group will not use a dust control device with the cut-off saw. The second group will use water as a dust control, which is attached to the cut-off saw directly by hose. The third group will use a local exhaust ventilation system as a dust control, which requires a vacuum pack to be worn. For all groups, you will be required to wear a sampling pump or real-time instrument on your belt in order to monitor particulate concentrations in the breathing zone. The sampling pump or real time instrument will be attached by tygon tubing to a cyclone and cassette, which will be clipped to the lapel. Regardless of the group you are in, you will be required to wear safety glasses, hearing protection, and a dust mask for the duration of the study. In addition, to ensure proper fit of the paper dust masks, you may not display facial hair that interferes with the efficiency of the dust mask. Pictures and/or video will be taken to correlate work practices with analysis results.

Duration of Participation
The study will take less than 1 hour.

Risks
There is no additional risk associated with this study beyond the normal, daily job requirements.

Benefits
You will have no direct benefits for participating in this study.

Compensation
You will receive no compensation for participating in this study.

Injury or Illness
Purdue University will not provide medical treatment or financial compensation if you are injured or become ill as a result of participating in this research project. This does not waive any of your legal rights nor release any claim you might have based on negligence.

Confidentiality

All information gathered will be kept confidential, results of this study will be submitted for publication without any subject identifiable information by using assigned sample ID numbers, and when your data is not being directly examined or used by the researchers it will be kept in a locked storage box accessible only to the research team. Any videos/photos taken of you during this study will not be used in published materials and/or for educational purposes without your permission. If photos are used, all efforts will be made by the researchers to block out the face of the individual if you request. Data, photos, and video recordings will be kept three years after the project is completed and will be destroyed by the project researchers thereafter. The project's research records may be reviewed by The Center for Disease Control and Prevention and by departments at Purdue University responsible for regulatory and research oversight.

Use of photos in published materials and/or for educational purposes

☐ No, I do NOT give my permission to use any photos taken of myself during this study in published materials and/or educational purposes.

☐ Yes, I give my permission to use any photos taken of myself during this study in published materials and/or educational purposes with the understanding that my identity will be blocked if requested.

Block my identity: ☐ Yes ☐ No

Voluntary Nature of Participation

You do not have to participate in this research project. If you agree to participate you can withdraw your participation at any time without penalty. Your decision to participate/not participate will not have any influence on the relationship you have with E&B Paving, Inc.

Contact Information:

[redacted]

Documentation of Informed Consent

I have had the opportunity to read this consent form and have the research study explained. I have had the opportunity to ask questions about the research project and my questions have been answered. I am prepared to participate in the research project described above. I will receive a copy of this consent form after I sign it.

______________________________ __________________

Participant's Signature Date

____

Participant's Name

______________________________ __________________

Researcher's Signature Date

Appendix E: Sawing Tasks.

Table E-1. Overview of Task Descriptions used for Task-Based Analysis.

Task Task		Descriptions
1) Start	Begin:	Sample commencement.
	Task:	Prepares to make first saw cut.
2) Flat Cut 1	Begin:	Sawing commences for the first saw joint.
	Task:	Cut front, flat section of the curb.
3) Head Cut 1	Begin:	Sawing commences on incline of the back, head of the curb. Cut
	Task:	head of curb for the first saw joint.
4) Walk 1	Begin:	Sawing is terminated for the first saw cut.
	Task:	Move equipment approximately 10 feet to second curb joint.
5) Flat Cut 2	Begin:	Sawing commences for the second saw joint.
	Task:	Cut front, flat section of the curb.
6) Head Cut 2	Begin:	Sawing commences on incline of the back, head of the curb. Cut
	Task:	head of curb for the second saw joint.
7) Walk 2	Begin:	Sawing is terminated for the second saw cut.
	Task:	Move equipment approximately 10 feet to third curb joint.
8) Flat Cut 3	Begin:	Sawing commences for the third saw joint.
	Task:	Cut front, flat section of the curb.
9) Head Cut 3	Begin:	Sawing commences on incline of the back, head of the curb. Cut
	Task:	head of curb for the third saw joint.
10) Finish	Begin:	Sawing is terminated for the third saw cut.
	Task:	All immediate actions following last cut.

Notes: The completion point of each task is the time immediately before the commencement of the next task. The last task is defined as a fifteen second period.

Appendix F: Side-by-Side Comparison.

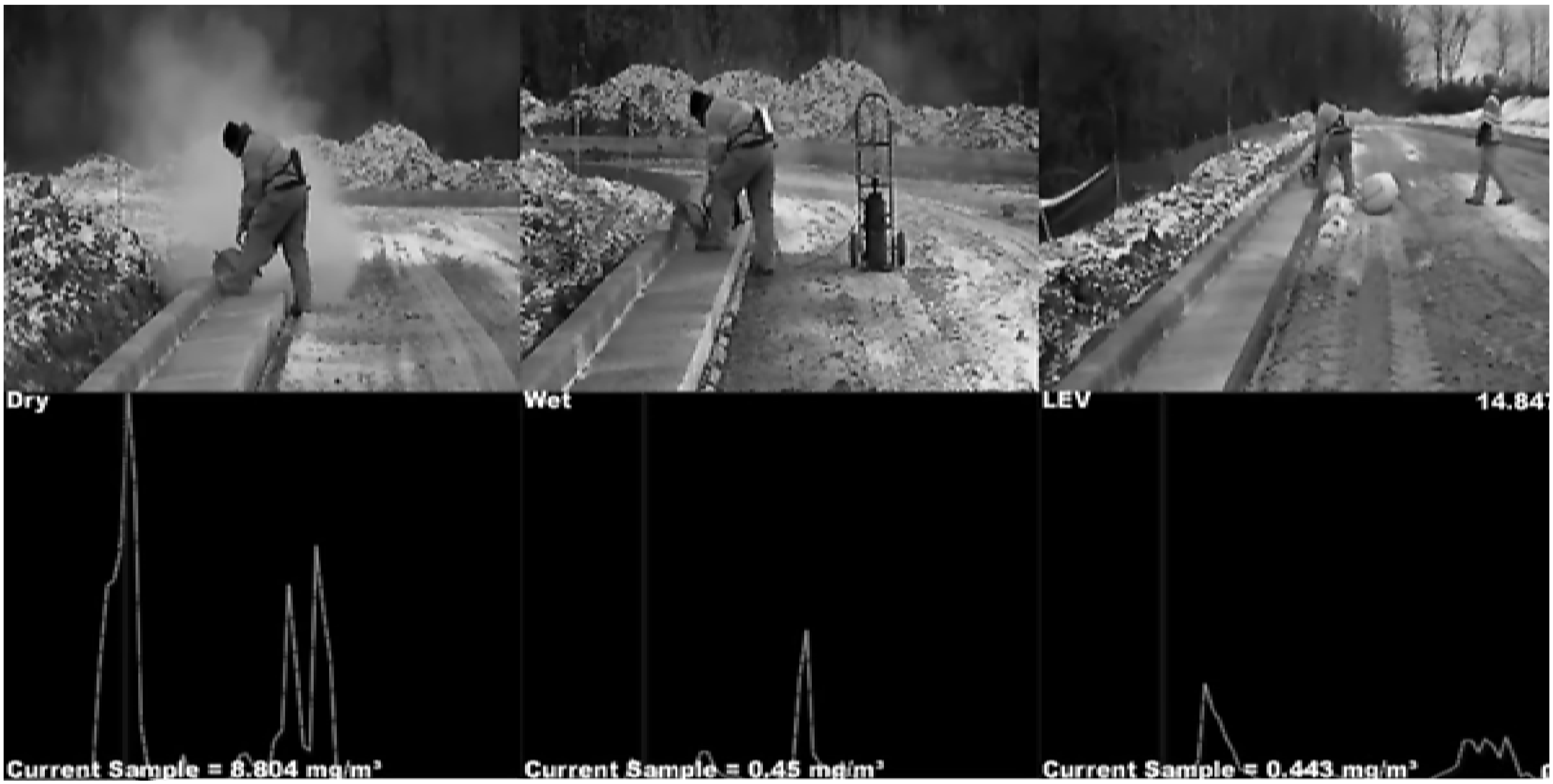

Figure F-1. Screenshot of Side-by-Side VEM Comparison of Saw Methods.

Appendix G: Supplementary Data Summaries.

Table G-1. Summary of Supplementary Data for DSM.

Trial	RSP Dust (mg/m^3)	CDR (in^3/min)	Temperature (°F)[A]	RH (%)[A]	Wind Speed (mph)[A]	RWD
1	21.27	17.30	48.66	100.00	0.00	Right
2	15.94	14.22	49.75	100.00	0.00	Right
3	48.57	13.70	57.37	94.11	0.00	Front
4	10.33	13.50	56.82	100.00	0.00	Right
5	12.36	12.52	56.94	100.00	0.00	Right
6	12.08	9.50	58.67	100.00	0.31	Right
7	25.45	11.75	58.87	99.91	0.27	Left Front
8	5.84	14.72	51.38	93.89	0.19	Front
9	6.84	10.67	60.33	67.65	0.81	Right
10	23.50	16.42	64.06	60.74	3.09	Right Back
11	44.88	14.20	64.93	61.65	3.66	Right Back
12	35.58	16.61	64.93	61.65	3.66	Right Back
13	21.61	18.27	64.93	61.65	3.66	Right Back
14	5.22	16.52	75.55	55.60	0.00	Left Back
15	20.72	16.47	75.27	56.21	0.00	Left Back
16	15.57	11.73	56.60	35.12	0.00	Right
17	12.57	12.50	56.60	35.18	0.00	Right

Notes: RWD=Relative Wind Direction. CDR=Concrete Displacement Rate.
[A] Arithmetic mean for sampling period.

Table G-2. Summary of Supplementary Data for WSM.

Trial	RSP Dust (mg/m^3)	CDR (in^3/min)	Temperature (°F)[A]	RH (%)[A]	Wind Speed (mph)[A]	RWD
1	1.85	9.55	52.73	98.37	8.33	Right Back
2	1.88	10.23	52.44	99.46	7.95	Right Back
3	1.90	15.19	52.45	99.90	6.68	Right Back
4	15.56	5.10	30.89	100.00	0.06	Right Front
5	16.86	5.98	31.87	100.00	0.05	Left Front
6	2.07	3.94	35.21	99.15	3.44	Left Back
7	2.01	4.34	37.89	91.24	2.99	Left Back
8	2.04	5.06	37.89	91.24	2.99	Left Back
9	2.04	7.83	37.89	91.24	2.99	Left Back
10	2.02	5.38	37.89	91.24	2.99	Left Back
11	1.91	6.41	37.89	91.24	2.99	Left Back
12	1.40	4.97	47.64	88.79	0.00	Left Back
13	1.87	4.67	57.97	61.86	0.15	Left Front
14	1.64	4.02	53.18	72.89	3.71	Left Front

Notes: RWD=Relative Wind Direction. CDR=Concrete Displacement Rate.
[A] Arithmetic mean for sampling period.

Table G-3. Summary of Supplementary Data for LSM.

Trial	RSP Dust (mg/m^3)	CDR (in^3/min)	Temperature (°F)[A]	RH (%)[A]	Wind Speed (mph)[A]	RWD
1	2.05	9.41	49.00	74.71	0.00	Front
2	1.99	8.40	50.36	76.46	0.00	Front
3	2.04	10.33	52.63	63.92	1.05	Back
4	2.22	7.95	54.11	60.15	1.61	Front
5	10.42	12.35	58.37	71.87	2.93	Right Back
6	13.77	8.62	59.06	70.44	0.00	Right Back
7	5.81	7.73	76.61	51.86	0.00	Left Back
8	1.71	8.56	58.78	32.23	0.00	Right
9	2.02	6.48	57.46	33.71	0.00	Right
10	2.14	6.77	57.01	34.28	0.00	Right
11	1.97	7.13	56.76	34.68	0.00	Right
12	2.10	8.58	59.60	68.69	0.85	Right

Notes: RWD=Relative Wind Direction. CDR=Concrete Displacement Rate.
[A] Arithmetic mean for sampling period.

Appendix H: Weather Conditions.

Table H-1. Descriptive Statistics for Temperature and Relative Humidity during Filter Cassette Sampling.

		Temperature (°F)			Relative Humidity (%)		
Control Method	N	AM(SD)	Median	Min-Max AM	(SD)	Median	Min-Max
DSM	17	60.1 (7.6)	58.7	48.7-75.5	75.5 (23.9)	67.6	35.1-100
WSM	14	43.1 (9.1)	37.9	38.9-58.0	91.1 (11.1)	91.2	61.9-100
LSM	12	57.5 (7.0)	57.2	49.0-76.6	56.1 (17.8)	62.0	32.2-76.5

Notes: N = number of samples, AM (ASD) = arithmetic mean (arithmetic standard deviation).

Table H-2. Descriptive Statistics for Wind Speed during Filter Cassette Sampling.

		Wind Speed (mph)		
Control Method	N	AM(SD)	Median	Min-Max
DSM 17		.92 (1.5)	0.00	0.00-3.6
WSM 14		3.2 (2.8)	2.99	0.00-8.3
LSM 12		.54 (.93)	0.00	0.00-2.9

Notes: N = number of samples, AM (ASD) = arithmetic mean (arithmetic standard deviation).

Appendix I: ANCOVA DSM Analysis.

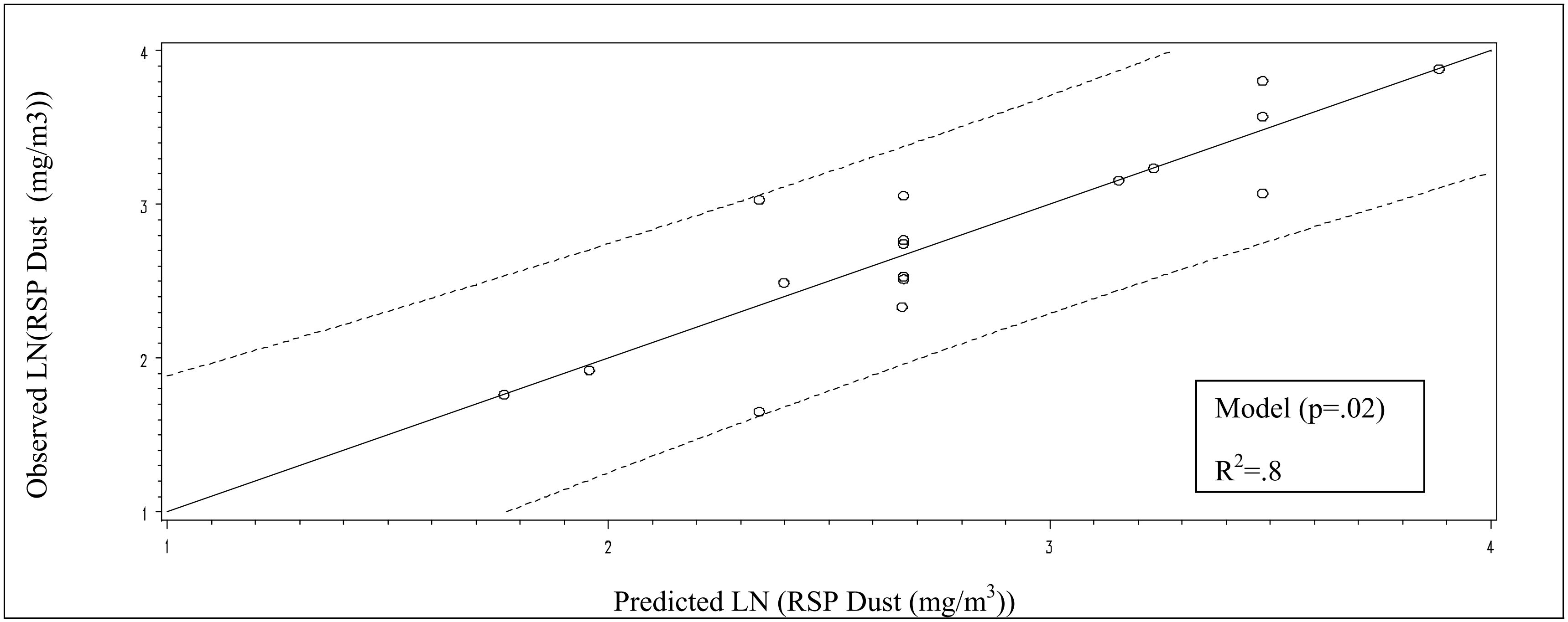

Figure I-1. The Natural Log of Observed versus Predicted RSP Dust Concentrations Determined from an ANCOVA Model including Wind Speed, RWD, and a Wind Speed, RWD Interaction Term.

Appendix J: Real-Time Sampling Trials.

Table J-1. Summary of Real-Time RSP Dust Concentrations for Sampling Trials.

			RSP Dust Concentration (mg/m^3)						
Method	Trial	T(sec)	GM (GSD)	AM (SD)	Median	Min - Max	Median Peak	μ^A	Reduction (%)^B
DSM	1	74	0.61 (4.88)	2.51 (3.71)	0.72	0.01 - 14.24			
DSM	2	86	0.21 (4.76)	1.76 (3.75)	0.15	0.01 - 17.37			
DSM	3	84	0.40 (4.91)	3.16 (5.37)	0.48	0.01 - 25.95	17.4	2.48	
WSM	1	88	0.17 (2.71)	0.38 (0.52)	0.15	0.02 - 2.09			
WSM	2	99	0.18 (1.79)	0.34 (0.74)	0.12	0.02 - 5.77			
WSM	3	107	0.19 (3.13)	0.70 (1.13)	0.16	0.02 - 5.20	5.20	0.47	80.9
LSM	1	137	0.15 (3.45)	0.51 (1.07)	0.17	0.01 - 8.87			
LSM	2	118	0.16 (2.13)	0.57 (1.05)	0.16	0.01 - 7.89			
LSM	3	117	0.19 (1.00)	.0.51 (0.63)	0.22	0.01 - 3.00	7.89	0.53	78.6

Notes: T=time in seconds, GM(GSD)=Geometric Mean (Geometric Standard Deviation), AM (ASD)=Arithmetic Mean (Arithmetic Standard Deviation, μ=grand mean.

A $\mu = \left(\sum_{i=1}^{3} AM \right) / 3$

B $\% = \left(\mu_{DSM} - \mu_{Control} \right) / \mu_{DSM} \times 100$

Appendix K: Comparison of Real-Time Sampling Periods.

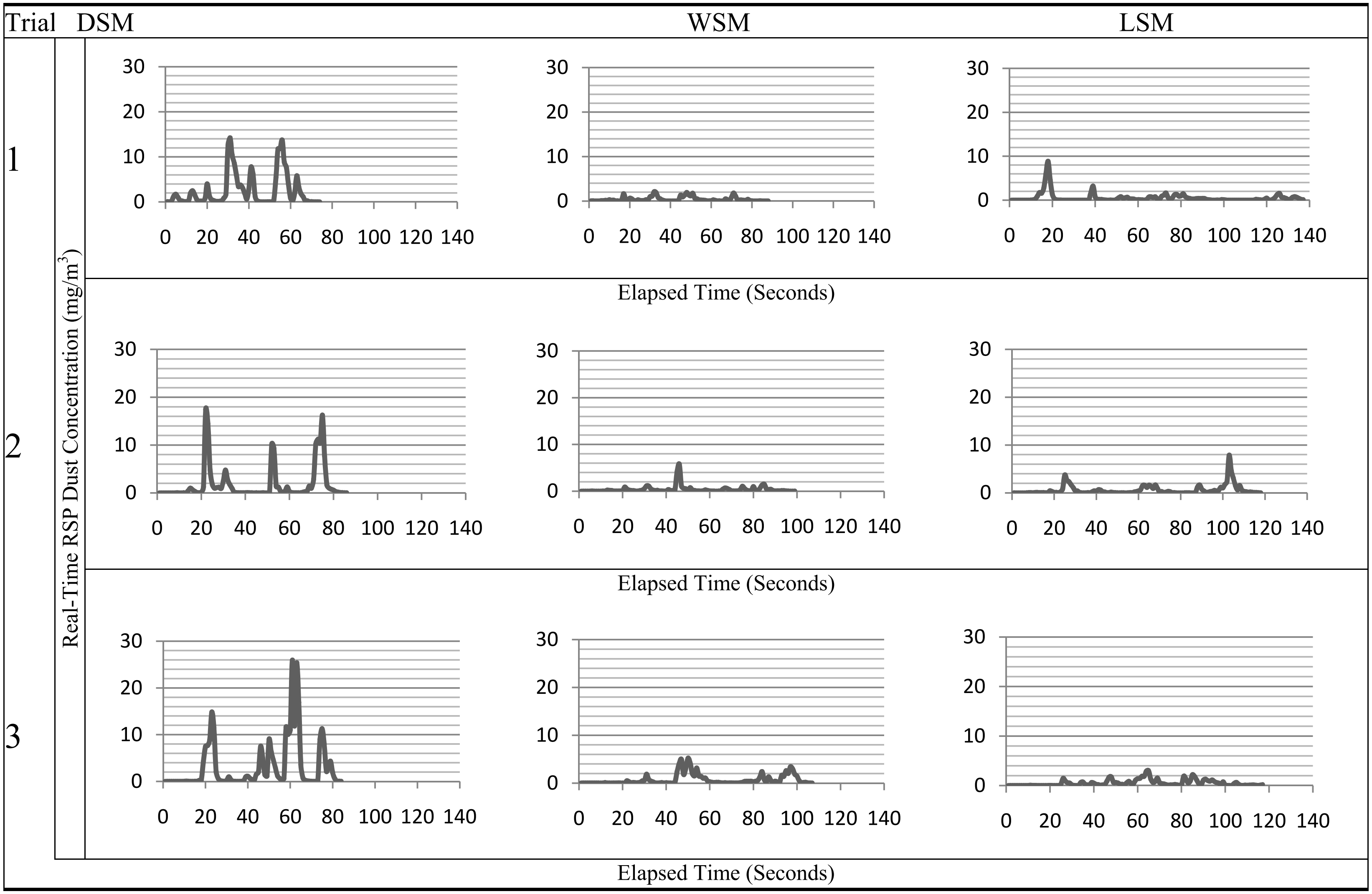

Figure K-1. Plots of Real-Time RSP Dust Concentrations for Three Sampling Periods of Each Saw Method.

Appendix L: Task-Based Real-Time Summary.

Table L-1. Task-Based Real-Time RSP Dust Concentrations for DSM.

	RSP Dust Concentration (mg/m³)								
	Trial 1			Trial 2			Trial 3		
Task	GM (GSD)	Median	Min-Max	GM (GSD)	Median	Min-Max	GM (GSD)	Median	Min-Max
1) Start	0.04 (1.89)	0.05	0.02 - 0.08	0.02 (1.13)	0.02	0.01 - 0.02	0.02 (1.61)	0.01	0.01 - 0.06
2) Flat Cut 1	0.46 (2.70)	0.33	0.09 - 1.72	0.13 (4.04)	0.10	0.02 - 0.99	0.08 (6.28)	0.03	0.02 - 4.27
3) Head Cut 1	0.44 (4.41)	0.57	0.05 - 2.49	3.13 (3.12)	1.74	0.98 - 17.4	5.28 (2.84)	7.67	0.62 - 14.8
4) Walk 1	0.69 (2.90)	0.69	0.20 - 4.02	2.03 (1.81)	2.45	0.94 - 4.77	0.14 (3.54)	0.17	0.02 - 0.99
5) Flat Cut 2	0.54 (4.18)	0.30	0.16 - 12.5	0.13 (4.47)	0.06	0.04 - 1.72	0.04 (2.93)	0.03	0.02 - 0.34
6) Head Cut 2	6.78 (1.69)	7.28	3.40 - 14.2	0.02 (1.49)	0.02	0.01 - 0.05	1.00 (2.86)	1.04	0.18 - 7.49
7) Walk 2	2.52 (2.26)	2.87	0.64 - 7.75	0.18 (17.1)	0.03	0.02 - 10.2	3.58 (2.15)	4.78	1.16 - 8.96
8) Flat Cut 3	0.04 (2.36)	0.04	0.01 - 0.23	0.26 (3.64)	0.32	0.03 - 1.34	2.16 (4.04)	2.03	0.27 - 11.6
9) Head Cut 3	5.78 (2.86)	8.27	0.44 - 13.7	0.26 (5.16)	0.27	0.02 - 2.88	2.05 (9.62)	3.60	0.07 – 26.0
10) Finish	0.26 (7.07)	0.26	0.02 - 5.81	0.74 (9.65)	0.77	0.02 - 16.3	0.43 (10.9)	0.60	0.02 - 11.3

Table L-2. Task-Based Real-time RSP Dust Concentrations for WSM.

	RSP Dust Concentration (mg/m^3)								
	Trial 1			Trial 2			Trial 3		
Task	GM (GSD)	Median	Min-Max	GM (GSD)	Median	Min-Max	GM (GSD)	Median	Min-Max
1) Start	0.09 (1.85)	0.09	0.04 - 0.29	0.02 (1.17)	0.02	0.02 - 0.03	0.03 (1.28)	0.02	0.02 - 0.04
2) Flat Cut 1	0.15 (3.14)	0.09	0.04 - 1.65	0.07 (2.13)	0.05	0.03 - 0.23	0.04 (1.75)	0.03	0.02 - 0.11
3) Head Cut 1	0.20 (2.27)	0.15	0.05 - 0.65	0.21 (2.50)	0.20	0.05 - 0.89	0.11 (2.62)	0.08	0.02 - 0.50
4) Walk 1	0.65 (2.68)	1.01	0.15 - 2.09	0.23 (3.91)	0.34	0.03 - 1.16	0.24 (3.77)	0.35	0.02 - 1.88
5) Flat Cut 2	0.09 (3.27)	0.04	0.02 - 0.78	0.08 (2.20)	0.07	0.02 - 0.25	0.12 (6.45)	0.08	0.02 - 4.16
6) Head Cut 2	1.35 (1.26)	1.36	0.93 - 1.94	0.64 (4.20)	0.35	0.14 - 5.77	1.12 (3.24)	1.49	0.13 - 5.20
7) Walk 2	0.30 (2.87)	0.26	0.06 - 1.75	0.22 (2.51)	0.22	0.06 - 0.74	0.07 (1.74)	0.06	0.03 - 0.18
8) Flat Cut 3	0.10 (1.84)	0.10	0.05 - 0.27	0.06 (2.73)	0.06	0.02 - 0.44	0.40 (1.17)	0.39	0.31 - 0.56
9) Head Cut 3	0.24 (4.50)	0.31	0.02 - 1.82	0.23 (3.14)	0.27	0.03 - 1.31	0.53 (2.76)	0.62	0.08 - 2.41
10) Finish	0.08 (2.47)	0.06	0.02 - 0.40	0.10 (3.50)	0.08	0.02 - 1.47	0.45 (5.62)	0.98	0.03 - 3.42

Table L-3. Task-Based Real-time RSP Dust Concentrations for LSM.

Task	RSP Dust Concentration (mg/m^3)								
	Trial 1			Trial 2			Trial 3		
	GM (GSD)	Median	Min-Max	GM (GSD)	Median	Min-Max	GM (GSD)	Median	Min-Max
1) Start	0.02 (1.93)	0.02	0.01 - 0.08	0.03 (1.91)	0.02	0.01 - 0.09	0.02 (1.58)	0.02	0.01 - 0.06
2) Flat Cut 1	0.13 (9.14)	0.04	0.02 - 8.87	0.12 (2.44)	0.10	0.04 - 0.82	0.02 (1.37)	0.02	0.02 - 0.03
3) Head Cut 1	0.13 (4.60)	1.78	0.03 - 3.21	0.26 (6.97)	0.42	0.02 - 3.74	0.16 (5.19)	0.27	0.02 - 1.47
4) Walk 1	0.46 (1.48)	0.52	0.26 - 0.81	0.36 (1.55)	0.37	0.20 - 0.69	0.32 (1.88)	0.27	0.14 - 0.74
5) Flat Cut 2	0.25 (2.67)	0.18	0.04 - 0.91	0.05 (2.15)	0.05	0.01 - 0.19	0.40 (2.40)	0.41	0.08 - 1.76
6) Head Cut 2	0.78 (1.84)	0.90	0.17 - 1.66	0.97 (1.74)	1.14	0.30 - 1.68	1.16 (2.00)	1.34	0.29 – 3.00
7) Walk 2	0.29 (1.50)	0.35	0.13 - 0.42	0.17 (1.78)	0.18	0.06 - 0.32	0.80 (2.80)	0.39	0.11 - 1.53
8) Flat Cut 3	0.03 (1.94)	0.03	0.02 - 0.15	0.06 (5.72)	0.02	0.01 - 1.67	0.43 (3.20)	0.45	0.07 - 2.20
9) Head Cut 3	0.06 (2.89)	0.06	0.02 - 0.47	0.68 (3.08)	0.52	0.14 - 7.89	0.35 (4.00)	0.68	0.02 - 1.30
10) Finish	0.47 (2.01)	0.59	0.14 - 1.55	0.34 (4.17)	0.24	0.04 - 4.63	0.11 (2.54)	0.10	0.01 - 0.66

Appendix M. Task-Based Visualization.

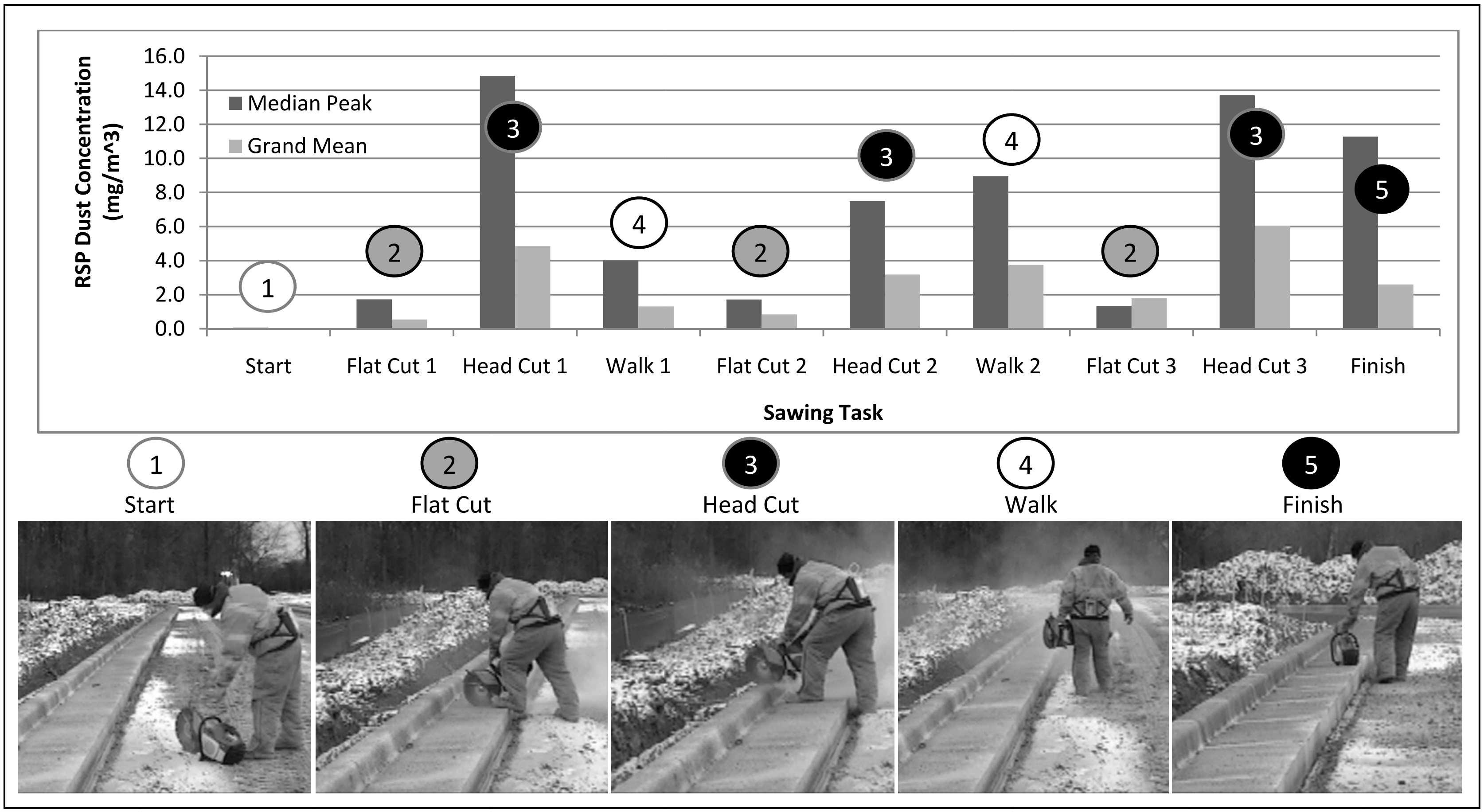

Figure M-1. DSM Task-Based Visualization of Real-Time Trials.

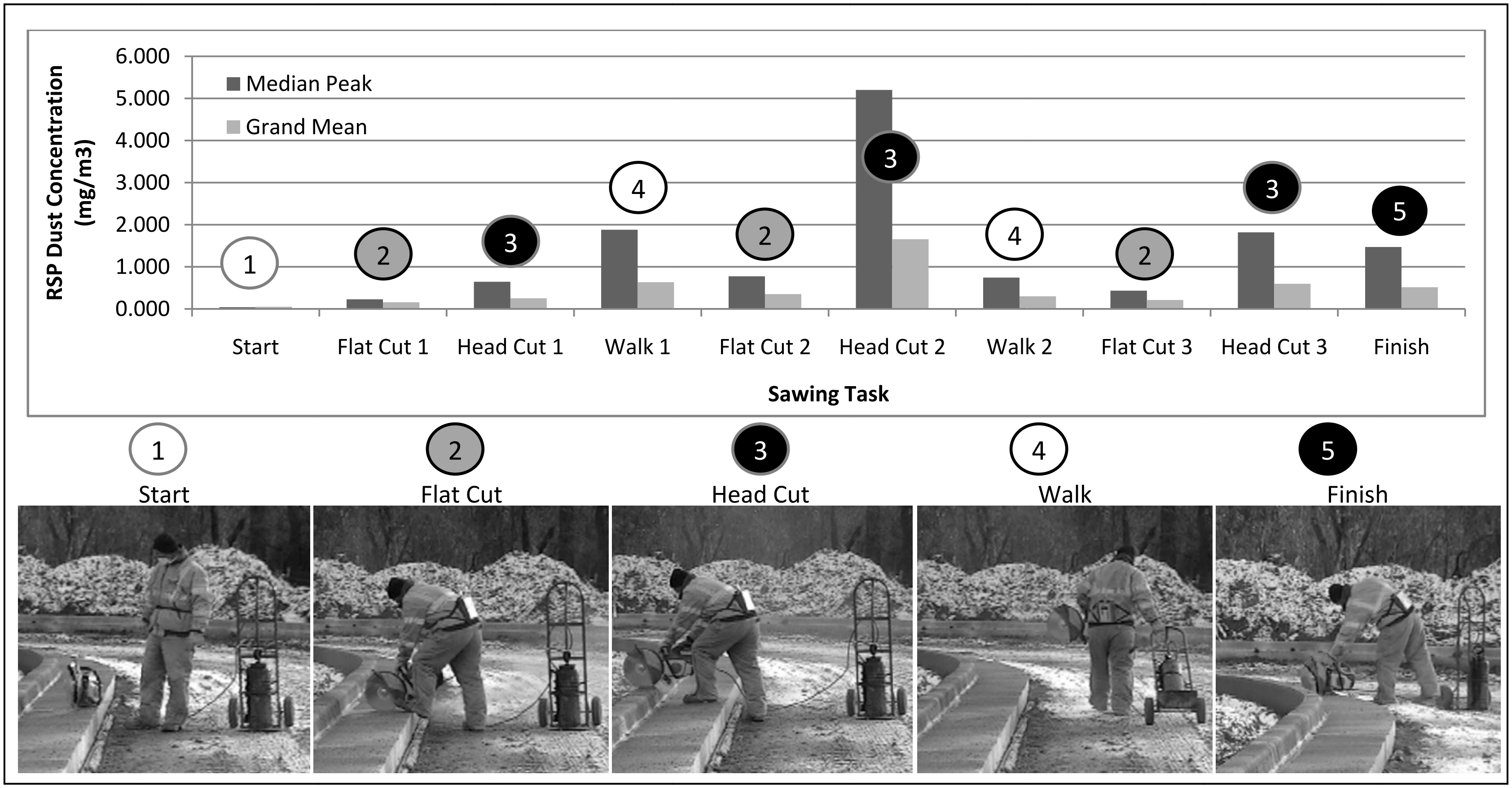

Figure M-2. WSM Task-Based Visualization of Real-Time Trials.

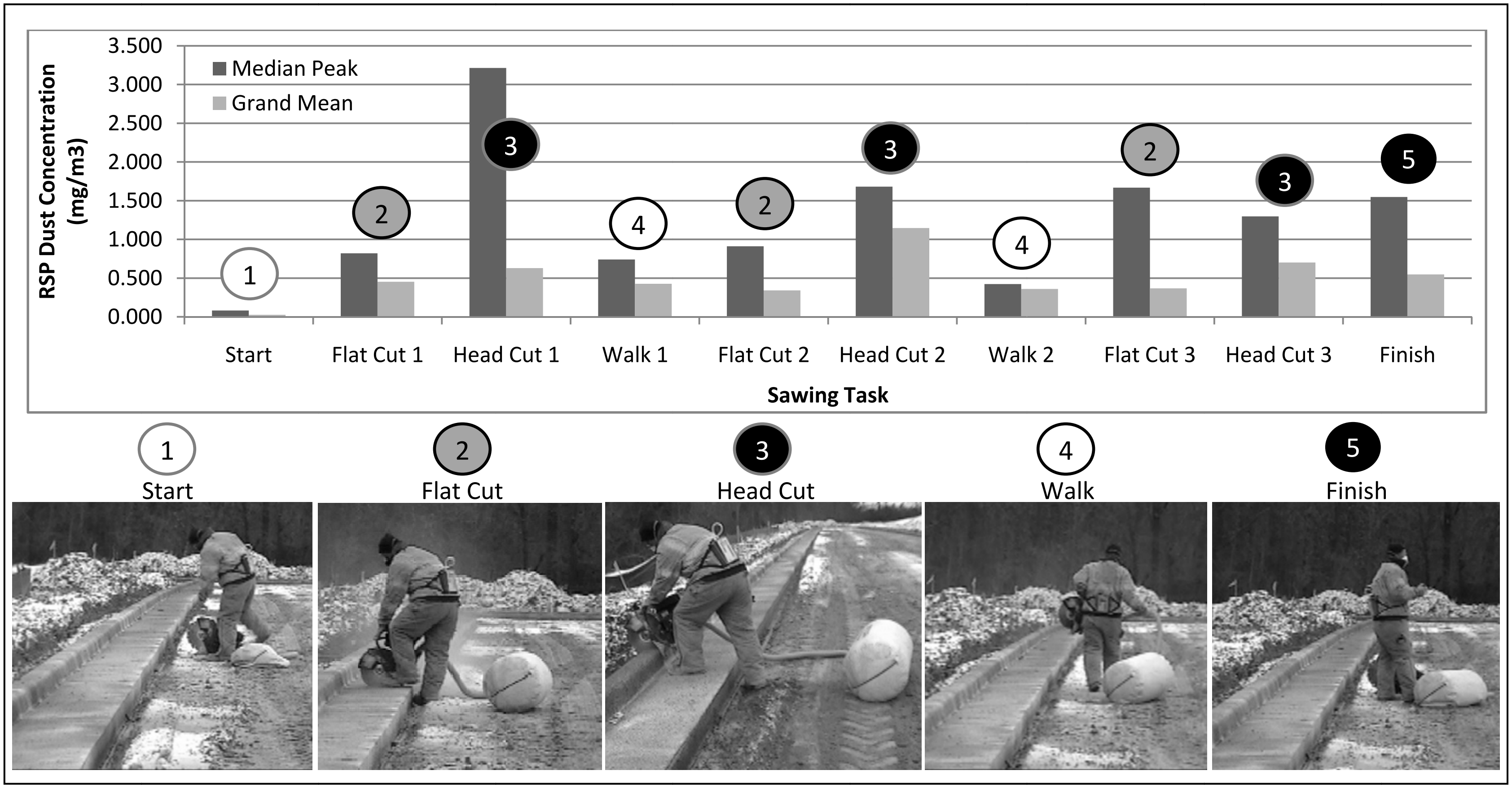

Figure M-3. LSM Task-Based Visualization of Real-Time Trials.