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An Exploratory Study: Assessment of Modeled Dioxin Exposure in Ceramic Art Studios

National Center for Environmental Assessment
Office of Research and Development, Washington, DC 20460

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ABSTRACT

The purpose of this report is to describe an exploratory investigation of potential dioxin exposures to artists/hobbyists who use ball clay to make pottery and related products. Dermal, inhalation and ingestion exposures to clay were measured at the ceramics art department of Ohio State University in Columbus, OH. The measurements were made in two separate studies: one in April 2003 and one in July 2004. This assessment combines the results of these two studies. Estimates of exposure were made based on measured levels of clay in the studio air, deposited on media representing food and on the skin of artists. Dioxin levels in the clay were based on levels reported in the literature for commercial ball clays commonly used by ceramic artists.

Hypothetical dioxin dose estimates were calculated for each subject assuming that all used a 20% ball clay blend with 162 pg TEQ/g. The single-day total doses across the 10 subjects ranged from 0.32 to 7.1 pg TEQ/d, with an average of 1.44 pg TEQ/d (SD = 2.0). The dermal pathway was the major contributor to total dose, exceeding 67% for all subjects. A Monte Carlo simulation was conducted to explore how doses could vary in a broad population of artists. This simulation suggested a mean total dose of 6.4 pg TEQ/d (SD = 8.4), median of 3.5 pg TEQ/d, and 90th percentile of 14.8 pg TEQ/d.

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LIST OF ABBREVIATIONS AND ACRONYMS

ACGIH	American Conference of Governmental Industrial Hygienists
˚C	degrees Centigrade
CDD	chlorinated dibenzo-*p*-dioxin
CDD/F	chlorinated dibenzo-*p*-dioxin and chlorinated dibenzofurans
CDF	chlorinated dibenzofuran
cm	centimeter
DI	deionized
EDS	energy dispersive spectroscopy
ET	extrathoracic
g	gram
GFF	glass fiber filters
HpCDD	heptachlorodibenzo-*p*-dioxin
Hz	hertz
HxCDD	hexachlorodibenzo-*p*-dioxin
ICRP	International Commission on Radiological Protection
IRB	Institutional Review Board
kg	kilogram
K_{ow}	octanol-water partition coefficient
L	liter
LRB	laboratory record book
m	meter
mg	milligram
mL	milliliter
mm	millimeter
MMAD	mass median aerodynamic diameter
MPPD	Multiple Path Particle Dosimetry
MSS	model sum of squares
NA	not available
NIST	National Institute of Standards and Technology

LIST OF ABBREVIATIONS AND ACRONYMS (continued)

NM	not measured
OCDD	octachlorodibenzo-*p*-dioxin
OSHA	Occupational Safety and Health Administration
OSU	Ohio State University
PCB	polychlorobiphenyls
PCDD	polychlorinated dibenzo-*p*-dioxin
PeCDD	pentachlorodibenzo-*p*-dioxin
pg	pictogram
ppt	parts per thousand
PU	pulmonary
r^2	regression coefficient squared
RIVM	National Institute of Public Health and the Environment
RSS	residual sum of squares
SD	standard deviation
SEM	scanning electron microscopy
TB	tracheobronchial
TCDD	tetrachlorodibenzo-*p*-dioxin
TEF	toxic equivalency factor
TEQ	toxic equivalent
TSS	total corrected sum of squares
TWA	time-weighted average
UMDES	University of Michigan Dioxin Exposure Study
U.S. EPA	United States Environmental Protection Agency
WHO	World Health Organization
µg	microgram
µm	micrometer

PREFACE

Dioxins were discovered in ball clay in 1996 as a result of an investigation to determine the sources of elevated dioxin levels in two chicken samples from a national survey of poultry. The investigation indicated that the contamination source was ball clay added to chicken meal as an anti-caking agent. The purpose of this study is to evaluate another potential exposure scenario associated with ball clay, namely its use in ceramic art studios. This exploratory investigation makes preliminary exposure estimates that can be used to evaluate whether more detailed follow-up analyses are needed. Hypothetical dioxin exposure estimates were calculated using an assumption of dioxin levels in the ball clay based on measurements from other studies. The study was conducted during 2003 and 2004 by the National Center for Environmental Assessment with contract support provided by Battelle in Columbus, Ohio.

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1. INTRODUCTION AND BACKGROUND

Ball clay is a natural clay mined commercially in the United States, primarily in Kentucky, Tennessee, and Mississippi. A total of 1.21 million metric tons was mined in the United States in 2005. Its plasticity makes ball clay an important commercial resource for a variety of commercial uses. In 2005, it was used as follows: floor and wall tile—40%, sanitary ware (sinks, toilets, etc.)—25%, exports—17%, ceramics—11%, fillers, extenders and binders—4%, pottery—1.5%, and miscellaneous purposes—1.9% (USGS, 2007).

Dioxins were discovered in ball clay in 1996 as a result of an investigation to determine the sources of elevated dioxin levels in two chicken samples from a national survey of poultry (Ferrario et al., 1997). The investigation indicated that soybean meal added to chicken feed was the source of the dioxin contamination. Further investigation showed that the dioxin contamination occurred when ball clay was mixed with the soybean meal as an anti-caking agent (Ferrario et al., 2000b; U.S. FDA, 2000). In 1997, the U.S. Food and Drug Administration (FDA) asked producers or users of clay products in animal feeds to cease using ball clay in all animal feeds and feed ingredients (U.S. FDA, 1997).

During the same time period that the present study was conducted, a completely independent study called the University of Michigan Dioxin Exposure Study (UMDES) was being conducted (Franzblau et al., 2008). UMDES measured chlorinated dibenzo-*p*-dioxins (CDDs), chlorinated dibenzofurans (CDFs), and polychlorinated biphenyls (PCBs) in serum of 946 subjects who were a representative sample of the general population in five Michigan counties. The individual with the highest blood level (211 ppt TEQ) among all 946 subjects had practiced ceramics art in her home for over 30 years. A follow-up analysis was performed to explore the source of this subject's exposure. Based on the similarity of the congener profile of the subject's blood and the clay she used, Franzblau et al. concluded that exposure from the ceramics work was the most likely reason for the elevated blood levels. The clay used by the subject was a liquid formulation with unknown geologic origin. Sample analysis showed that it contained 223 ppt TEQ with a profile that matched ball clay. Franzblau et al. concluded that ceramic clay may be a significant nonfood and nonindustrial source of human exposure to dioxins and recommended further research to more precisely characterize the routes of exposure.

The purpose of this study is to explore the possible dioxin exposures of artists using ball clay in ceramic art studios. The study was conducted at a single facility with 10 artists and therefore cannot be considered to be representative of all possible types of studios and practices. Ceramic art is conducted in a wide variety of studios ranging from small residential operations to large commercial facilities. Cleanliness, ventilation, and safety practices also vary widely within these types of studios. This study was conducted at the Ohio State University (OSU) Ceramics

Art Department. The OSU studio is a modern facility with excellent ventilation and maintenance. During the peer review of this study, an industrial hygienist commented that the OSU studio was an unusually clean and newly renovated facility (Eastern Research Group, 2008). Accordingly, the exposures measured in this study are most representative of similar university studios. Many different kinds of activities can occur in these studios including mixing clay, sculpting, operating a wheel, tending kilns, etc. Although many of these practices occurred at the OSU facility, this study is not representative of all possible ceramic art activities.

This exploratory investigation makes preliminary exposure estimates that can be used to evaluate whether more detailed follow-up analyses are needed. The limited resources available for this study required a strategy to base the analysis on existing data to the fullest extent possible.

Dioxin exposure is primarily a function of the dioxin concentration in the clay and an individual's level of exposure to the clay. Although studies in the literature provided information about dioxin levels in clay, no information could be found on clay exposure levels in ceramic art studios. Therefore, this study was designed to measure total clay exposures in a ceramic art studio. No dioxin measurements were made in this study, rather the dioxin levels in ball clay were assumed based on measurements from other studies. Three exposure pathways were evaluated: inhalation, dermal contact, and incidental ingestion. The evaluations involved measuring levels of clay particulates in air, clay residues on skin, and clay deposition on media representing food and beverages. These data provided a basis for estimating potential dioxin exposures and resulting doses, conducting an initial analysis of which exposure pathways contribute most to total dose, and evaluating how individual behaviors affect exposure/dose. Ultimately, the data helped develop distributions for input parameters for conducting a Monte Carlo analysis to estimate how dioxin exposure/dose may vary across a wide population of artists. Figure 1 provides a conceptual diagram of the key components of this study.

An alternative way to evaluate dioxin exposures is by blood testing. While this provides a direct measure of dioxin exposure, it represents exposures from all sources, not just work in an art studio. Also, a blood study would not have provided any insights about how dioxin exposures may occur in an art studio. Normal background exposures vary widely and factors such as diet and age are known to have large impacts on dioxin body burden. Accordingly, a blood study would require a large number of subjects with controls to reduce the effects of these

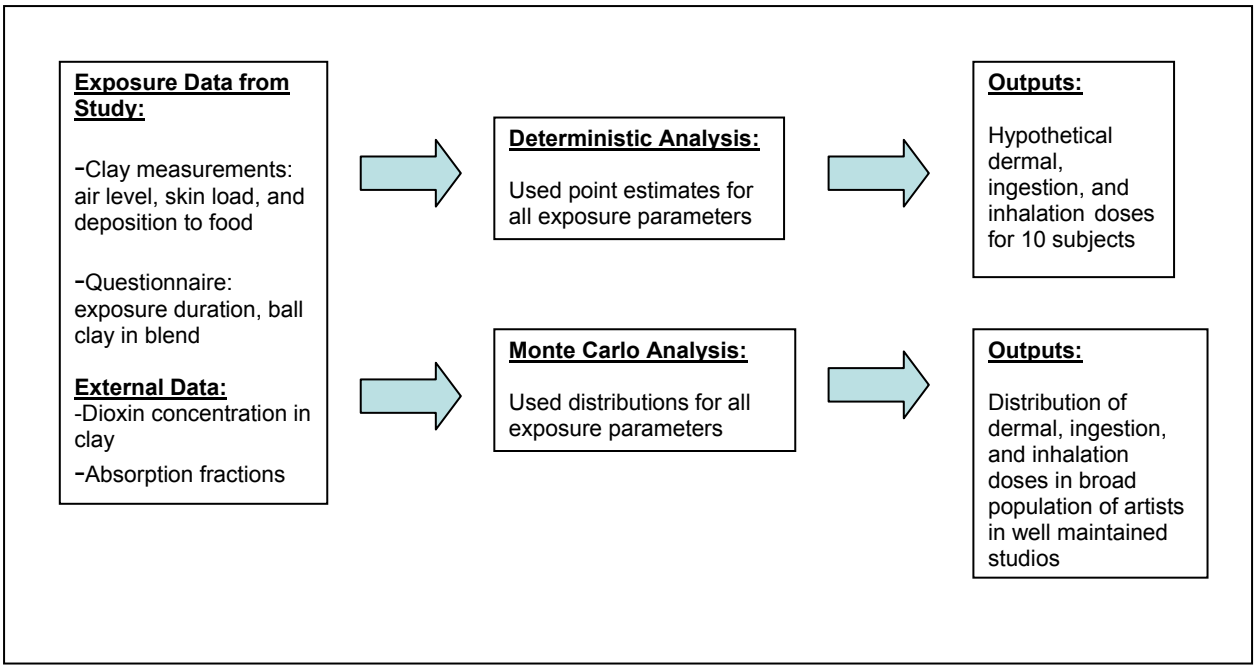


Figure 1. Conceptual diagram.

factors. Also blood tests have very high analytical costs. On the basis of costs alone, blood testing was beyond the scope of this effort. The clay exposure testing done here provided a low cost way to explore the problem and gives future researchers an informed basis for deciding if blood testing or other types of follow-up work are needed.

Dioxin concentrations and exposures are presented in terms of toxic equivalents (TEQs). TEQs allow concentrations of dioxin mixtures to be expressed as a single value computed by multiplying each congener concentration by a toxicity weight (toxic equivalency factor or TEF) and summing across congeners. TEFs are expressed as a fraction equal to or less than 1 with 1 corresponding to the most toxic dioxin congener, 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (2,3,7,8-TCDD). The TEQ data presented here are based on TEFs from the 1998 World Health Organization (WHO) recommendations (Van den Berg et al., 1998). In 2005, WHO updated the TEFs (Van den Berg et al., 2006). As discussed in Chapter 4, these updates had little impact on the literature values used here, so no adjustments were made.

The term "dioxins" is used in this study to refer collectively to the tetra- through octa-chlorinated dibenzo-*p*-dioxins and chlorinated dibenzofurans (CDD/Fs) with chlorine substitutions in all of the 2,3,7,8 positions. This term is commonly defined to include the 12 co-planar pentachlorobiphenyls (PCBs) which also demonstrate dioxin-like toxicity. However, PCBs are not addressed in this study. PCBs have been shown to make up a small

fraction of the total TEQs in a wide variety of background soils (U.S. EPA, 2007) and, therefore, are probably not important contributors to TEQs in ball clay.

2. APPROACH OVERVIEW

While working in a ceramics studio, artists may be exposed to dioxin-contaminated clay via three pathways: dermal contact, particle inhalation, and incidental ingestion. Exposure could also occur via open cuts or eyes and this possibility is discussed in Chapter 9 on uncertainty. The general strategy and procedures used to characterize each pathway are described below.

2.1. GENERAL STRATEGY

The site selected for this study was the Ceramics Area in Hopkins Hall at OSU in Columbus, OH. The Ceramics Area, housed in the basement of Hopkins Hall, has eight rooms, including classrooms, studios, a storage area, a glaze-mixing area, a clay recycling area, and a furnace room. This facility was selected because it offered a convenient location for assessing exposures during a variety of typical ceramic art activities.

An extensive ventilation system is used through out the studio with hoods located in several areas such as where clay mixing is conducted. The kilns are located in two rooms which are isolated from classrooms and other areas frequented by the students. These rooms are dedicated to kiln operations and no art work is performed in them. The studio has six kilns fired with natural gas (sizes in cubic feet: 28 [2 units], 40, 70, 7, and 25) and nine electric kilns (sizes in cubic feet: 60 [2 units], 27, 5 [4 units], 28, and 0.3). The small electric unit is unvented and used to test the temperature program on small pieces. All other kilns are equipped with ventilation hoods (vented outside the building). The kilns are generally heated slowly to a maximum temperature of about 1,200°C (2,200°F) and pieces are baked for about 9 to 15 hours. They are generally operated 2–3 times/week and daily during busy periods at the end of semesters.

The exposure measurements were carried out in two separate studies. The first study was conducted in April 2003 and the second in July 2004. The results of both studies have been combined in this report. Seven artisans and one nonartisan staff member in the OSU Ceramics Department were recruited to serve as subjects for the first study, and two additional artisans were recruited for the second study. An open solicitation was presented to the students and departmental staff, and the first volunteers were selected. The subjects included three males and seven females ranging in age from about 20–40 years. Approval for human subjects was obtained via the Battelle Institutional Review Board (IRB) and the U.S. Environmental Protection Agency (EPA). Upon approval by the Battelle IRB and EPA, OSU determined that review by their IRB was not necessary. The testing was conducted while the subjects conducted

a variety of unscripted tasks, including clay mixing/preparation, sculpting, pottery wheel work, and molding.

To assess dioxin exposure levels, it is necessary to estimate dioxin levels in the various exposure media (i.e., clay used by the artists, dust particles suspended in the studio air, and dust settled onto surfaces). No actual dioxin measurements were made in this study. Rather, dioxin levels were estimated using literature-reported concentrations of dioxins in ball clay and information about the amount of ball clay in the clay mixtures used by the artists. Chapter 4 discusses the details about this procedure.

A questionnaire was administered to subjects during the first study to gather information on their routines involving clay artwork. Chapter 6 summarizes the questionnaire data as presented in Appendix A.

2.2. CHARACTERIZATION PROCEDURES

The following procedures were used to characterize each exposure pathway.

2.2.1. Dermal Contact

Dermal contact with clay can occur via direct handling of the clay, deposition from the air onto exposed skin, transfer from surfaces, and splashing during wheel operations. The amount of clay on skin was measured using rinsing procedures. Additionally, surface wipes were collected in work areas to evaluate dermal exposures via transfers from surfaces. To further evaluate dermal exposure, a dermatologist examined the condition of the stratum corneum, the outermost layer of skin, before and after Subjects 1–8 worked with clay. The primary focus of this examination was to determine if any damage to skin may have occurred that would affect dermal absorption.

2.2.2. Inhalation

Both personal and area air-monitoring techniques were used to assess inhalation exposures. Personal air samplers provide data most representative of an individual's exposure because they sample the air in a person's breathing zone and reflect changes in concentration due to their movement. An area sampler provides a general indication of exposure for people in its vicinity and also can achieve lower detection levels. Both the personal and area-monitoring techniques provided particle size-selective data, so that the deposition site of the particles in the respiratory tract (nose/mouth, tracheobronchial airways, and alveolar region) could be determined.

Two types of personal air samplers were used: real-time and time-integrating. Similarly, two types of area air samplers were used: real-time and time-integrating. The real-time air

samplers provided data on particle levels on a nearly continuous basis (every minute). The integrating samplers collected particles over the entire time period of a work activity, yielding a time-weighted average (TWA) concentration. In this sampling design, the real-time exposure monitoring was used to assess frequency, magnitude, and duration of peak exposures as well as TWA across the entire sampling time, while the integrating samplers provided information on average exposures.

2.2.3. Ingestion

Inadvertent ingestion of clay or dust can occur in several ways. Clay particles in the air can deposit on food or in beverages. Deposition onto surrogate food samples (a quartz filter was used to represent food and a beaker of water was used to represent a beverage, see Section 3.1.5. for further details) was measured to evaluate this pathway. Ingestion can also occur via transfers from hands to food or cigarettes (though no smoking was allowed in the OSU studio) and via transfers to the mouth resulting from wiping the hands or licking the lips. These possibilities were evaluated qualitatively through observations about individual behaviors. Finally, ingestion can also occur via particle deposition in the nose, mouth, and tracheobronchial airways; clearance to the throat; and swallowing. This process was evaluated using inhalation modeling (see Appendix B).

3. SAMPLING METHODS

Methods used for collecting, preparing, and analyzing samples are described below.

3.1. SAMPLE COLLECTION

Samples were collected from personal air, area air, skin rinses, surface wipes, and surrogate food and beverages.

3.1.1. Personal Air Sampling

The Respicon™ Model 8522 particle sampler (TSI Incorporated, Shoreview, MN) is a two-stage virtual impactor with a three-stage gravimetric filter sampler. The sampler sorts airborne particulate matter into three size ranges. Each size range is collected on a 37-mm glass fiber filter (GFF). The particle size collection ranges are as follows: stage 1, aerodynamic particle diameter (D_{ae}) < 4 µm; stage 2, 4 < D_{ae} < 10 µm; and stage 3, 10 < D_{ae} < 100 µm.

Before the start of sampling, three preweighed GFFs were removed from their protective polystyrene containers (47-mm Millipore petri slides) and loaded into the Respicon™ using nonmetallic filter forceps. A unique laboratory record book (LRB) identification number was assigned to each GFF during tare weighing, and this weight was recorded onto the sampling data sheet at that time. The Respicon™ was then assembled, and the total flow checker head was installed. A personal sampling pump (SKC model no. 224-PCXR4, Eighty Four, PA) was attached to the total flow head, and the flow rate through the Respicon™ was adjusted to 3.11 L per minute (L/min) $\pm$ 2%, according to the manufacturer's specifications. All flows were verified by employing a calibrated National Institute of Standards and Technology (NIST)-traceable Buck calibrator (Model M5, A.P. Buck, Orlando, FL). After confirmation of the manufacturer's suggested flow rates at each stage of the sampler, the total flow checker was replaced with the standard (100 µm) inlet head. A nylon chest harness (TSI Incorporated, Shoreview, MN) was used to place the Respicon™ in each subject's breathing zone, approximately 15–20 cm below the chin. The personal sampling pump was attached to the subject's belt and connected to the Respicon™. Sampling was initiated by starting flow through the Respicon™ and continued throughout a subject's entire work shift, typically 2–2.5 hours. The average sampling volume was 387 L. Following sampling, the pump was turned off, the Respicon™ was disassembled, and the filters were returned to their polystyrene petri dish containers for transportation back to the laboratory for gravimetric analysis. Quality control samples, such as field blank samples and matrix spike samples, were collected and analyzed for each sampling technique (see Section 3.2.3).

The personal DataRAM-1000 (pDR-1000, Thermo Electron Corporation, Franklin, MA) sampler was also used to measure personal particle exposure passively. No pump is required for this instrument; instead, the air surrounding the sampler circulates freely through the open sensing chamber by natural convection, diffusion, and background air motion. Particle concentrations are measured using a light-scattering (nephelometry) technique. This instrument responds optimally to particles with diameters in the range of 0.1–10 μm but will also respond to a lesser extent to larger diameter particles. Via internal calibration, the sampler converted particles/m^3 to mg/m^3 as final data units.

Before the start of sampling, the instrument sensor was zeroed by placing it in a resealable bag into which particle-free (filtered) air was pumped. All zero operations were performed successfully. To begin sampling, the instrument was clipped to the subject's waistline (on the belt or strap holding the SKC pump) and the unit was activated. The pDR-1000 collected data at 1 Hz and was programmed to record these data as 1-minute averages over the duration of the sampling period. At the conclusion of sampling (typically 2–2.5 hours), data logging was stopped and the instrument was turned off. The data were then uploaded to a personal computer using software provided by the manufacturer and an RS-232 serial port connection.

3.1.2. Area Air Sampling

To assess the particle size and concentration in the ceramic studio's air, a 6-stage Delron® cascade impactor (Delron Research Products, Powell, OH) was employed. Each stage filters out successively smaller particles so that the following particle sizes are collected in successive stages: >32 μm, 16–32 μm, 8–16 μm, 4–8 μm, 2–4 μm, and 0.5–2 μm; the final GFF collects all particles smaller than 0.5 μm in diameter. Particles accumulate on glass slides underneath each impactor orifice. To prevent particle loss due to bouncing, a small amount of vacuum grease was applied to each glass slide. The area coverage of the grease on the slide was determined by the approximate size of the impactor nozzle below which the slide was to be placed. Correct airflow rate through the impactor ensures that the correct particle sizes are collected on each stage. A carbon-vane pump (Gast Co., Benton Harbor, MI), with a critical orifice that provides a pressure drop of at least 430 mm of mercury, was used to ensure the flow rate of 24 L/min.

Before the start of sampling, preweighed glass slides were removed from their protective polystyrene petri slide containers and loaded into the impactor using clean forceps or tweezers. Unique LRB numbers, assigned to each slide during tare weighing, were recorded on sample data forms. The impactor tower was then assembled and flow was initiated to verify the required pressure drop. For each sample, the pressure drop was between 480 and 510 mm of mercury. Flows were also verified using the Buck calibrator. Sampling times were approximately 2–2.5 hours, giving an average sample volume of approximately 2,900 L. Following sampling,

the impactor was disassembled and all slides were returned to their respective petri dish containers for transportation back to the laboratory for gravimetric analysis.

The Climet® CI-500 innovation laser particle counter (Redlands, CA) was a second sampling device used to measure area particle concentrations. In a manner similar to the pDR-1000, the Climet® CI-500 measures particle number concentration using nephelometry. A self-contained pump sampled air at a constant flow rate of approximately 3 L/min. In the count mode, the Climet® CI-500 measures particles in six particle size ranges: 0.3–0.5 μm, 0.5–1 μm, 1–2.5 μm, 2.5–5 μm, 5–10 μm, and >10 μm. The sampling frequency for the instrument is 1 Hz, and the data were logged as 1-minute averages. The particle counts were converted from particles/m^3 to mg/m^3 as final data units. The particle counts did not exceed the manufacturer's recommended maximum (200–250 counts/cm^3 at 3 L/min) at any time except for a few minutes during two of the sampling periods. No instrument zero or span checks were necessary. Following sampling, the data were uploaded to a computer using an RS-232 serial cable and software provided by the manufacturer. The Climet® CI-500 was located in close proximity to the cascade impactor and generally very near the subject. For example, when the subject was working with clay at a wheel, the two air samplers were placed on the side of the wheel opposite the subject at a height and distance from the wheel similar to the subject's mouth and nose. The inlet to the Climet® was oriented in a vertical direction.

3.1.3. Skin Sampling

The total skin area of hands, arms, face, feet, and legs was estimated using a combination of direct measurements and regression models based on body weight and height (U.S. EPA, 1997). The subject's exposed body parts were rinsed with a dilute soap solution (~2% soap in deionized [DI] water, by weight). Approximately 100–150 mL of the soap solution was used to rinse each exposed body part. After each body part was rinsed, the washbasin contents were transferred to a polypropylene bottle with small amounts of DI water rinses. The bottle was labeled and sealed with a screw-top cap. The washbasin was then rinsed again, wiped out, and reused. Between the first and second studies, the procedures differed as described below.

3.1.3.1. April 2003

All subjects wore short-sleeved shirts, long pants, socks, and shoes. Therefore, the only exposed skin areas were the hands and forearms, and the rinsing was limited to these body parts. At three times during each subject's work session, the subject's exposed skin was examined for clay residue. When clay was observed visually, the affected areas of the subject's body were rinsed. Rinses were performed at approximately equally spaced intervals, and the last rinse

usually coincided with the conclusion of the sampling period. The average of the three measurements was used to represent the session.

3.1.3.2. July 2004

Both subjects wore short-sleeved shirts, short pants, and sandals. Therefore, the exposed skin areas included the hands, arms, legs, and feet, and the rinsing was expanded from the first tests to include all of these body parts. The subjects' faces were also rinsed during these tests. Although no visible residues were apparent on the faces, this area was included for the sake of completeness.

The rinse samples were collected in a washbasin using a squirt bottle of soap solution while the subjects used their hands to gently wipe off the affected area. Rinses were conducted in the following manner:

- **Hands.** Moving downward from the wrist, the technician rinsed the residual clay off both sides of the artisans' hand; the residual clay from each hand was rinsed into separate containers and analyzed separately.

- **Arms.** Moving downward from the elbow, the artisans rinsed the residual clay from their arms.

- **Feet.** Moving downward from the ankle, the artisans rinsed the residual clay from their feet.

- **Legs.** Moving downward from the top of the exposed area of the legs, the artisans rinsed the residual clay from their legs.

- **Face.** The artisans rinsed the residual clay from their faces.

Skin rinse samples were collected at the close of each work session. In addition, if at any point during the work session the subject indicated the need to wash an exposed body part, it was rinsed into a sample container reserved for that body part.

3.1.4. Surface Wipe Sampling

A 20 × 20 cm horizontal surface near the subject's workspace was selected and cleaned with dilute soap solution before the subject began working with any clay. These surfaces were porous concrete tabletops. Wipe samples of this area were taken immediately after cleaning (to confirm that low levels were present before starting the work session) and at the end of the work session. The wipe sampling procedure consisted of the following steps. The selected area was wiped with 10 × 10 cm rayon gauze wipes wetted with ~5 mL isopropanol using the following

procedure. The wipe was secured between the thumb and forefinger of one hand, and the surface was wiped five times in one direction using evenly applied pressure. The soiled side of the wipe was folded to the inside and, in an orthogonal direction, the surface was wiped five more times. This soiled side of the wipe was again folded to the inside and the wipe was placed into its prelabeled, resealable bag for transportation back to the laboratory for gravimetric analysis. The entire wiping process above was then repeated using one additional wipe.

3.1.5. Surrogate Food and Beverage

An 85-mm diameter quartz fiber filter and a 125-mL polypropylene jar filled with 100 mL DI water served as surrogates for food and beverage samples, respectively. Before clay work began, both were placed in a location where the artisan indicated he or she might normally place food or drink. In most cases, this location was away from the direct work area but still in the same room. However, occasionally clay workers placed food and beverage directly adjacent to their work. To begin sampling, the lid of the polycarbonate petri dish containing the food surrogate and the screw-cap lid on the beverage surrogate were removed. Following the conclusion of sampling, the lid to the petri dish was replaced and sealed with Teflon® tape, and the polypropylene jar was secured for transportation back to the laboratory for gravimetric analysis.

3.2. SAMPLE PREPARATION AND ANALYSIS

Procedures used for sample preparation, analysis, and quality control are described below.

3.2.1. Filtration and Drying

To collect the clay rinsed from the subject's skin during the skin rinse sampling procedure and the clay deposited into the surrogate beverage sample, the clay-liquid suspensions were filtered through a preweighed 85-mm diameter quartz fiber filter in a Buchner funnel using vacuum filtration. Any remaining clay in the sample container was rinsed with several small aliquots of DI water to ensure complete transfer of the clay to the filter. All filters from the vacuum filtration procedure were subsequently placed on clean 10-cm watch glasses and dried overnight at 100°C (212°F). The gauze wipes for surface residues were dried in this fashion as well. No drying was required for the 37-mm Respicon™ filters or glass slides.

3.2.2. Gravimetric Analysis

The accuracy of the analytical balance (AT-20, Mettler-Toledo) used for all gravimetric analyses was confirmed daily with weights approved by NIST. The calibration weights ranged from 0.001 mg to 100 g. All 37-mm GFFs, 85-mm quartz fiber filter paper, 37-mm glass slides, and gauze wipes were conditioned in a temperature- and humidity-controlled balance room (temperature 22–23°C (72–73°F), relative humidity 46–56%) for a minimum of 24 hours before tare and final weights were recorded. For conditioning, the lid of the container holding the filter or slide was left slightly ajar, and the resealable bags containing the gauze wipes were left open. For both kinds of filters and glass slides, three separate weights were recorded to the nearest µg. The weight was acceptable if the range of the three independent measurements was less than 10 µg. For gauze wipes, the three separate weights were recorded to the nearest tenth of a mg and the acceptability criterion was that the range of the measurements be less than 1 mg.

3.2.3. Quality Control Samples

At least one field blank sample was collected for each type of gravimetric sample, including the Respicon™, cascade impactor, food and beverage, and surface wipe samples. Such samples were collected by transporting the sampling media to the field location and placing them into their respective sampling device or position for sampling. As soon as the medium was ready for sampling, it was collected as if the sampling time had come to a close and transported back to the laboratory for gravimetric analysis. The detection limits for the gravimetric measurements were determined by multiplying the standard deviation of the field blank net weights by 3. The detection limits for each type of gravimetric measurement were as follows: 0.0025–0.015 mg/m^3 for each stage of the cascade impactor, 0.878 mg/m^3 for each stage of the Respicon™, 10.6 mg for the surface wipes, 0.6–1 mg for the food/beverage deposition samples, and 0.6–1.6 mg for the dermal rinse samples.

As a quality control check, the skin rinse, surface wipe, and food and beverage sampling and analysis methods were tested in a controlled laboratory setting (Battelle Laboratory in Columbus, OH). For the skin rinse method evaluation, approximately 3 g of clay (obtained from one of the artisan subjects) was handled carefully without dropping any until the entire sample was spread over the hands and forearms of a Battelle researcher. The skin rinse and analysis method described above was performed, and recoveries of 87 $\pm$ 3% of the clay applied were obtained. This compares favorably with Kissel et al. (1996), who obtained 93% recovery when rinsing wet soil from the skin of human subjects using a similar sampling method. Similarly, for the surface wipe method, approximately 1 g of clay was deposited onto a precleaned laboratory bench, the wipe method described above was performed, and recoveries of 94 $\pm$ 5% were obtained. For the food and beverage samples, approximately 50 mg of clay was added to those

sampling matrices and recoveries of 90 and 95%, respectively, were obtained using the gravimetric analysis procedures described above.

4. DIOXIN CONTENT OF CLAY AND STUDIO RESIDUES

As discussed earlier, this study made no dioxin measurements in clays, dust residues, or other materials from the Ohio State University ceramics studio. Instead, the possible levels were estimated on the basis of other studies. A number of studies have measured dioxin levels in raw and processed ball clay. Raw clay is the clay as it comes out of the ground. Processed clays are the result of the initial processing, which is usually conducted at or near the mining site before shipping. This processing typically involves drying with hot air at 120˚C and pulverizing in a series of milling stages (Ferrario and Byrne, 2002). The following studies describe dioxin levels in raw and processed clay:

- **Ferrario and Byrne (2002, 2000).** Both papers present data for processed ball clay used at one ceramics manufacturer. The mean of seven samples of processed ball clay was 3,172 pg/g TEQ. Additional data are presented on dioxin levels in clay mixtures and fired products. The authors noted that dioxin levels in the dust samples collected at the facility were the same as those in the unfired clay mixtures.

- **Ferrario et al. (2000a).** This study compared the mean levels in eight raw clay samples from Mississippi (see Table 1) to the mean levels in four processed ball clay samples. This comparison showed that the processed clays had much lower levels of 2,3,7,8- TCDD and higher levels of 1,2,3,4,7,8-hexachlorodibenzo-*p*-dioxin (HxCDD), 1,2,3,4,6,7,8-heptachlorodibenzo-*p*-dioxin (HpCDD), and octachlorodibenzo-*p*-dioxin (OCDD) than the raw clay. The mean total TEQ of the processed clay (977 pg/g TEQ) was 37% lower than the raw clay (1,513 pg/g TEQ).

- **Ferrario et al. (2000b).** This study also presents the data for raw and processed clay described in Ferrario et al. (2000a). In addition, it presents dioxin levels in a variety of other types of clays and discusses the evidence of a natural origin for their presence.

- **Ferrario et al. (2007, 2004).** These studies collected processed ball clay directly from four art-supply retailers. All ball clay types sold by these retailers were purchased in 22.7-kg (50-pound) bags. One type of ball clay was sold by all four retailers, five types were sold by two of the retailers, and seven types were sold by only one retailer. Thus, a total of 21 bags, representing 13 different types of ball clays, were purchased and sampled. A ceramics expert confirmed that the most commonly used ball clays for making artware and pottery were represented in these samples. Table 2 summarizes these data.

Table 1. Raw ball clay dioxin concentrations

Congener	PCDD concentration (pg/g dry weight)			
	Range	Median	Mean	Mean TEQ
2,3,7,8-TCDD	253–1,259	617	711	711
1,2,3,7,8-PeCDD	254–924	492	508	508
1,2,3,4,7,8-HxCDD	62–193	134	131	13
1,2,3,6,7,8-HxCDD	254–752	421	456	46
1,2,3,7,8,9-HxCDD	1,252–3,683	1,880	2,093	209
1,2,3,4,6,7,8-HpCDD	1,493–3,346	2,073	2,383	24
OCDD	8,076–58,766	4,099	20,640	2
Total				1,513

HpCDD = heptachlorodibenzo-*p*-dioxin; HxCDD = hexachlorodibenzo-*p*-dioxin; OCDD = octachlorodibenzo-*p*-dioxin; PCDD = polychlorinated dibenzo-*p*-dioxin; PeCDD = pentachlorodibenzo-*p*-dioxin; TCDD = tetrachlorodibenzo-*p*-dioxin; TEQ = toxic equivalent.

Source: Ferrario et al. (2000a).

Because the data from Ferrario et al. (2007, 2004) represented the types of clays most likely used in ceramic art studios, these data were selected as the most representative ones to be used in this study. Accordingly, it was assumed here that the dioxin TEQ levels in clay could range from 289 to 1,470 pg/g with an average of 808 pg/g. Table 2 shows the TEQs from this study were calculated on the basis of the WHO-98 TEFs (Van den Berg et al., 1998). In 2005, WHO updated the TEFs (Van den Berg et al., 2006). These updates increased the TEF for OCDD from 0.0001 to 0.0003. None of the TEFs for the other six congeners used to estimate the ball clay TEQs were changed by the WHO update. The increase in the OCDD TEF would cause the overall average to increase by 6%. It was decided to use the TEQ estimates for ball clay as originally reported instead of updating it on the basis of the 2005 WHO TEFs. This was based on two reasons, first the change would have been relatively minor and second it would have complicated comparisons to exposure estimates which have not yet been updated on the basis of the new TEFs.

Table 2. Processed ball clay dioxin concentrations (pg/g)

	Average	Standard deviation	Median	Minimum	Maximum	WHO-TEF[a]	Avg TEQ
PCDDs							
2,3,7,8-TCDD	76	60	63.5	21.8	291	1	76.0
1,2,3,7,8-PeCDD	374	144	387	125	588	1	374
1,2,3,4,7,8-HxCDD	335	141	313	142	636	0.1	33.5
1,2,3,6,7,8-HxCDD	526	204	523	167	944	0.1	52.6
1,2,3,7,8,9-HxCDD	1,480	608	1,570	394	2,550	0.1	148
1,2,3,4,6,7,8-HpCDD	9,780	4,480	8,600	3,940	19,500	0.01	97.8
OCDD	254,000	88,200	233,000	118,000	471,000	0.0001	25.4
Total							
TCDD	1,450	606	1,600	412	2,370		
PeCDD	4,600	1,890	4,880	1,560	7,140		
HxCDD	13,500	5,710	12,800	4,800	21,900		
HpCDD	25,000	11,700	24,400	9,320	44,900		
Total TEQs[b]	808	318	771	289	1,470		808

[a] World Health Organization Toxic Equivalency Factors (WHO-TEFs) based on Van den Berg (1998)
[b] The overall average presented by Ferrario et al. (2007) is based on averaging the mean congener levels across samples. An alternative approach is to compute the average on the basis of the TEQ for each sample. This approach yields an average of 819 pg/g (SD = 303 pg/g). Similarly, the median TEQ is 810 pg/g based on the individual samples. The minimum and maximum TEQ values are reported on the basis of the individual samples.

HpCDD = heptachlorodibenzo-*p*-dioxin; HxCDD = hexachlorodibenzo-*p*-dioxin; OCDD = octachlorodibenzo-*p*-dioxin; PCDD = polychlorinated dibenzo-*p*-dioxin; PeCDD = pentachlorodibenzo-*p*-dioxin; TCDD = tetrachlorodibenzo-*p*-dioxin; TEQ = toxic equivalent.

Source: Ferrario et al. (2007, 2004).

All of these studies indicate that ball clay has relatively high levels of CDDs and very low levels of CDFs. Based on Ferrario et al. (2007, 2004), about 95% of the TEQs in processed clay are contributed by four congener groups: TCDDs (9%), pentachlorodibenzo-*p*-dioxin (PeCDDs) (46%), HxCDDs (28%), and HpCDDs (12%).

Artists commonly use a mixture of clays to achieve various physical properties and visual effects. The percentage of ball clay in the mixture can vary widely. The amount of ball clay in the mixtures used on days when the testing occurred ranged from 0 to 100% with an average of 21.5% (see Table 3). Although 4 of the 10 subjects used mixtures containing no ball clay on the test days, on other days these subjects would likely use mixtures that do contain ball clay. This is because students are required to conduct a variety of projects, and some of these are better suited to using ball clay and others are not. Accordingly, it was assumed here that the ball clay portion of clay mixtures used by artists can range from 0 to 100% with an average of 20%. Furthermore, it was assumed that the dioxin levels in the nonball clays were negligible. This is supported by Ferrario et al. (2000b), who analyzed 15 different mined clays and concluded their dioxin levels were significantly lower than levels in ball clay.

Table 3. Percentage ball clay in the clay mixtures used during this study

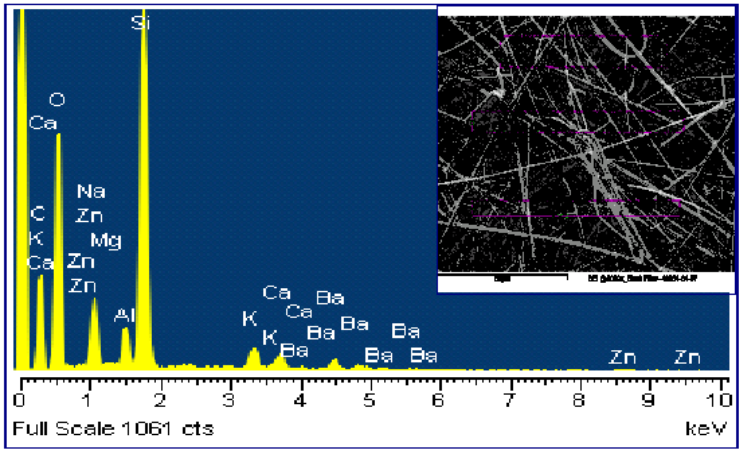
Subject	Percentage ball clay
1	0
2	27
3	48
4	0
5	20
6	0
7	0
8	15
9	100
10	5

Finally, it was assumed that the dusts suspended in the air and settled onto food or skin would have the same dioxin levels as the clay. Material other than clay may contribute to these dusts, further diluting dioxin concentrations. This possibility was evaluated using scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS). These techniques were applied to four types of samples:

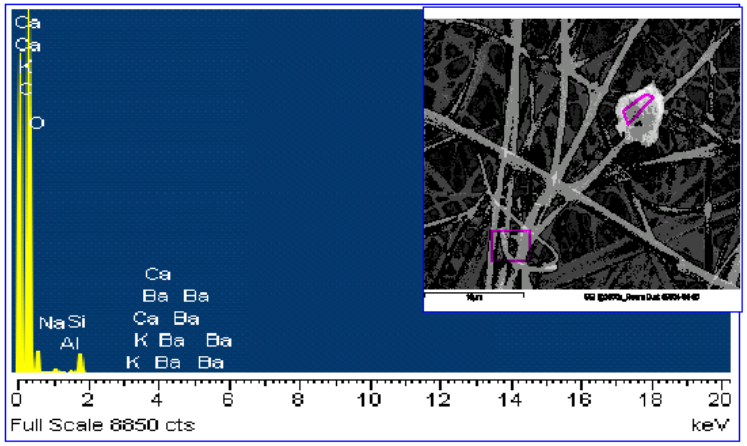
- Blank GFF
- Dust on a GFF collected from a storeroom at the Battelle Laboratory (not impacted by clay)
- Air particles on a Respicon™ GFF collected in the studio
- Clay used by subjects

Figure 2 shows SEM photographs and elemental spectra of samples associated with Subject 6. A visual comparison of the SEM photographs suggests that the particles on the Respicon™ filter appear to differ from those in the storeroom dust. Also, the spectra of the particles on the Respicon™ filters resemble clay more than those of storeroom dust. The clay samples and Respicon™ filter samples had high abundances of titanium, iron, and aluminum, which were not seen in the GFF blank or in the storeroom dust sample. Similar results were found for all eight subjects in the April 2003 tests, as shown in Appendix C. The analysis was not repeated in the July 2004 tests. These observations suggest that clay dominates the air particles collected in the studio. On this basis, it was assumed that the studio dust was dominated by clay and no further dilution factor was needed to adjust dioxin concentrations.

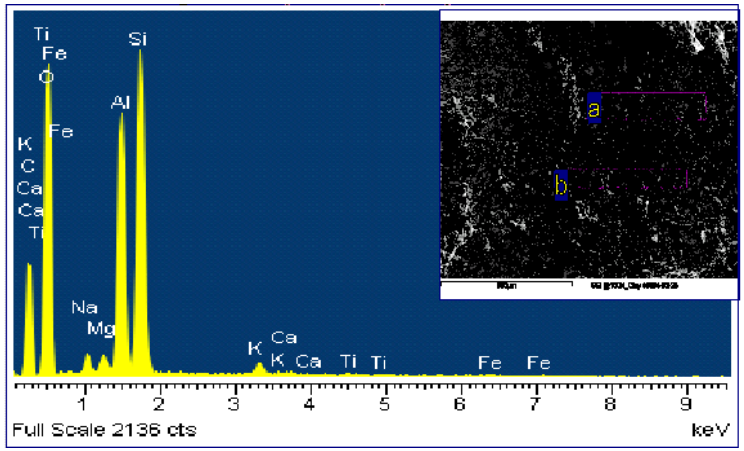
Blank glass fiber filter (GFF)



Dust particles on GFF in Battelle storeroom



Sample of clay used by Subject 6



Clay particles on Respicon filter used by Subject 6

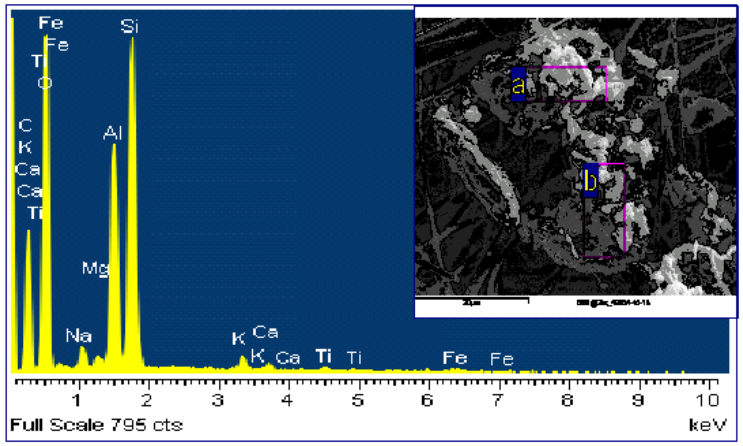


Figure 2. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) data.

5. DOSE ESTIMATION PROCEDURES

This chapter presents the procedures used to estimate the dioxin dose to artisans from all three routes of exposure: dermal contact, inhalation, and ingestion. Because the dermal dose is expressed on an absorbed basis, the dose by other pathways must also be expressed on an absorbed dose basis. This provides an equivalent basis for comparison and addition across pathways. All doses are presented as daily estimates. No adjustments are made for the frequency with which artists work with clay. Therefore, these dose estimates should be interpreted as the dose that could occur on a day that clay work is conducted, rather than as a long-term average.

5.1. DERMAL CONTACT

A fraction absorbed approach is used to estimate dermal absorption. This method has been widely used to assess dermal exposures to solid residues and is endorsed in current Agency guidance (U.S. EPA, 2004, 1992). Kissel et al. (2007) have proposed a more mechanistic model. This model has not yet been incorporated into Agency guidance and therefore, was not chosen as the primary basis for this assessment. However, the model is presented in Appendix D with a discussion of how it could be applied to this situation.

5.1.1. Estimating Particle Loading on Skin

As described earlier, rinsing procedures were used to determine the total amount of clay on exposed skin. This mass was divided by the exposed skin area to derive a loading in units of mg/cm^2.

5.1.2. Estimating Monolayer Load

The monolayer is the layer of particles immediately adjacent to the skin. According to the monolayer theory, the only significant dermal absorption comes from chemicals contained in this first layer (U.S. EPA, 2004, 1992). This theory would not apply in all situations such as those involving rapid absorption and long exposure times. In such situations the monolayer could be depleted, and the contaminant in higher layers could diffuse downward and ultimately be absorbed into the skin. Experimental evidence supporting the monolayer theory has been published by Duff and Kissel (1996), Roy and Singh (2001), and Touraille et al. (2005). These studies used exposure times of 24 hours or longer and were conducted with 2,4-D, BaP, and 4-cyanophenol. The similarity of these chemicals to dioxins and the use of exposure times similar to the ones of concern here, suggest that the monolayer theory should be applicable to exposure scenarios considered in this study.

To properly apply the dermal absorption fractions, it was necessary to determine whether residue loads on skin exceeded monolayer loads. The monolayer load for a specific soil can be estimated on the basis of the median particle size. Assuming spherical particles and face-centered packing, the monolayer loads can be calculated as follows (U.S. EPA, 2004):

$$L_{mono} = \pi \rho d_p / 6 \quad (1)$$

where

L_{mono} = monolayer load (mg/cm^2)
ρ = particle density (mg/cm^3)
d_p = physical particle diameter (cm)

The average particle density of the processed clays analyzed by Ferrario et al. (2004) was 2.64 g/cm^3. Clays typically have very small particles relative to other components of soil. The U.S. Department of Agriculture (USDA) defines clays as having less than 2 µm diameter particles (Brady, 1984). Table 4 shows the particle size specifications for a Tennessee ball clay (Ceramics Materials Info, 2003). Reviewing the specifications for a variety of commercial ball clays, median particle sizes ranged from about 0.5 to 1.0 µm (Ceramics Materials Info, 2003).

Table 4. Particle size distribution of Tennessee ball clay

Particle diameter (µm)	20	10	5	2	1	0.5	0.2
% finer than	99	97	93	81	72	56	35

Source: Ceramics Materials Info (2003).

The particle sizes found in the studio air had median physical diameters ranging across subjects from 8 to 27 µm (this is derived from the mass median aerodynamic diameter [MMAD] range of 13 to 44 µm described in Appendix B and converted to physical diameters using the procedure in Appendix B, Footnote 1). These airborne particles appear larger than what would be expected from the original clay product. This may be explained by the bonding of particles caused by the addition of water to the clay or the firing process, which fuses particles. Particles that accumulate on the skin primarily from air deposition are likely to resemble the air particles more than the original clay particles. Particles that transfer to skin primarily from direct handling of the clay should more closely resemble the original clay product than the airborne particles. Accordingly, the particle sizes of the clay residues on skin could vary widely, with

medians ranging from 0.5 to 27 μm. For purposes of the central exposure estimates, the geometric mean of this range is assumed, i.e., 3.7 μm. This implies a monolayer load of 0.5 mg/cm^2. Chapter 9 further discusses the uncertainty resulting from this assumption.

5.1.3. Estimating Fraction Absorbed

Three studies have examined dermal absorption of TCDD from soil (Roy et al., 2008; Shu et al., 1988; Poiger and Schlatter, 1980). The Roy et al. (2008) data were selected as the best basis for estimating dermal absorption fractions applicable to the ceramics studio. This was because the test soil was most fully described allowing comparisons to the clay, and multiple exposure times were used allowing evaluation of how dose varies with time.

Roy et al. (2008) conducted a variety of experiments in which TCDD was applied to soil on human skin in vitro, rat skin in vitro, and rat skin in vivo. The experiments were conducted with both a low organic carbon soil and a high organic carbon soil. Ferrario et al. (2007, 2004) studied 21 samples of processed ball clay used in ceramics studios. They found that the organic carbon content of these samples ranged from 0.06 to 1.1% with a median and geometric mean of approximately 0.4%. This level is very similar to the level in the low organic carbon soil used by Roy et al. (0.45%). Accordingly, this discussion focuses on the Roy et al. results for the low organic carbon soil applied to human skin in vitro. For purposes of evaluating human exposure to TCDD contaminated soil, Roy et al. (2008) made three adjustments to their 24-hour absorption percentage from the human skin in vitro tests:

- The amount of TCDD found in the skin at the end of the experiment (0.20%) was added to the amount in the receptor fluid to get total absorption
- The absorption percentage was multiplied by two to reflect the ratio observed between the rat in vivo tests with low carbon soil and rat in vitro tests with low carbon soil
- The absorption percentage was multiplied by another factor of two to make it applicable to soil loads less than or equal to the monolayer

Table 5 shows that in the present study, these adjustments were made for each data point. Finally these adjusted data were fit to a polynomial function relating absorption percentage and time (see Figure 3). The equation for this function is as follows (converting percent to fraction):

$$AF_{dermal} = (0.0005t^2 + 0.05t + 0.7692)/100 \quad (2)$$

where

AF_{dermal} = dermal absorption fraction
t = time (hour)

Table 5. Percent absorbed over time

Time (hr)	Receptor Fluid[a] (%)	Receptor Fluid + Skin[b] (%)	Adjusted[c] (%)	Best Fit[d] (%)
1	0.02	0.22	0.88	0.82
2	0.08	0.28	1.12	0.87
4	0.07	0.27	1.08	0.98
8	0.02	0.22	0.88	1.20
24	0.28	0.48	1.92	2.26
48	0.91	1.11	4.44	4.32
72	1.54	1.74	6.96	6.96
96	2.25	2.45	9.8	10.18

[a] Percent absorbed into receptor fluid from human skin in vitro testing by Roy et al. (2008).
[b] Addition of 0.2% absorbed into skin at end of experiment.
[c] Multiplied by a factor of 2 for the in vitro:in vivo ratio and by another factor of 2 for application to soil loads equal to or less than monolayer.
[d] Based on Eq. 2.

hr = hour.

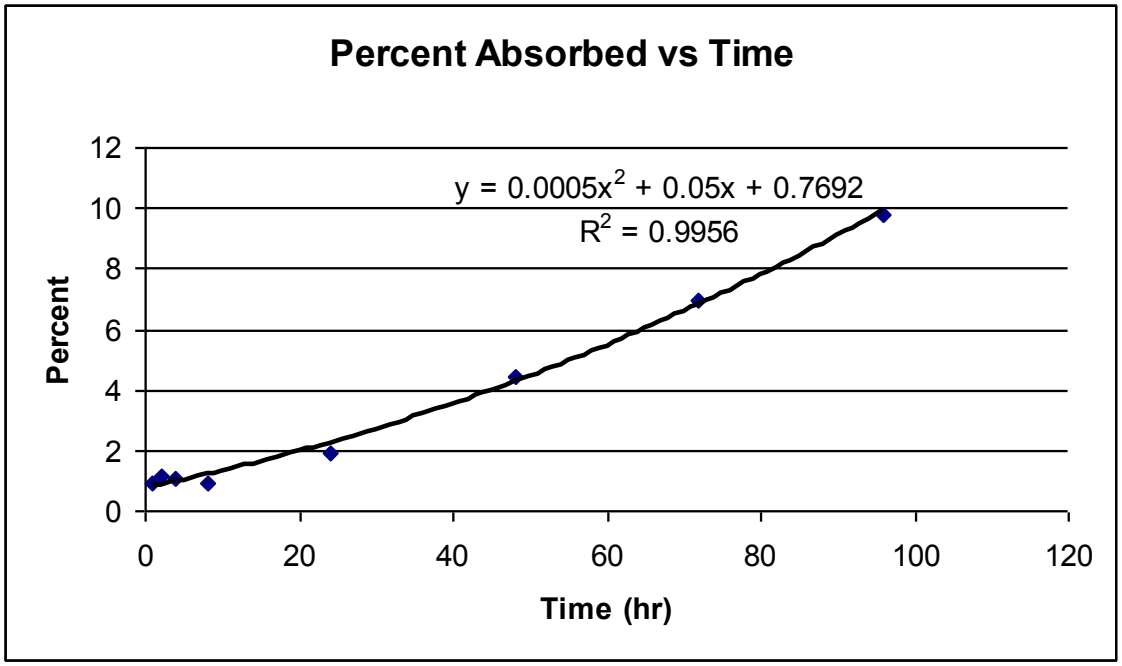


Figure 3. Scatter plot of adjusted absorption data versus time with trend line.

Source: Adapted from Roy et al. (2008).

5.1.4. Calculating Dermal Dose

The rinsing experiments indicated that clay loading exceeded the monolayer load in some, but not all, cases. The dermal absorption fractions presented above were applied to the measured loads where these were less than or equal to monolayer loads. At soil loadings greater than monolayer, the dermal absorption fraction was applied to only the monolayer load. Accordingly, the dose of dioxins absorbed through the skin of the artisan subjects during this study was estimated using the following equation for each body part and then summed:

$$D_{dermal} = SA\ L\ C\ AF_{dermal} \quad (3)$$

where

D_{dermal} = dermally absorbed dose (pg TEQ/d)
SA = skin area exposed (cm^2)
L = daily clay loading on skin (measured or monolayer, whichever is less) (mg/cm^2-day)
C = dioxin concentration in clay (pg TEQ/g)
AF_{dermal} = dermal absorption fraction

The approach used in this study assumes that dermal exposure is limited to the skin area which is not covered by clothing. As discussed in Chapter 9, a number of studies have shown that dusts can penetrate clothing and deposit on skin. Since none of these studies were specific to ceramic art studios it is uncertain how they apply in this situation (see Chapter 9 for a full discussion of the uncertainties associated with this issue).

5.2. INHALATION

The portion of particles that enter the respiratory tract through the nose or mouth (inhalability) depends mainly on particle size, route of breathing (through the nose or mouth), wind speed, and a person's orientation with respect to wind direction. Inhaled particles may be either exhaled or deposited in the extrathoracic (ET), tracheobronchial (TB), or pulmonary (PU) airway. The deposition of particles in the respiratory tract depends primarily on inhaled particle size, route of breathing, tidal volume, and breathing frequency (American Conference of Governmental Industrial Hygienists, 2004; International Commission on Radiological Protection, 1994). Appendix B presents a detailed discussion of how to consider these factors and estimate the amount of particulate that deposits in various regions of the respiratory tract.

The absorbed inhalation dose is estimated as follows:

$$D_{inhalation} = D_r \, C \, AF_r \, (1\text{g}/1{,}000 \text{ mg}) \qquad (4)$$

where

$D_{inhalation}$ = inhalation dose (pg TEQ/d)
D_r = dose of particles to region r of the respiratory tract (mg/d)
C = dioxin concentration on particles (pg/g)
AF_r = absorption fraction for region r of the respiratory tract

This equation is used to estimate the absorbed dose to the three regions of the respiratory tract (ET, TB, and PU) and then summed to derive total inhalation dose. In general, particles deposited in the ET and TB regions clear rapidly (within 1–2 days) to the throat and are swallowed. Accordingly, the absorption of dioxin from particles deposited in these regions is treated as if the particles had been ingested with an absorption fraction of 0.3 (U.S. EPA, 2003). The particles depositing in the PU region remain there a long time, and most of them are ultimately absorbed directly into the body (assumed absorption fraction of 0.8 based on U.S. EPA, 2003). Chapter 9 discusses inhalation uncertainties.

5.3. INGESTION

The ingestion dose is estimated by assuming that all particles deposited on the surrogate food and beverage samples are ingested. For both types of samples, the dose was calculated using the equation below:

$$D_{ingestion} = (F + B)\ C\ AF_{ingestion} \quad (5)$$

where

$D_{ingestion}$ = ingestion dose (pg TEQ/d)
F = deposited clay on food (g/d)
B = deposited clay on beverage (g/d)
C = dioxin concentration in clay (pg TEQ/g)
$AF_{ingestion}$ = absorption fraction for ingestion

$AF_{ingestion}$ was assumed to equal 0.3 based on recommendations in U.S. EPA (2003) for ingestion of dioxin in soil. The ingestion of dioxin from inhaled particles is included in the inhalation dose as discussed above. Chapter 9 discusses ingestion uncertainties.

5.4. TOTAL DOSE

The total absorbed dose was estimated to be the sum of the dermal absorption, inhalation, and ingestion doses as shown below:

$$D_{total} = D_{dermal} + D_{inhalation} + D_{ingestion} \quad (6)$$

where

D_{total} = total dose (pg TEQ/d)
D_{dermal} = dermally absorbed dose (pg TEQ/d)
$D_{inhalation}$ = inhalation dose (pg TEQ/d)
$D_{ingestion}$ = ingestion dose (pg TEQ/d)

6. QUESTIONNAIRE RESULTS

The complete questionnaire and all responses are presented in Appendix A. The questionnaire focused on characterizing each subject's work with clay in terms of frequency/duration, type of activity, clothing worn, and impact on skin. Table 6 summarizes the questionnaire results for the amount of time that the subjects spent working directly with clay. The subjects worked with clay, on average, for 30 hours per week and 38 weeks per year over a 6-year period. The times varied widely, however, reflecting the types of students involved. A student obtaining an advanced degree in ceramics is likely to work with clay daily over many years. In contrast, a student who takes a pottery class to fulfill a general education requirement is likely to experience similar exposures, but only for 1–3 hours per day over the duration of the class (9 months or less).

Table 6. Questionnaire questions on duration and frequency of subject's clay work

Question (n = 8)	Mean (SD)	Median	Max	Min
Approximately how many hours per week do you work with clay?	30 (21)	23	70	10
Approximately how many weeks per year do you work with clay?	38 (10)	38	52	20
How long (years) have you been doing clay work with this level of intensity?	6 (8)	3	24	1

SD = standard deviation.

Table 7 summarizes the participants' answers to several questions about their clay work. Some of the questions address the types of clothing worn, how often the subjects wash their hands, and whether the subjects could correlate any skin health effects with working with clay. All eight subjects answered that they have dry skin because of the clay work. In general, the subjects wash their hands soon after working with clay: their faces and arms within a few hours and the rest of their bodies within 24 hours. The responses indicate that one subject gets a rash when using the wheel for throwing, another subject has nasal congestion due to clay work, and another subject's fingernails do not grow well.

Table 7. Questionnaire questions about clay work

Question (*n* = 8)	Summary of answers (number of subjects with similar answers)
What type of clay artwork do you do?	Hand building/sculptural work (7), throwing on wheel (3), mixing clay, and maintenance work (1).
What types of clothing do you wear while you work?	In general, long sleeves and pants in cool weather and short sleeves and pants or shorts in warm weather; both closed-toe shoes and sandals are worn at times.
What areas of skin typically are exposed to the clay while you work?	Always face and hands; arms, legs, and feet when exposed.
In relation to the time you complete working with clay, when do you wash parts of your body that have been exposed to clay?	Soon after: hands (8), arms (1), face (1). Within a few hours: arms (2), face (6). Within 24 hours: face (1), rest of body (4).
How do you wash your skin after you work with clay?	Soap and water or just water (8).
Do you correlate any skin health issues with how much you work with clay? If yes, what?	Dryness (8), rash on hands when using wheel (1), nasal congestion (1), fingernails do not grow well (1).

7. COMPARING EXPOSURES ACROSS SUBJECTS

In this chapter, a hypothetical dioxin dose is estimated for each subject and used to evaluate which pathways and activities contribute most to total dose. This is done by assuming that each subject uses clay with the same level of dioxin. More specifically, it is assumed that each subject uses a clay mixture with 20% ball clay and that the ball clay contains 808 pg TEQ/g (these are typical values as discussed in Chapter 4). Accordingly, the dioxin levels in the clay were assumed to be 20% of 808 pg TEQ/g or 162 pg TEQ/g. This concentration was also assumed to apply to inhaled dust and dust settled onto food. A variety of other factors were also held constant across subjects to facilitate this analysis:

- **Exposure duration.** Chapter 6 presents the questionnaire results, which indicate a median weekly time for clay work of 23 hours. Assuming a 5-day work week, this would correspond to about 4 hours/day. This value was applied to all subjects.

- **Monolayer load.** The monolayer load varies depending on particle size but is assumed here to be 0.5 mg/cm^2 for all subjects. This is based on the geometric mean of the range of possible median particle sizes, i.e., 0.5 to 27 μm (see Section 5.1 for further discussion of this issue).

- **Dermal absorption fraction.** This will depend on exposure time, as discussed in Section 5.1. The time that the skin is exposed to clay will vary with individual behaviors and body parts. Some body parts (such as hands and faces) are likely to be washed more frequently than others (such as feet, legs, and arms), resulting in longer exposure times. The questionnaire data collected during this study (see Chapter 6) suggest that the artists generally wash their hands soon after working with clay, wash their faces and arms within a few hours, and wash the rest of their body within 24 hours. Accordingly, the exposure time for feet and legs was assumed to be 24 hours, and the absorption fraction corresponding to 24 hours was applied (2.3%). The exposure time for hands, arms, and face was assumed to be 4 hours with a corresponding 1.0% absorption.

- **Ingestion absorption fraction.** This was set to 0.3 based on recommendations by EPA for ingestion of dioxin in soil (U.S. EPA, 2003).

- **Inhalation absorption fraction.** This was set to 0.3 for ET and TB regions based on the assumption that the area is rapidly cleared to the gastrointestinal tract. It was set to 0.8 for the PU region based on recommendations by EPA for inhalation of dioxin in air (U.S. EPA, 2003).

The hypothetical dioxin dose for each subject is calculated using the constant values described above and their individual exposure conditions (e.g., dust level in air, clay load on skin, clay load on food). The dose estimates are considered to be hypothetical because they are

based on assumed dioxin levels in the various exposure media rather than on studio-specific measurements. Chapter 8 uses Monte Carlo simulations to analyze the possible variability in dose resulting from a range of dioxin levels in clay, ball clay mixtures, and exposure factors.

This chapter first addresses each pathway separately (dermal contact, inhalation, and ingestion) and then addresses total dose. Individual exposures vary widely, and it is important to consider the subject's activity and clothing in evaluating the results. Table 8 is provided as a reference for this purpose with summaries of each participant's activities and clothing.

7.1. DERMAL CONTACT

As described in Section 5.1, the mass of clay rinsed from the skin was used to estimate clay loadings on the skin for each exposed body part. The rinsing data are presented in Appendix E. Section 5.1 also explains that the skin loading is compared to the monolayer load, and the absorption fraction is applied to the lower amount. Table 9 shows the dermal absorption estimate for each subject. Subjects 1 through 8 wore clothing that limited their exposures to only hands and arms (although arm exposure was detected on only Subjects 1 and 6). The estimates for Subjects 9 and 10 include hands, arms, legs, and feet because they wore clothing allowing exposure to these areas. All subjects could have had exposure to the face, but this was evaluated only for Subjects 9 and 10. Pictures of the clay residues on skin are shown in Appendix F. Table 9 shows that 6 of the 10 subjects had skin loadings exceeding the monolayer. The absorbed dose ranged from 0.23 to 7.09 pg TEQ/d with a mean of 1.35 pg TEQ/d (SD = 2.05).

The relationships between the activities of the subjects and their dermal exposure are discussed below:

- **Wheel work (Subjects 6 and 9).** This activity led to the highest dermal exposures. The high exposures were caused by the close proximity of the subjects to the wheel, the splashing of wet clay onto their bodies, and the use of both hands to mold the clay. The total dermal dose for Subject 9 was about 4 times greater than that for Subject 6, resulting primarily from their clothing difference. Both had similar hand and arm exposure, but Subject 9 had high exposure to legs and feet and Subject 6 had no exposure in these areas.

Table 8. Artisan activities of each subject

Artisan/staff (minutes sampled)	Description of activity	Clothing
Test 1, April 2003		
Subject 1/male (153 min)	Wedged clay on a wedging board to remove air from the clay before kneading and shaping clay by hand. Used a wooden press to press the clay into flat, approximately 2.5-cm thick sheets. Also, pounded semi-dry clay into balls, placed in ball mill for smoothing rough edges.	Short-sleeved shirt, long pants, socks, shoes
Subject 2/male, nonartisan staff (84 min)	Poured powdered components into large mixer for clay manufacture while wearing dust mask and while the dust removal system was operational. Weighed out portions of clay, and bagged and stored them. Subject moved to gas kiln room, where he cut blocks, built the kiln up a bit, and vacuumed. Finally, subject used compressed air to clean the dust off himself.	Short-sleeved shirt, long pants, socks, shoes
Subject 3/female (124 min)	Subject wedged clay and covered a prefabricated mold with clay using her hands to mold and shape the clay.	Short-sleeved shirt, long pants, socks, shoes
Subject 4/female (121 min)	Subject cut pre-wedged and formed blocks of clay into 5-cm thick pieces, loaded the blocks into a pneumatic press, pressed a pattern into each, cut blocks to the proper shape, and then stacked the finished pieces to be fired.	Long-sleeved shirt (rolled up), long pants, socks, shoes
Subject 5/male (136 min)	Subject hand rolled clay into 60-cm long "snake-like" cylinders, which he then hand-formed into conical pots.	Short-sleeved shirt, long pants, socks, shoes
Subject 6/female (123 min)	Subject threw a variety of clay items, including a pitcher, a vase, pots, and bowls on the pottery wheel.	Short-sleeved shirt, long pants, socks, shoes
Subject 7/female (124 min)	Subject wedged, rolled, cut, and hand-built a variety of items.	Short-sleeved shirt, long pants, socks, shoes
Subject 8/female (138 min)	Subject wedged, rolled, shaped, cut, and hand-built large pieces of clay and placed them on a mold.	Short-sleeved shirt, long pants, socks, shoes
Test 2, July 2004		
Subject 9/female, five sessions (295–476 min)	Subject threw a variety of clay items, including plates, bowls, vases, and cups, on the pottery wheel.	Short-sleeved shirt, short pants, sandals
Subject 10/female, three sessions (406–438 min)	Subject sculpted detailed designs into clay tiles and plaques; also chipped small bits of excess clay off pieces of art that had already been fired.	Short-sleeved shirt, 3/4-length pants, sandals

min = minute.

Table 9. Hypothetical estimates of dermal dose

Body part	Clay load on skin (mg/cm^2) [a]	Skin area (cm^2)[b]	Fraction uncovered	Absorbed dioxin dose (pg TEQ/d)[c,d,e]
Subject 1				
Hands	0.38	970	1.0	0.58
Arms	0.15	2,406	0.5	0.29
Total				0.87
Subject 2				
Hands	[2.01]	970	1.0	0.77
Subject 3				
Hands	[0.51]	865	1.0	0.69
Subject 4				
Hands	0.17	855	1.0	0.23
Subject 5				
Hands	[2.61]	1,005	1.0	0.80
Subject 6				
Hands	[9.25]	790	1.0	0.63
Arms	[2.99]	2,005	0.6	0.95
Total				1.58
Subject 7				
Hands	0.26	785	1.0	0.33
Subject 8				
Hands	[1.90]	715	1.0	0.57

Table 9. continued.

Body part	Clay load on skin (mg/cm^2) [a]	Skin area (cm^2)[b]	Fraction uncovered	Absorbed dioxin dose (pg TEQ/d)[c,d,e]
Subject 9				
Hands	[10.12]	857	1.0	0.68
Arms	[1.50]	2,265	0.75	1.35
Lower legs	[0.72]	2,161	1.0	3.96
Feet	0.26	1,151	1.0	1.09
Face	0.03	374	1.0	0.02
Total				7.09
Subject 10				
Hands	0.20	783	1.0	0.24
Arms	0.04	2,271	0.9	0.13
Lower legs	0.11	2,095	0.1	0.08
Feet	0.03	1,109	1.0	0.11
Face	0.04	368	1.0	0.02
Total				0.59

[a] All bracketed loads exceed monolayer of 0.5 mg/cm^2 and were reduced to this value in absorption calculation.
[b] Skin area is for total body parts; for two-sided parts, it is the sum of right and left sides.
[c] Absorption = skin load (mg/cm^2-day) × skin area (cm^2) × fraction uncovered × dioxin concentration in clay (pg TEQ/g) × 10^{-3} mg/g × absorption fraction.
[d] All calculations assume dioxin concentration in clay = 162 pg TEQ/g and absorption fraction is 2.3% for feet and legs, and 1.0% for hands, arms, and face.
[e] Results from Subjects 1 through 8 are based on one work session, from Subject 9 are based on average of five sessions, and from Subject 10 are based on average of three sessions.

TEQ = toxic equivalent.

- **Mixing (Subject 2).** Subject 2 was involved in the mixing and handling of dry clays and furnace/kiln maintenance during the work session. This activity produced relatively large hand loadings.

- **Wedging and molding (Subjects 1, 3, 4, 5, 7, and 8).** Wedging clay involves kneading and hitting clay against a tabletop to purge air pockets from the clay. During the wedging process, the clay is firm and dry as compared with clay used on the wheel. This activity produced a wide range of hand loadings (from 0.17 to 2.61 mg/cm^2).

- **Sculpting (Subject 10).** This involved sculpting activities on dry clay. At times, fine detailing tools were used that involved very little contact with the clay, resulting in low hand loading.

Table 10 shows the percent contribution to the dermal dose by body part for Subjects 9 and 10. Subjects 9 and 10 were tested in July 2004 and wore summer clothing, which allowed exposure to their legs and feet. Leg and foot exposure accounted for 71% of the total dose for Subject 9 and 33% of the total dose for Subject 10. This reflects the relatively large surface areas and higher absorption fraction (due to longer exposure time) for these parts. The uncovered portion of Subject 10's lower legs was only 10%, so the leg contribution to total dose was much less than that of Subject 9. Facial exposures were low, accounting for only 0.2–4% of total dose.

Table 10. Percent contribution to dermal dose by body part

Body part	Percentage of dose	
	Subject 9 (wheel)	Subject 10 (sculpture)
Hands	10	41
Arms	19	22
Legs	56	14
Feet	15	19
Face	0.2	4

7.1.1. Clay Loads on Surfaces

The horizontal surfaces in ceramic art studios can have high dust loads resulting from air deposition. Most clay on the hands of artisans probably results from direct contact with clay, but some could also result from contact with surfaces. In the interest of exploring this issue, wipe samples were collected from the work surface of each subject. The sampled surfaces were porous concrete tabletops. The artisans involved in wedging used a nonporous plastic composite surface. Table 11 shows the surface sampling results. The surface dust loads ranged from 0.2 to 7 mg/cm^2, which are high compared with dust loads on floors in residences (i.e., 0.005 to 0.7 mg/cm^2) (Lioy et al., 2002). The efficiency of transfers from surfaces to hands will vary depending on the type of surface, type of residue, hand condition, force of contact, etc. Rodes et al. (2001) conducted hand press experiments on particle transfer to dry skin and measured transfers with central values of about 50% from hard surfaces. Table 11 shows that several of the ratios of hand loads to surface loads exceed 50% by a wide margin. Subject 6 was working on a wheel and clearly had hand loads resulting from direct contact with clay. Similarly, Subjects 5 and 8 had very high hand loads that must have resulted from direct clay contact. The other subjects had ratios ranging from 0.05 to 0.30, which are in the range that could result from surface transfers. Observation of the subjects indicated that almost all contact with the work surface also involved some contact with the clay. Therefore, the hand residues are most likely derived from a combination of direct clay contact and transfers from surfaces.

Table 11. Comparing clay loads on surfaces to clay loads on hands

Subject	Clay loading on surface (mg/cm^2)	Clay load on hand (mg/cm^2)	Ratio of hand load to surface load
1	7.002	0.38	0.05
2	NA	2.01	NA
3	2.966	0.51	0.17
4	0.572	0.17	0.30
5	0.774	2.61	3.4
6	0.238	9.25	38.9
7	1.206	0.26	0.22
8	0.419	1.90	4.5

NA = Nonartisan subject was not working at a surface during sampling, so this type of sample was not collected.

7.1.2. Dermatologist Report

The dermatologist did not diagnose any serious skin health problems among the subjects. Small abrasions and common skin conditions such as dryness and cracking, as the subjects reported on the questionnaires, were noted, but changes in these conditions could not be detected based on before and after observations.

7.2. INHALATION

Estimating the inhalation dose involved measuring particle concentrations in air and modeling deposition to various regions of the respiratory system. Classroom exposures were not estimated.

7.2.1. Particle Levels in Air

As described in Chapter 3, four different sampling techniques were used during the April 2003 tests to measure clay particle concentrations in air: two personal monitors and two area monitors. The data from all four devices are shown in Appendices G and H. The Respicon™ personal air sampler normally would have been the best indicator of individual exposures, but the blanks were high, resulting in a high detection limit and a high frequency of nondetects in the data. Instead, the cascade impactor was chosen as the best indicator of daily exposure. Although this is an area sampler, it was located near the subjects and the subjects were generally stationary during the test. Thus, it should have been a reasonable indicator of individual exposures. Also, the cascade impactor uses deposition collectors and gravimetric techniques to estimate air concentrations; consequently, it is a more direct measurement technique than the other two instruments (pDR-1000 and Climet®), which use light scattering to estimate particle concentration. These optical devices provide a nearly continuous readout of concentration levels, making them better suited to evaluating short-term fluctuations in particle levels rather than long-term concentrations.

Only the cascade and Climet® monitors were used in the July 2004 tests. The instruments were located even closer to the individuals, i.e., within 30 cm of their breathing zones. The data were used in a fashion consistent with the April 2003 tests, i.e., daily exposures were based on the cascade data and the Climet® was used to evaluate short-term fluctuations.

Table 12 presents the air data for each subject on the basis of the cascade measurements. The MMADs were estimated by fitting the data to log-normal distributions (see the discussion in Appendix B). Table 12 indicates that the range for total particulate matter is 0.084 to 0.99 mg/m^3. Note that the upper end of this range is less than the Occupational Safety and Health Administration (OSHA) standard for total particulates of 15 mg/m^3 (OSHA, 2004).

Table 12. Particle concentrations in air and mass median aerodynamic diameter (MMAD) based on cascade impactor

Subject	MMAD (µm)	Total concentration (mg/m^3)
1	26.9	0.35
2	44.6	0.47
3	18.5	0.99
4	25.0[a]	0.37
5	25.0[a]	0.13
6	20.2	0.61
7	13.0	0.51
8	26.7	0.64
9	32.6	0.084
10	16.0	0.24

[a] Nondetects prevented calculation of the MMAD for these subjects; they were assumed equal to the average over the remaining first eight subjects.

Subject 3's concentration was the highest because students were cleaning the floor near the area samplers (see the discussion below). Subject 9's concentration was the lowest, resulting from a relatively low activity level during the testing time period. Subject 5's concentration was also low, likely because a steady breeze entered through an open window in the room in which sampling was occurring. All of the other subjects had fairly similar concentrations. Subject 2 was the only one who changed room locations during the sampling period and the sampling equipment was moved with him.

The two subjects using wheels (Subjects 6 and 9) had very different air exposures. Because a great deal of water is used to moisten clay during wheel molding (the clay was saturated with water and a pan of water was placed directly next to the artisans for their use), this setting would not be expected to produce much clay dust, which was observed for Subject 9. Subject 6, however, had fairly high air levels. Subject 6 was located near a classroom that, as discussed below, had high activity levels. Therefore, this subject's high air levels may have been associated more with the classroom activities than the wheel activities.

Figure 4 shows the plot of concentration versus time (based on the Climet® CI-500 area particle counter) for Subject 3, who worked in an area designated for graduate student work adjacent to a large classroom. Approximately 50 minutes into the sampling session, about 20 students from the adjacent classroom began sweeping and wiping down the surfaces. This activity continued for approximately 15 minutes and generated a significant cloud of dust. Figure 4 shows particle levels began rising at about 50 minutes, peaked sharply at 60–70 minutes, and declined to low levels at about 80 minutes.

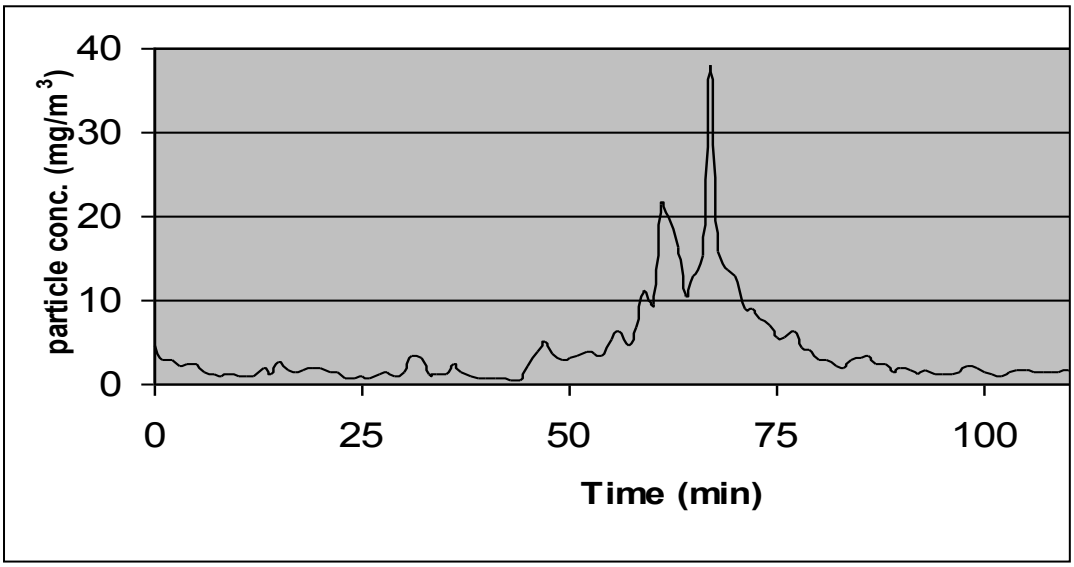


Figure 4. Real-time particle concentration for Subject 3 using the CI-500 particle counter.

During two of Subject 10's sculpture work sessions, a small dog was present. The dog's movement disturbed dust on the floor of the ceramics studio and, in turn, increased the particle concentration. Figures 5 and 6 are the real-time traces for the Climet® monitor for the sculpting work sessions during which the dog was present. The dog was present for the entire first sculpting work session. This was reflected in the relatively constant variation in the particle concentration throughout the work session. During the second sculpting work session, the dog did not arrive until 138 minutes into sampling. Note the increase in overall particle concentration and increase in variability of particle concentration after arrival of the dog. The presence of a dog in the studios and classrooms is not likely to be a common occurrence,

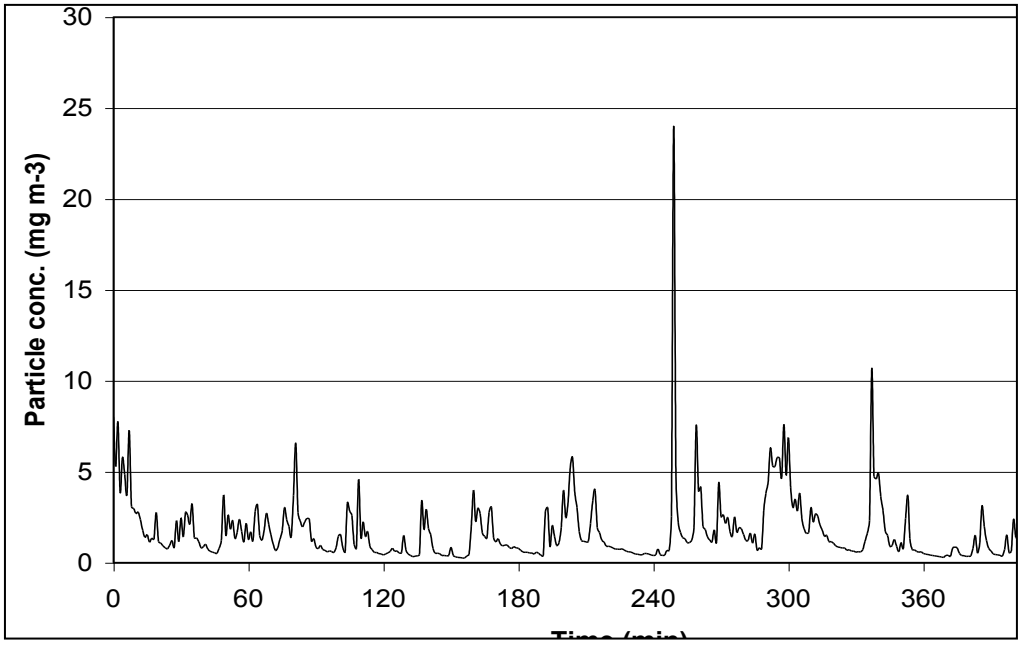


Figure 5. Sculpture Session 1 with dog present.

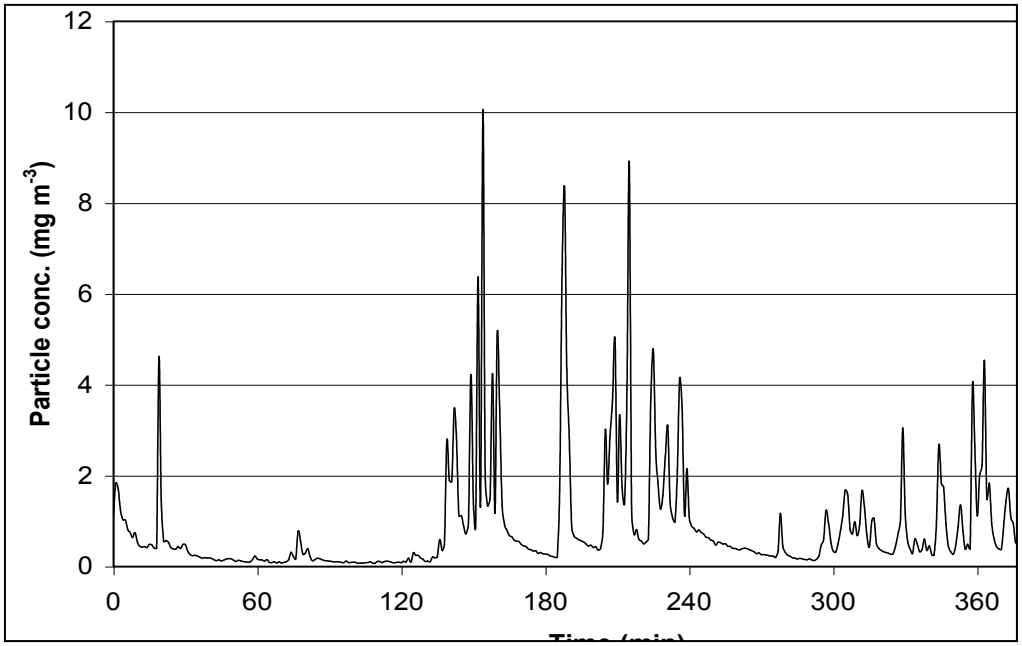


Figure 6. Sculpture Session 2 with dog present.

especially during the regular school year. Therefore, the particle concentrations during the work sessions when the dog was present (1 and 2) were not used to estimate the exposures for this subject. It should be noted, however, that pets, which may be present in many ceramic art studios, can increase the suspended dust levels and spread dust to other areas.

7.2.2. Inhalation Dose

Table 13 shows the absorbed dose in various regions of the respiratory system for all 10 subjects. The total inhalation doses ranged from 0.006 to 0.09 pg TEQ/d with an average of 0.04 pg TEQ/d. Most particle deposition was found to occur in the ET region. Appendix B presents the modeling to support these estimates.

Table 13. Hypothetical estimates of inhalation dose

Subject	Absorbed dose (pg TEQ)[a]			
	ET[b]	TB[b]	PU[c]	Total
1	0.032	0.001	0.003	0.035
2	0.033	0.001	0.003	0.036
3	0.082	0.002	0.010	0.094
4	0.028	0.001	0.002	0.031
5	0.012	0.000	0.001	0.014
6	0.054	0.001	0.004	0.059
7	0.049	0.001	0.006	0.057
8	0.048	0.001	0.003	0.052
9	0.005	0.000	0.001	0.006
10	0.022	0.001	0.002	0.025

[a] Dose calculated using procedures in Appendix B for nasal breathing; subject exposure concentrations from Appendix H; 4-hour exposure duration and dioxin concentration of 162 pg TEQ/g clay.
[b] Absorption fraction of 0.3 assumed, since these regions rapidly clear into the gastrointestinal tract.
[c] Absorption fraction of 0.8 assumed, in part, due to slow particle clearance from this region.

ET = extrathoracic; PU = pulmonary; TB = tracheobronchial; TEQ = toxic equivalent.

The inhalation exposure estimates assume that no respiratory protection was used. Generally, this was true, however, Subject 2 used a dust mask while pouring powdered clay into a mixer for clay preparation. This reduced his inhalation exposures relative to levels reported here.

7.2.3. Classroom Exposure

Estimating student exposures in a classroom setting was not an objective of this study. However, some insight on this issue can be gained from the data for Subjects 1, 3, and 6. These subjects performed their clay activities adjacent to the undergraduate classroom during times when undergraduate classes of 20–25 students were participating in clay-related activities. The area particle samples collected for these subjects are generally representative of the inhalation exposure of students in those classes. As discussed above, students in this class swept the floor during Subject 3's testing period, producing elevated particle concentrations for about 30 minutes.

7.3. INGESTION

The ingestion dose was calculated by assuming that all deposited material on the surrogate food and beverage samples was ingested. As Table 14 shows, clay deposition onto the food and beverage samples reached detectable levels in only 5 out of 16 total samples. The deposition amounts for the nondetects were assumed to equal half the detection limit. The resulting ingestion doses ranged from 0.03 to 0.1 pg TEQ/d. The field technicians did not observe hand-to-mouth activities for any of the subjects. Also, none of the subjects ate food or smoked without first washing the clay from their hands. No deposition samples were collected for Subjects 9 and 10.

7.4. TOTAL DOSE

Table 15 lists the hypothetical estimates of total dioxin dose derived by summing across exposure pathways for each subject. The total doses ranged from 0.32 to 7.10 pg TEQ/d with an average of 1.44 pg TEQ/d. Table 16 shows the percentage contribution of each exposure pathway to the total dose of each subject. Dermal absorption is the major contributor to total dose for all subjects, exceeding 67% for all subjects. Ingestion and inhalation contribute similar amounts, generally in the range of 1–20%. Table 17 shows the dose estimates by activity. The highest total doses were associated with wheel activities.

Table 14. Clay deposition and hypothetical estimates of ingestion dose

Subject	Clay deposited onto food (mg)	Clay deposited into beverage (mg)	Ingestion dose (pg TEQ/d)[a, b]
1	0.71	0.66	0.07
2	<DL	<DL	0.03
3	<DL	<DL	0.03
4	<DL	0.72	0.05
5	<DL	<DL	0.03
6	<DL	<DL	0.03
7	1.66	<DL	0.1
8	1.50	<DL	0.09

[a] Ingestion dose (pg TEQ) = (deposited clay on food [mg] + deposited clay on beverage [mg]) × dioxin concentration in clay (pg TEQ/g) × absorption fraction × (1 g/1,000 mg).
[b] All calculations assume dioxin concentration in clay = 162 pg TEQ/g, absorption fraction = 0.3, all deposited clay is ingested, and nondetects were set equal to half the detection limit.

DL = detection limit (0.60 mg); TEQ = toxic equivalent.

Table 15. Hypothetical estimates of total dioxin dose (pg TEQ/d)

Subject	Estimated dioxin dose (pg TEQ/d)			
	Inhalation	Ingestion	Dermal absorption	Total
1	0.035	0.07	0.87	0.97
2	0.036	0.03	0.77	0.84
3	0.094	0.03	0.69	0.81
4	0.031	0.05	0.23	0.32
5	0.014	0.03	0.80	0.84
6	0.059	0.03	1.58	1.67
7	0.057	0.1	0.33	0.49
8	0.052	0.09	0.57	0.71
9	0.006	NM	7.09	7.10
10	0.025	NM	0.59	0.62
Mean (SD)	0.041 (0.025)	0.05 (0.03)	1.35 (2.05)	1.44 (2.02)
Median	0.036	0.04	0.73	0.82
Minimum	0.006	0.03	0.23	0.32
Maximum	0.094	0.10	7.09	7.10

NM = not measured; SD = standard deviation; TEQ = toxic equivalent.

Table 16. Percent contribution to total dioxin dose

Subject	Percentage of dose		
	Inhalation	Ingestion	Dermal absorption
1	3.6	7.2	89.2
2	4.3	3.6	92.1
3	11.5	3.7	84.7
4	9.9	15.8	74.3
5	1.6	3.6	94.8
6	3.5	1.8	94.7
7	11.7	20.6	67.7
8	7.4	12.7	79.9
9	0.1	NM	99.9
10	4.1	NM	95.9

NM = not measured.

Table 17. Dose estimates by activity

Activity	Subject	Inhalation dose (pg TEQ/d)	Ingestion dose (pg TEQ/d)	Dermal dose (pg TEQ/d)	Total dose (pg TEQ/d)
Wedging and molding	1	0.035	0.07	0.87	0.97
	3	0.094	0.03	0.69	0.81
	4	0.031	0.05	0.23	0.32
	5	0.014	0.03	0.80	0.84
	7	0.057	0.1	0.33	0.49
	8	0.052	0.09	0.57	0.71
Mixing	2	0.036	0.03	0.77	0.84
Wheel	6	0.059	0.03	1.58	1.67
	9	0.006	NM	7.09	7.10
Sculpting	10	0.025	NM	0.59	0.62

NM = not measured; TEQ = toxic equivalent.

8. MONTE CARLO SIMULATION OF THE EXPOSURE DATA

Chapter 7 presented hypothetical dose estimates for each subject, assuming that all were using typical amounts of ball clay with average dioxin levels. In this chapter, Monte Carlo simulations are used to explore the doses that could occur in a broad population of artists with a wide range of behaviors using ball clay with differing levels of dioxin. The simulations are based largely on the range of activities observed during this study. As noted in the Introduction, the OSU studio has a modern ventilation system and is well maintained. Therefore, these simulations are most representative of how doses may vary in similar facilities. A wider range of results would be expected across all types of ceramic art facilities. Appendix I provides a detailed outline of the Monte Carlo procedure.

The general strategy for selecting input value distributions was as follows. The distribution of skin surface areas across adults in the general population was assumed to be log-normal with mean and standard deviation from the *Exposure Factors Handbook* (U.S. EPA, 1997). Similarly, the dioxin concentration in clay was assumed to have a log-normal distribution with mean and standard deviation from Ferrario et al. (2007, 2004). The rationale for choosing log-normal distributions was that physiological parameters and environmental media concentrations are commonly found to have these types of distributions. The remaining exposure factor parameters were based on observations from this study. These were generally assumed to have triangular distributions with ranges based on minimum and maximum values and peaks based on means. The rationale for choosing a triangular distribution was that (1) the small sample sizes associated with the study observations prevented fitting the data to standard distributions and (2) it reflected the likelihood that a central value would occur most often. In some cases (e.g., clay load on face), only two data points were available and a uniform distribution was assumed. Table 18 lists the distributions assumed for all input variables.

Crystal Ball 7 software was used to conduct 1,000 trial simulations. For each simulation trial, a set of parameter values was obtained by randomly sampling the parameter distributions shown in Table 18 and then computing the dioxin dose. Chapter 5 presents the equations used to calculate the dose. All simulation trials first select a set of values for the dioxin concentration in ball clay, the fraction of ball clay in the blend used by the artist, gender, and the exposure duration. Table 18 shows the general parameters. The simulation then calculates the dose from the dermal, inhalation, and ingestion pathways, as discussed below:

- **Dermal.** The simulation was designed to first select a total body surface area from log-normal distributions for females and males. Subsequently, skin surface areas for

Table 18. Monte Carlo simulation input parameters and sampling distributions

Parameter	Distribution	Basis
General parameters		
Dioxin concentration in ball clay (pg TEQ/g)	Log-normal (mean = 808, SD = 318)	Ferrario et al. (2007, 2004) (*n* = 21)
Fraction of ball clay in blend	Triangular (0, 0.2, 1.0)	Data in this study (*n* = 10)
Exposure duration (hr/d)	Triangular (1, 4, 10)	Judgment and data from this study (*n* = 8)
Gender selector	Uniform (0, 1.0)	Used to select male 50% of time, and female 50% of time
Dermal absorption parameters		
Total body surface area for males (cm^2)	Log-normal (mean = 19,700, SD = 1,900)	*Exposure Factors Handbook* (U.S. EPA, 1997) (*n* = 32)
Total body surface area for females (cm^2)	Log-normal (mean = 17,300, SD = 1,680)	*Exposure Factors Handbook* (U.S. EPA, 1997) (*n* = 57)
Clothing selector	Uniform (0, 1.0)	This is applied using Table 19. Judgment and data from this study (*n* = 8)
Clay load on hand (mg/cm^2)	Triangular (0.1, 3.0, 10)	Range and mean based on observations from this study (*n* = 10)
Clay load on arm (mg/cm^2)	Triangular (0.04, 0.35, 3.0)	Data in this study (*n* = 4)
Clay load on leg (mg/cm^2)	Uniform (0.1, 0.70)	Data in this study (*n* = 2)
Clay load on feet (mg/cm^2)	Uniform (0.03, 0.3)	Data in this study (*n* = 2)
Clay load on face (mg/cm^2)	Uniform (0.03, 0.04)	Data in this study (*n* = 2)
Ingestion parameters		
Clay load on food (mg)	Triangular (0.3, 0.7, 1.66)	Range and mean based on observations from this study (*n* = 8)
Clay load on beverage (mg)	Triangular (0.3, 0.5, 0.72)	Range and mean based on observations from this study (*n* = 8)
Inhalation parameters		
Particle concentration in air (mg/m^3)	Triangular (0.08, 0.44, 0.99)	Range and mean based on observations from this study (*n* = 10)
Median particle size (μm)	Triangular (13, 25, 45)	Judgment and data from this study (*n* = 10)
Lung parameters	Male—50%; female—50%	Based on general population
Fraction of time engaged in light vs. moderate exertion.	Uniform (0, 1.0)	Judgment
Breathing type	Oronasal—13%; nasal—87%	Brown (2005)

hr = hour; d = day; SD = standard deviation; TEQ = toxic equivalent.

individual body parts were calculated by multiplying the total surface area by the average percentage of total surface area. These percentages were obtained from U.S. EPA, 1997: hands—5.2%; arms—14%; legs—31.8%; feet—6.8%; and face—2.5% (assumes face area equals one-third of head area). This approach ensures that simulation trials have realistically matched body part areas. Since the body part area calculations give total areas, a fraction unclothed was used to reduce this to the exposed area. These fractions were based on four clothing scenarios as shown in Table 19. These clothing scenarios were based on questionnaire responses and judgment about typical apparel for a moderate climate. A clothing scenario was selected randomly for each simulation trial according to the time fractions shown in Table 19. Distributions were also assumed for the clay loads on skin. These were assumed to be spread uniformly over the entire unclothed area. As discussed in Section 5.1, dermal absorption was assumed to be limited to the monolayer that was held constant at the median value of 0.5 mg/cm^2 (the impact of changing this value is discussed as an uncertainty issue in Chapter 9). Finally, the absorption fractions (as presented in Section 5.1) were applied to derive the absorbed dose from exposed body parts and then summed to derive total dermal dose.

- **Inhalation.** Section 5.2 summarizes and Appendix B presents the procedures used to calculate the inhalation dose. Distributions were used to represent the variability in total particulate concentration in air and median particle size (see Table 18). Breathing was assumed to be either oronasal (13%) or nasal (87%), based on Brown (2005). Inhalation parameters (see Appendix B) were based on gender. The rate of breathing was determined by the fraction of time engaged in light versus moderate exertion. These fractions were varied randomly from 0 to 1.0 using a uniform distribution. Depositions to various parts of the respiratory system were modeled as described in Appendix B, multiplied by the absorption fraction, and summed to derive the total inhalation dose.

- **Ingestion.** The variability in ingested dose was simulated using distributions for the levels of clay in the food and beverages as shown in Table 18. As discussed in Section 5.3, all deposited material was assumed to be ingested.

Two Monte Carlo stimulations were conducted. The first simulation was designed to evaluate the influence of clay use only. Accordingly, it was conducted using the distributions for dioxin concentration in the clay and the fraction of ball clay in the blend used by the artists. All other inputs were held constant at their central values. The summer clothing scenario was used (i.e., short-sleeved shirt, short pants, sandals). This simulation produced a mean total dose of 14 pg/d, median of 12 pg/d, and 90th percentile of 28 pg/d. These results are best compared to the hypothetical dose estimate for Subjects 9 and 10 (see Chapter 7) because they wore summer clothing matching the simulation assumption. Subject 9 had a dose estimate of 7.1 pg/d, corresponding to about the 25th percentile of the simulation. Subject 10 had a dose of 0.62 pg/d, corresponding to about the 2nd percentile of the simulation. This simulation suggests that clay

Table 19. Clothing scenarios based on questionnaire responses

Clothing scenario	Time fraction	Fraction unclothed		
		Arms	Legs	Feet
Long-sleeved shirt, long pants, shoes	0.2	0	0	0
Short-sleeved shirt, long pants, shoes	0.6	0.67	0	0
Short-sleeved shirt, short pants, shoes	0.1	0.67	0.67	0
Short-sleeved shirt, short pants, sandals	0.1	0.67	0.67	1.0

choice alone can account for a wide range of exposures with the potential to elevate exposures above the hypothetical estimates for the 10 subjects.

The second simulation used the distributions for all parameters as shown in Table 18. This simulation produced a mean total dose of 6.4 pg/d, median of 3.5 pg/d, and 90th percentile of 14.8 pg/d. The standard deviation (8.43) exceeds the mean indicating that the results have a wide spread. The hypothetical dose estimates of most subjects would have corresponded to low percentiles of this simulation except Subject 9 (75th percentile). Table 20 shows the simulation results for each pathway. The simulation means for each pathway exceeded by 3 to 4 times the pathway means of the hypothetical dose estimates for the 10 subjects. As observed during the field study, the ingestion and inhalation doses are much smaller than the dermal dose. The total dose is plotted as a frequency diagram in Figure 7 and as a cumulative probability diagram in Figure 8. Figure 7 shows a highly skewed distribution with a peak around 2 pg TEQ/d and a long tail to the right extending to about 28 pg TEQ/d. A detailed report showing all inputs and outputs for this simulation is presented in Appendix J.

A sensitivity analysis was performed using the Crystal Ball 7 software. Each input parameter was evaluated using contribution to variance. Figure 9 shows the results of this analysis applied to the total dose; it shows that the fraction of ball clay in the blend contributed most to variance (45.2%), followed by clothing selected (36.2%) and dioxin concentration (13.8%). Figures 10, 11, and 12 show similar sensitivity analyses were also conducted for each exposure pathway separately.

Overall, the simulation suggests that higher exposures than those reflected in the hypothetical dose estimates of the 10 subjects may occur. This results from the skewed input distributions, which generally have long right-hand tails. Also 6 of the 10 subjects had hand

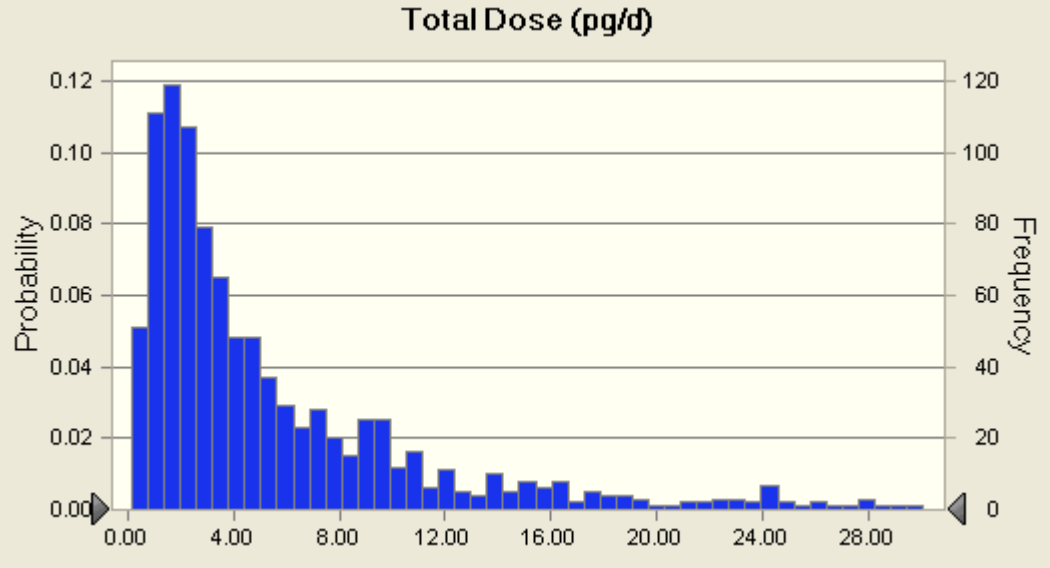


Figure 7. Frequency distribution of total dose (pg TEQ/d) based on Monte Carlo simulation.

Table 20. Descriptive statistics of dioxin doses from ball clay use, based on a Monte Carlo simulation

Pathway	Mean	Standard deviation	Median	90th percentile
Dermal dose (pg TEQ/d)	6.2	8.3	3.2	14.4
Ingestion dose (pg TEQ/d)	0.14	0.10	0.11	0.26
Inhalation dose (pg TEQ/d)	0.11	0.13	0.07	0.26
Total dose (pg TEQ/d)	6.4	8.4	3.5	14.8

pg = picogram; TEQ = toxic equivalent.

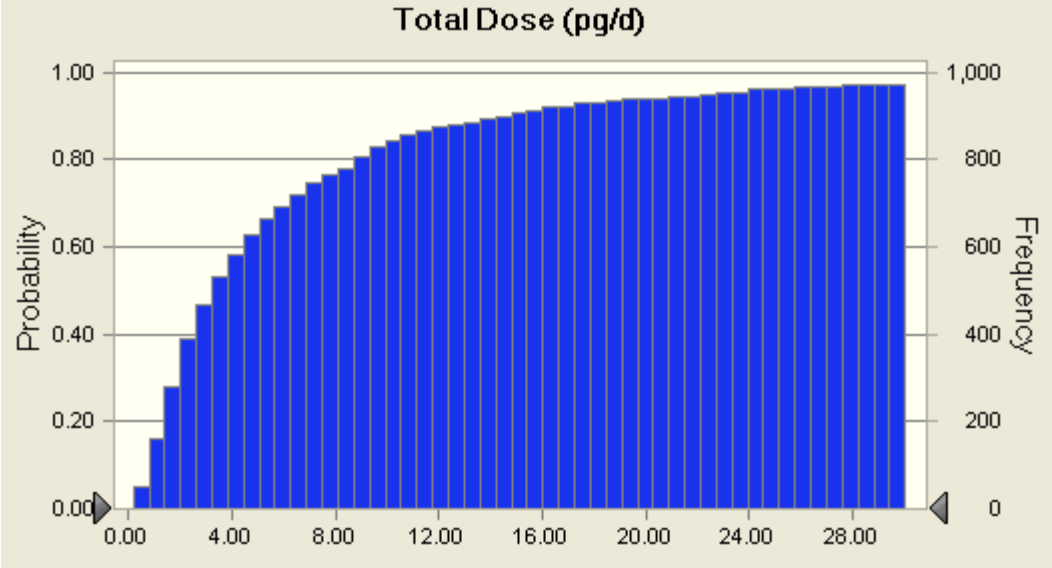


Figure 8. Cumulative probability distribution of total dose (pg TEQ/d) based on Monte Carlo simulation.

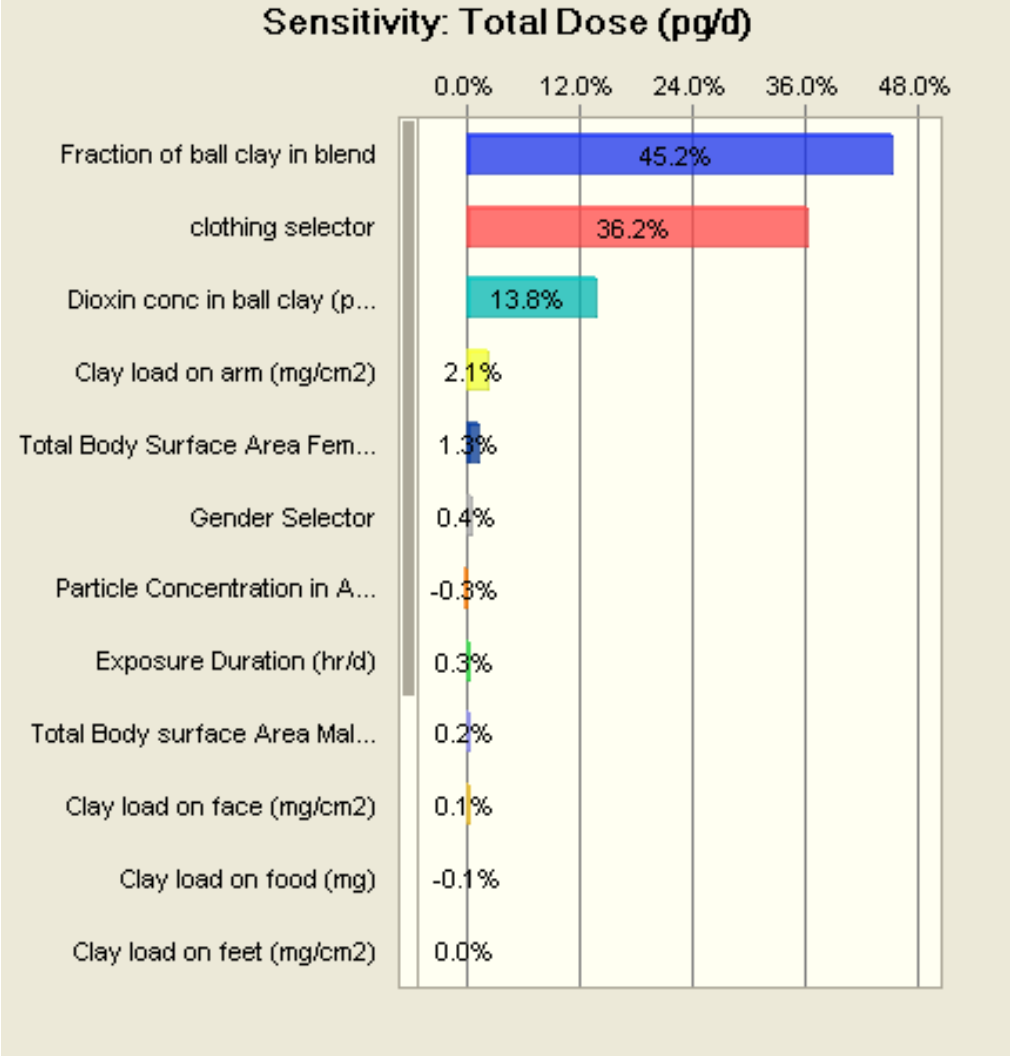


Figure 9. Sensitivity analysis based on percent contribution to variance for total dose.

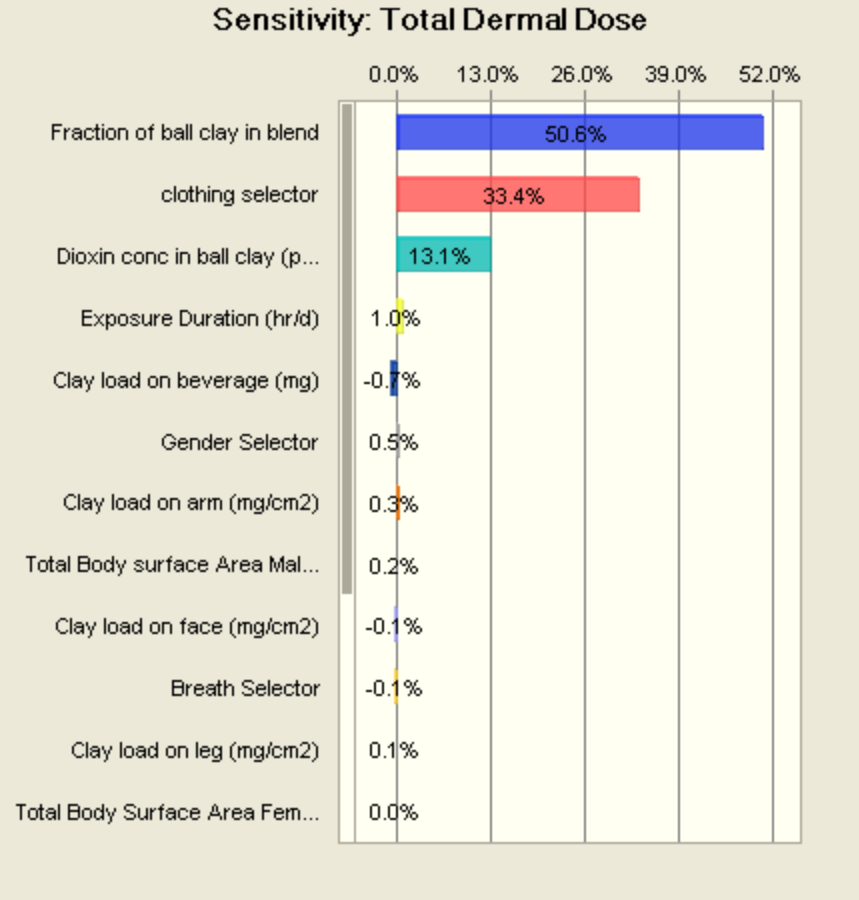


Figure 10. Sensitivity analysis based on percent contribution to variance for dermal dose.

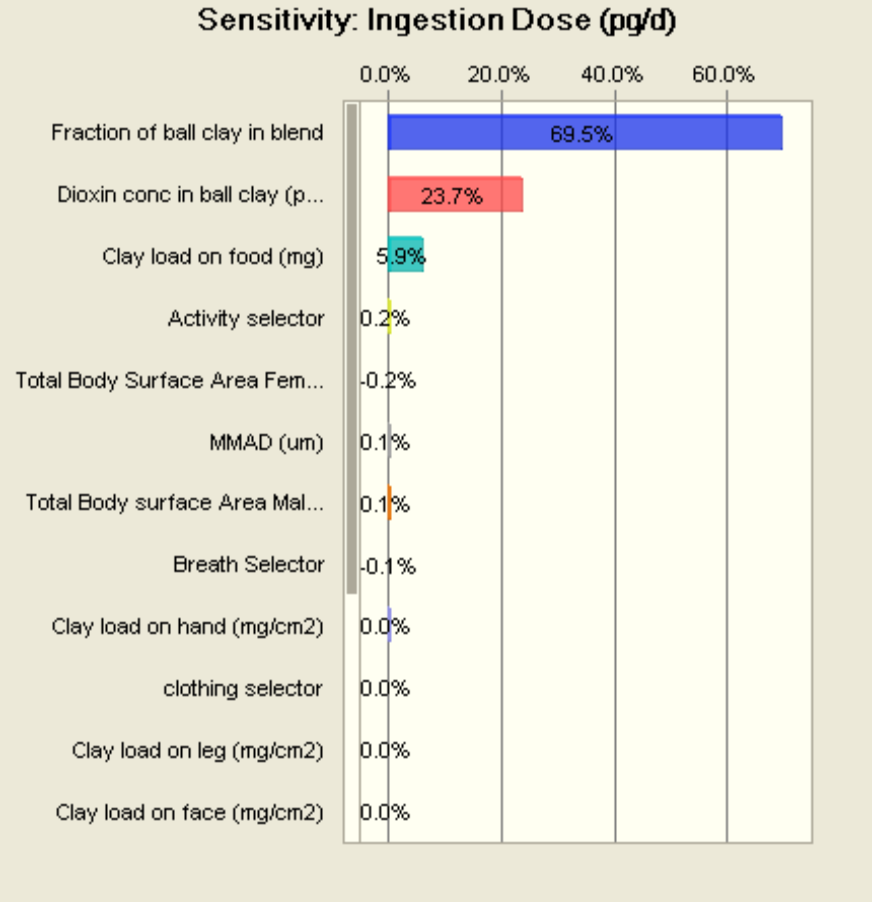


Figure 11. Sensitivity analysis based on percent contribution to variance for ingestion dose.

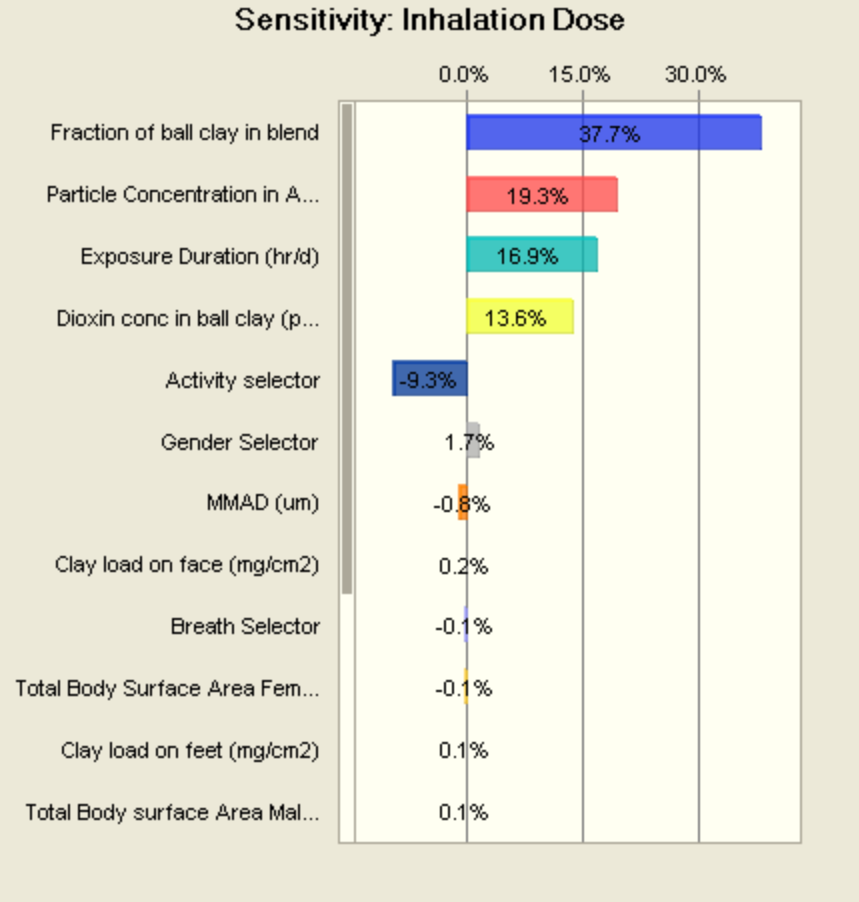


Figure 12. Sensitivity analysis based on percent contribution to variance for inhalation dose.

exposure only, and the simulation uses a range of clothing that will result in more skin exposure in most trials.

Many of the input distributions used in this simulation were based on very limited data or judgment. A number of the distributions were based on data from this study, and the degree to which the study subjects represented a broader population of artists is unknown. Similarly, the degree to which the studio conditions observed in this study represent a broader set of studios is unknown. The simulation should be interpreted as a preliminary indication of how to extrapolate the study results to a broader population of artists working in well maintained academic facilities.

9. UNCERTAINTY

This chapter discusses general uncertainty issues and uncertainties related to the three exposure pathways: dermal, inhalation, and ingestion.

9.1. GENERAL UNCERTAINTY ISSUES

The sensitivity analyses showed that the dioxin concentrations in clay and the fraction of ball clay used account for a large part of the overall variance in the exposure estimates. Thus, it is important to consider the uncertainty in the assumptions regarding these two parameters.

The dioxin levels in ball clay were assumed on the basis of the study by Ferrario et al. (2007, 2004). An important uncertainty issue is whether the ball clay sampled by Ferrario is representative of the ball clay used in the studio and by the broader community of ceramic artists. Ferrario et al. (2007, 2004) explained that the major mining companies market a total of 32 ball clay products of which 13 were sampled. Although marketing data were not available to do true statistical sampling, a ceramics expert confirmed that the most commonly used ball clays were included in this study. The samples were collected from 22.7-kg (50-pound) bags in the same form as delivered to ceramic studios. Four of the 21 samples analyzed by Ferrario et al. (2007, 2004) matched exactly the primary type of ball clay used in the OSU ceramics studio.

As explained earlier, ceramic artists use a wide range of clay blends with ball clay contents ranging from 0 to 100%. The hypothetical dose estimates were based on the assumption of 20% ball clay in the blend, which is the average fraction used by the 10 subjects in this study. It is unknown how representative this is of the wider population of ceramic artists. The ball clay fraction assumption may also affect other exposure factors. For example, it could affect how much clay adheres to skin. Soil adherence to skin has been shown to be influenced by moisture content and particle size. Ball clay is similar to other clays in terms of these properties. The primary way that ball clay is unique from other clays is its high plasticity. It is not known how this property would affect skin adherence.

9.2. DERMAL EXPOSURE UNCERTAINTIES

9.2.1. Absorption Fraction

A fraction absorbed approach is used to estimate dermal absorption based on current Agency guidance. Appendix D presents an alternative approach using a more mechanistic model. This model predicts an absorbed dose that is about three times higher than the fraction absorbed approach. The mechanistic model appears very promising but it has had limited testing, and it is not yet clear whether it provides more realistic estimates.

The exposures in the studio are caused by clay, but the dermal absorption fraction is derived from soil experiments. An important uncertainty issue is whether clay has properties that differ significantly from soil and consequently make the soil-derived absorption estimates invalid for clay. The soil used by Roy et al. (1990) was 16.7% clay. This fraction of the soil should have properties similar to those of the studio clay. The organic carbon content of the clay is approximately the same as that of the low organic soil used by Roy et al. In terms of particle size, clays typically have lower particle sizes than soil and would be expected to more strongly sorb organic contaminants (e.g., dioxins) as compared with normal soils, all other factors being equal. As discussed in Chapter 5, commercial ball clay specifications report a median particle size of about 0.75 μm, which is smaller than that of the Roy et al. (1990) soil (median diameter of about 10 μm). The particle sizes measured in the studio air had median diameters ranging from 8 to 27 μm, which are larger than those of the soils used by Roy et al. (1990). This may be explained by the bonding of particles caused by the addition of water to the clay or the firing process, which fuses particles. Thus, it appears that the particle size of the soil used by Roy et al. falls within the range present in the studio.

The residues found on the skin are likely to vary with body location and activity. For example, a wheel operator will have hand residues similar to the raw clay but the residue on the face may more resemble room dust. The dermal absorption from these different types of residues may vary. No information is currently available to account for these types of differences.

The studies on dermal absorption of dioxin from soil by Roy et al. and other investigators have exclusively used TCDD. It is important to consider whether results for TCDD can be extrapolated to the other dioxin congeners found in clay. As mentioned previously, Table 21 lists the compounds of concern in the clay are the tetra- through octa-CDD congener groups. This table indicates that molecular weight and the octanol-water partition coefficient (K_{ow}) increase with chlorine substitution. Molecular weight and K_{ow} have been identified as key chemical properties affecting dermal absorption (U.S. EPA, 1992). These properties also relate to how tightly bound chemicals are to soils and their release kinetics. The higher chlorinated congeners would be released from soils more slowly and permeate skin more slowly than TCDD. Thus, use of TCDD experiments to represent the penta–octa dioxin congeners found in clay probably leads to some overestimates of dermal absorption, but it is uncertain to what degree.

A related question is whether TCDD-derived dermal absorption values can be applied to TEQs. Table 21 shows only about 9% of the TEQ in processed clay is derived from TCDD. The TEFs used to determine TEQs discount the hepta- and octa- congeners much more

Table 21. Physical properties of dioxin congeners and concentration in processed clay

Congener	Molecular weight	Log K_{ow}[a]	Concentration in processed clay[b] (pg/g)	Concentration in processed clay[b] (pg TEQ/g)	% of total TEQ
TCDD	322	6.1 to 7.1	76	76	9
PeCDD	356.4	6.2 to 7.4	374	374	46
HxCDD	390.9	6.85 to 7.8	2,341	234	28
HpCDD	425.3	8.0	9,780	97.8	12
OCDD	459.8	8.2	254,000	25.4	3
Total				808	

[a] U.S. EPA (2000).
[b] Average values from Ferrario et al. (2007, 2004).

HpCDD = heptachlorodibenzo-*p*-dioxin; HxCDD = hexachlorodibenzo-*p*-dioxin; K_{ow} = octanol-water partition coefficient; OCDD = octachlorodibenzo-*p*-dioxin; PeCDD = pentachlorodibenzo-*p*-dioxin; pg = pictogram; TCDD = tetrachlorodibenzo-*p*-dioxin; TEQ = toxic equivalent.

than the tetra- and penta- groups. The overestimates of dermal absorption for the higher chlorinated congeners due to their higher molecular weights and K_{ow} values will be compensated to some extent by the large discounts during the TEQ calculation and thus make extrapolation of dermal absorption data from TCDD to TEQs more reasonable.

The amount of chemical that is dermally absorbed has been shown to be related to skin thickness and whether the skin is dead or alive (U.S. EPA, 1992). Skin thickness varies across body parts and across individuals. No information was found that could be used to account for these factors in this analysis.

Another source of uncertainty in the dermal absorption estimates concerns the condition of the skin. Some of the artists reported dryness and cracking of skin due to clay activities. These conditions were observed by the dermatologist, but correlation with clay activities could not be confirmed. Wheel operations involve work with wet clay which would hydrate the skin. The abrasive nature of this work could also reduce the thickness of the stratum corneum which is considered the primary barrier to permeation (U.S. EPA, 1992). It is possible that these conditions would allow more dermal permeation than normal intact skin. However, any

increased permeation would be limited to the surface areas associated with the damaged skin. Exposure could also occur through the eyes where absorption would likely be greater than intact skin. This would be limited to particles that contact the eye surface which is probably minimal.

9.2.2. Monolayer

As discussed in Section 5.1, the monolayer calculation is also an important source of uncertainty for the dermal absorption estimates. The monolayer load is estimated on the basis of the median particle size and assumption of ideal packing. Actual monolayers will be composed of a mix of sizes with complex packing that could result in loadings higher or lower than this theoretical estimate. It is also uncertain how to best characterize the size distribution of particles on the skin. The particles in the original clay product have a median particle size of about 0.5 to 1.0 μm, and the airborne particles have medians ranging from 8 to 27 μm. The particles on the skin could more closely resemble either the airborne particles or the clay particles, depending on the deposition mechanism. Accordingly, particle sizes of the clay residues on skin could vary widely, with medians ranging from 0.5 to 27 μm. For purposes of the central exposure estimates, the geometric mean of this range was assumed, i.e., 3.7 μm. This implies a monolayer load of 0.5 mg/cm^2. The monolayer loads corresponding to the upper and lower ends of the particle size range are 0.07 to 3.7 mg/cm^2. This uncertainty is dampened in the dose estimate as a result of the assumption that absorption occurs from only the monolayer. This dampening is especially strong for low-exposure subjects. For example, the dose estimates for Subject 4 (who had the lowest dermal exposure) corresponding to the low and high ends of the monolayer load range would be 0.1 and 0.23 pg TEQ/d. Thus, a 37-fold variation in monolayer load resulted in only a 2.3-fold variation in dose. The dampening is less (but still significant) for Subject 9 (who had the highest dermal exposures). For this subject, the doses corresponding to the low and high ends of the monolayer load range would be 1.1 and 15.8 pg TEQ/d, respectively. While the monolayer load assumption has a reduced impact on absorbed dose, it remains an important uncertainty.

9.2.3. Exposure Under Clothing

The peer reviewers of this study highlighted the possibility of under clothing exposure as an important uncertainty issue (Eastern Research Group, 2008). Kissel et al. (1998) demonstrated that clothing can reduce dermal exposure to soil during activities such as planting, pipe laying and play. However, Kissel's study and others (Fenske, 1988; Fenske et al., 1990; Raheel, 1991; Kawar et al., 1978) have shown that the clothing is not 100% effective in preventing dermal exposure. Under clothing exposure can result from both particle penetration through fabric and direct deposition of particles from air that circulates under loose fitting

clothing. The amount of under clothing exposure depends on the particle characteristics, clothing type, body location, and individual behavior. Driver et al. (2007) derived clothing penetration factors from a large exposure database for pesticide handlers. This analysis suggested a median penetration factor of 10%. No studies were found which were specific to ceramic artists or clay penetration through clothing. Given the lack of data specific to ceramic artists, the present study has assumed that any exposure occurring under clothing would be negligible compared to the amount occurring on unclothed areas. The uncertainty associated with this assumption is evaluated here using the data collected for Subjects 9 and 10.

Subjects 9 and 10 wore short-sleeved shirts and short pants. The skin surface areas covered by these articles of clothing were estimated using surface area data presented in U.S. EPA, 1997. For both subjects, the surface area covered by their shirts is estimated to be half of the trunk (0.5 × 35% = 17.5% of total body surface area) and 25% of the arms (0.25 × 14% = 3.5% of the total body area) for a total of 21% (17.5% + 3.5%) of the total body surface area. Subject 9 wore shorts covering about half of her legs, so the surface area covered by her shorts is estimated as half of the trunk (0.5 × 35% = 17.5% of total body surface area) plus one-half of the legs (0.5 × 32% = 16% of total body area) for a total of 33.5% (17.5% + 16%) of the total body surface area. Subject 10 wore short pants covering about 75% of the legs, so the surface area covered by her pants is estimated as half of the trunk (0.5 × 35% = 17.5% of total body surface area) plus 75% of the legs (0.75 × 32% = 24% of total body area) for a total of 41.5% (17.5% + 24%) of the total body surface area.. Both Subjects are assumed to have a total surface area of 17,000 cm^2 which is the mean for adult females.

The clay load on the pants is assumed to match the load measured on the lower legs and the load on the shirt is assumed to match the load measured on the arms. It is assumed that 10% of the clothing load penetrates to the skin, based on Driver et al. (2007). Based on these assumptions, the doses occurring from 24-hour exposures under clothing are estimated as 3.5 pg TEQ/d for Subject 9 and 0.53 pg TEQ/d for Subject 10 (see Table 22). These doses equal 50% of the dose from the unclothed area for Subject 9 and 58% of the dose from the unclothed area for Subject 10. These estimates are uncertain, but suggest that exposure under clothing can be important to consider and should be explored further in future research.

9.3. INHALATION UNCERTAINTIES

Data from the cascade sampler were used to estimate inhalation exposures. These data were considered to be the most reliable because no samples were below detection limits and the sampler uses a direct measurement method. The cascade, an area sampler, was located as near the subject as possible but normally would not represent an individual's exposure as accurately

Table 22. Exposure under clothing

	Clothing	Surface area covered (cm^2)	Clothing load (mg/cm^2)	Skin load under clothing (mg/cm^2)	Absorbed dose (pg TEQ/d)
Subject 9	Shirt	3,570	1.50	0.15	2.0
	Pants	5,700	0.72	0.072	1.5
Subject 10	Shirt	3,570	0.04	0.004	0.05
	Pants	7,050	0.11	0.011	0.3

TEQ = toxic equivalent.

as a personal air monitor. Unfortunately, the data from the Respicon™ personal monitor were dominated by nondetects and could not be used. The limited Respicon™ data that were above detection limits generally indicated higher levels than the cascade, suggesting that personal exposures may have been higher than those detected by the area monitor. Accordingly, use of the cascade data may have resulted in underestimates of inhalation exposures.

As discussed in Chapter 7, increases in suspended dust levels were associated with sweeping and the presence of a dog. It is likely that similar effects could be caused by other activities such as children playing or vacuuming. A small study, such as this one, cannot capture the broad range of activities and associated dust levels that may occur in a ceramic art studio.

This study estimated dioxin inhalation on the basis of particulate levels. Additional inhalation exposure is likely to occur via vapors. Franzblau et al. (2008) conducted a follow-up study to a large survey of dioxin levels in blood. The highest levels found in the survey were for an individual who conducted ceramic art activities in her home over thirty years. The study presents the hypothesis that inhalation of dioxins volatilized from an unvented kiln in her home was the dominant route of exposure. No measurements could be made to confirm the relative importance of the possible exposure pathways since the ceramic work was no longer being conducted and the authors recommended further investigation to confirm their hypothesis. The kilns at the OSU studio are well vented and therefore likely to be a less important source of exposure. Further thoughts on the potential for vapor inhalation at the OSU studio are presented below:

- Under equilibrium conditions at room temperature, about half of the TCDD is partitioned to particulate and rest is in vapor phase. As chlorination increases, the fraction partitioned to particulates increases, with PeCDD (dominant contributor to TEQs in ball clay) over 80% and OCDD almost 100% in particulate phase (U.S. EPA, 2004). So under equilibrium conditions at room temperature, exposure to dioxin TEQs in vapor phase would be less than half of dioxin particulate exposure.

- The dioxins in the clay will be vaporized during kiln operations. The OSU studio has 6 kilns fired with natural gas and 9 electric kilns. The kilns are generally heated slowly to a maximum temperature of about 1,200°C (2,200°F) which is comparable to commercial incinerators and sufficient to destroy dioxins. Therefore, vapor releases are of most concern during the initial warm-up phase. The OSU kilns are located in 2 rooms which are isolated from classrooms and other areas frequented by the students. An extensive ventilation system is used with hoods located over all kilns except one small electric unit. Any vapors which escape the kilns would be expected to return to room temperature equilibrium with particles after transport away from the kiln.

9.4. INGESTION UNCERTAINTIES

The only ingestion pathway quantitatively evaluated in this study was direct ingestion of clay deposited from the air onto food items. This was estimated by measuring deposition on to surrogate food/beverage samplers over the testing period (1–2 hours). Two uncertainties associated with this approach are discussed below:

- **Deposition area**—An 85 mm diameter (area = 57 cm^2) quartz fiber filter was used to simulate a small sandwich, cookie, bagel or other small snack item. A medium-sized hamburger bun has a surface area of approximately 62 cm^2 and a standard piece of bread has an area of approximately 100 cm^2. So larger snack items could have an area twice the sampler size. A 125-mL jar (diameter of about 6 cm, area = 28 cm^2) filled with deionized water was used to simulate a beverage such as coffee or soda. The diameter of the 125-mL jar closely matches that of a typical soda can. Coffee cups have diameters of 70 to 80 mm and a surface area which is about twice that of the 125-mL jar. Thus, food/beverage items with higher deposition areas could increase ingestion amounts by over twice the measured values.

- **Surface load**—Wipe samples were collected from surfaces near the work area of each subject. These loads ranged from 0.2 to 7 mg/cm^2. The maximum clay loading on the food was 1.66 mg or 0.03 mg/cm^2. Thus, the surface loads were much higher than the food loads. This is likely due to the location of the food samplers which were placed outside of the immediate work area at a location that the subjects indicated they would normally place foods or beverages. If food was placed near the work areas, deposition could increase by 10 times or more than the measured levels.

Clay ingestion may also occur via hand-to-food transfers. Snack foods such as potato chips, cookies, sandwiches, etc are typically eaten by hand. If hands are not washed prior to eating, clay on hands can be transferred to the food items and subsequently ingested. While this behavior may be common, it was not observed during this study. Accordingly, it is not included in the primary exposure assessment of this study. However, some idea of the possible importance of this pathway can be evaluated as follows. Hand contact with food is primarily limited to the fingertips which are assumed to equal 25 cm^2 (calculated as 5% of an average adult male hand—500 cm^2—U.S. EPA, 1997). Clay loads on hands measured 0.17 to 10.12 mg/cm^2. If 50% of the clay on fingertips are transferred to the food, then 2 to 125 mg could be ingested. Additional ingestion could result from multiple contacts with food items after the fingertips are replenished with clay. The maximum ingestion levels based on deposition was estimated as about 2 mg of clay. This suggests that hand-to-food transfers could increase ingestion by over 50-fold.

Other possible mechanisms for clay ingestion include hand-to-mouth transfers or deposition/splattering of clay on to lips and removal by licking. These behaviors were not observed during this study but could be a common occurrence. Smoking was not allowed in the study facility, but where this occurs, the potential for hand-to-mouth transfer is increased.

The average-soil-ingestion rate for adults in residential settings is estimated to be 50 mg/day (U.S. EPA, 1997, 1989). This is much higher than the maximum clay ingestion levels estimated in this study based on deposition (about 2 mg). It is difficult to evaluate how applicable this soil ingestion rate may be to clay ingestion in a ceramic art studio. However, the scenarios presented above imply that it may be possible. This was evaluated using a modification to the Monte Carlo simulation presented in Chapter 8. In this simulation, the ingestion rate was inputted as a flat distribution from 1 to 50 mg and all other inputs were kept the same as those described in Table 18. The mean ingestion dose increased by a factor of 17 (from 0.14 to 2.4 pg TEQ) and total dose increased by a factor of 1.3 (from 6.4 to 8.64 pg TEQ).

The above discussion suggests that a number of plausible scenarios could occur which would result in greater clay ingestion than observed in this study. The peer reviewers of this study emphasized their concern that this pathway may have been underestimated (Eastern Research Group, 2008). This is a high priority issue for future research and demonstrates the importance of good hygiene practices regarding food placement and hand washing to prevent these types of exposures.

10. CONCLUSIONS

Hypothetical dioxin dose estimates were calculated for each subject assuming that all used a 20% ball clay blend with 162 pg TEQ/g. The single-day total doses across the 10 subjects ranged from 0.32 to 7.1 pg TEQ/d, with an average of 1.44 pg TEQ/d (SD = 2.0). The dermal dose was the major contributor to total dose, exceeding 67% for all subjects. Ingestion and inhalation contributed similar amounts, generally in the range of 1 to 20% of total dose. Hand and arm exposure accounted for much of the dermal dose for all subjects. The two subjects who wore summer clothing had foot and leg exposures accounting for about 33 to 71% of the dermal dose. Facial exposures were low accounting for less than 4% of total dermal dose.

Clay exposure was found to be highly dependent on the type of work being performed. Throwing clay on the wheel resulted in much higher clay exposures than did any other clay activities. This is due to the increased contact with clay while working on the wheel and the wet, sticky consistency of the clay needed for that work. Emptying bags and mixing dried clays also led to high exposures.

A Monte Carlo simulation was performed to model how doses could vary in a broad population of artists with exposures outside the hypothetical scenario evaluated in this study. This simulation produced a mean total dose of 6.4 pg TEQ/d (SD = 8.4), median of 3.5 pg TEQ/d, and 90^{th} percentile of 14.8 pg TEQ/d. This mean is over times 4 times greater than the mean of the hypothetical dose estimates for the 10 subjects. All of the 10 subject doses corresponded to low percentiles of the Monte Carlo simulation except Subject 9 (75^{th} percentile). Also, it indicated that the fraction of ball clay in the blend, clothing, and dioxin concentration contributed most to variance in total dose. Many of the input distributions used in this simulation were based on very limited data or judgment. Therefore, the simulation results are best interpreted as preliminary indications of how to extrapolate the observations of this study to a broader population of artists in similar types of studios, i.e., well maintained academic facilities. It is likely that the range of exposures across all types of ceramic art facilities (individual, commercial, etc.) is wider than observed here and further study is recommended to explore this possibility.

This study included a comprehensive uncertainty analysis. The two most important uncertainties are highlighted below:

- Studies have shown that in a variety of occupational situations, particulates can penetrate clothing and deposit on skin. It is unclear if and to what extent this may occur in ceramic art studios. Accordingly, this study assumed that dermal exposure under clothing was negligible. An evaluation of this issue suggests that if exposure under clothing occurs, dermal doses may increase by 50% or more.

- The only ingestion pathway evaluated in this study was deposition on to food. Although not observed during this study, other pathways could occur such as hand-to-food transfers and hand-to-mouth transfers. Where these occur, ingestion doses could increase substantially, perhaps by over an order of magnitude relative to the ingestion estimates presented here.

In the general population, daily intakes of CDD/CDFs are estimated to average 0.65 pg TEQ/kg-day or 45 pg TEQ/d for a 70-kg adult (Lorber, 2002). More than 90% of this intake is derived from food ingestion. These intake values are based on the "administered" dose or the amount taken into the body before absorption. The hypothetical doses presented in this report are on an absorbed dose basis. Thus, the general population dose must be converted to an absorbed basis to compare it to the values presented here. Lorber (2002) reports that about 80% of dioxins in foods are absorbed into the body. Applying this factor, the general population adult dose on an absorbed basis is 36 pg TEQ/d. Comparing these values to the average of the hypothetical doses for the 10 subjects estimated here (1.44 pg TEQ/d) indicates that the ball clay dose is 4% of the general population adult dose (on a TEQ basis). Similarly, the Monte Carlo simulation suggested a mean dose of 6.4 pg TEQ/d which is 18% of the general population adult dose (on a TEQ basis). Note that the general population dioxin dose is a long-term average and the ball clay dioxin doses are estimates for a single day when exposure occurs. Accordingly, this comparison implies that ball clay use is a frequent event, so that the long-term daily average ball clay dose is similar to the single-day dose. If ball clay use is infrequent, then the long-term average dose from ball clay will be reduced and adjustments would be needed to make a valid comparison to the general population dioxin dose.

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APPENDIX A

SUBJECT QUESTIONNAIRE RESULTS

Table A-1. Subject 1

Question	Answer
Approximately how many hours per week do you work with clay?	50 hours.
Approximately how many weeks per year?	40 weeks.
How long have you been doing clay work with this level of intensity?	1 year.
What type of clay artwork do you do?	Hand building, sculptural work. Largely consists of rolling out slabs and assembling clay parts.
What types of clothing do you wear while you work?	Short sleeve t-shirt and jeans and closed toe shoes.
What areas of skin typically are exposed to the clay while you work?	Hands and forearms.
Do you correlate any skin health issues with how much you work with clay? If yes, what?	Yes. Dryness. No cracking/bleeding. I use lotion 3–4 times through the day.
In relation to the time you complete working with clay, when do you wash parts of your body that have been exposed to clay?	Hands: when rolling slabs—once per hour. when assembling clay—3 or more times per hour. Face: 1–2 times per day.
How do you wash your skin after you work with clay?	Water only.
Do you treat your skin with anything in particular after working with clay?	Yes, Aveeno® brand lotion.

Table A-2. Subject 2

Question	Answer
Approximately how many hours per week do you work with clay?	10–15 hours.
Approximately how many weeks per year?	15–25 weeks.
How long have you been doing clay work with this level of intensity?	24 years.
What type of clay artwork do you do?	Mixing clay and maintenance activities associated with the OSU Ceramics area.
What types of clothing do you wear while you work?	Long and short sleeves, long pants, work shoes.
What areas of skin typically are exposed to the clay while you work?	Hands, arms, and face.
Do you correlate any skin health issues with how much you work with clay? If yes, what?	Dryness and cracking.
In relation to the time you complete working with clay, when do you wash parts of your body that have been exposed to clay?	Hands: 2 minutes. Face: 5 hours.
How do you wash your skin after you work with clay?	Soap and water.
Do you treat your skin with anything in particular after working with clay?	Lotion during winter, but when my hands are very dry a product called Satin Hands® is used.

Table A-3. Subject 3

Question	Answer
Approximately how many hours per week do you work with clay?	25 hours.
Approximately how many weeks per year?	30 weeks.
How long have you been doing clay work with this level of intensity?	14 months.
What type of clay artwork do you do?	Functional—thrown on wheel. Structural—hand built.
What types of clothing do you wear while you work?	Jeans with t-shirt and sandals (summer) or long sleeves and closed toe shoes (winter).
What areas of skin typically are exposed to the clay while you work?	Hands, arms, face, neck, and feet.
Do you correlate any skin health issues with how much you work with clay? If yes, what?	Dry cracking skin and cuticles on hands, red small-bump rash on backs of hands and inner forearms when using wheel, nasal congestion.
In relation to the time you complete working with clay, when do you wash parts of your body that have been exposed to clay?	Arms and hands: 3 to 5 minutes. Feet, face, and neck: 1–10 hours.
How do you wash your skin after you work with clay?	Water only if returning to work, soap, and water when finished.
Do you treat your skin with anything in particular after working with clay?	Aveda® hand cream, Neutrogena® Swiss therapy lotion.

Table A-4. Subject 4

Question	Answer
Approximately how many hours per week do you work with clay?	More than 70 hours.
Approximately how many weeks per year?	50 weeks.
How long have you been doing clay work with this level of intensity?	2 years.
What type of clay artwork do you do?	Functional pots, cups, bowls, etc.
What types of clothing do you wear while you work?	Overalls, long/short sleeve shirts and sneakers.
What areas of skin typically are exposed to the clay while you work?	Face, hands, sometimes arms and legs.
Do you correlate any skin health issues with how much you work with clay? If yes, what?	Extremely dry with cracking on fingertips.
In relation to the time you complete working with clay, when do you wash parts of your body that have been exposed to clay?	Hands: 10 minutes. Face and body: 10–24 hours.
How do you wash your skin after you work with clay?	Water only if returning to work, soap, and water when finished.
Do you treat your skin with anything in particular after working with clay?	Heavy cream lotion or bag balm at the end of the day and at intervals throughout the day.

Table A-5. Subject 5

Question	Answer
Approximately how many hours per week do you work with clay?	More than 14 hours.
Approximately how many weeks per year?	35 weeks.
How long have you been doing clay work with this level of intensity?	6 years.
What type of clay artwork do you do?	Hand building objects about 1.5 feet tall.
What types of clothing do you wear while you work?	Short sleeves/pants and shoes.
What areas of skin typically are exposed to the clay while you work?	Hands, lower arms, face.
Do you correlate any skin health issues with how much you work with clay? If yes, what?	Yes, dryness, sometimes cracking.
In relation to the time you complete working with clay, when do you wash parts of your body that have been exposed to clay?	Hands: <5 minutes. Arms: 8 hours. Face: 0.5–8 hours.
How do you wash your skin after you work with clay?	Soap and water.
Do you treat your skin with anything in particular after working with clay?	Lotion.

Table A-6. Subject 6

Question	Answer
Approximately how many hours per week do you work with clay?	30–40 hours.
Approximately how many weeks per year?	30–40 weeks.
How long have you been doing clay work with this level of intensity?	25 weeks.
What type of clay artwork do you do?	Throwing objects using wheel, hand building, and sculptural work.
What types of clothing do you wear while you work?	Short sleeves, pants, shorts, and flip flops shoes.
What areas of skin typically are exposed to the clay while you work?	Arms, hands, feet, face.
Do you correlate any skin health issues with how much you work with clay? If yes, what?	Yes, dry skin on feet and hands and nails being unable to grow healthily.
In relation to the time you complete working with clay, when do you wash parts of your body that have been exposed to clay?	Hands: 30 minutes. Legs, feet, and face: 3–5 hours.
How do you wash your skin after you work with clay?	Soap and water.
Do you treat your skin with anything in particular after working with clay?	Lotion.

Table A-7. Subject 7

Question	Answer
Approximately how many hours per week do you work with clay?	10 hours.
Approximately how many weeks per year?	40 weeks.
How long have you been doing clay work with this level of intensity?	4 years.
What type of clay artwork do you do?	Clay sculpture. Rolling out slabs, pressing them into molds. Limited work throwing objects using wheel.
What types of clothing do you wear while you work?	Short sleeves and pants (winter/spring/fall) and shorts (summer).
What areas of skin typically are exposed to the clay while you work?	Arms, hands, and face.
Do you correlate any skin health issues with how much you work with clay? If yes, what?	Dryness and cracking.
In relation to the time you complete working with clay, when do you wash parts of your body that have been exposed to clay?	Hands: 1–2 minutes. Face and legs 1–2 minutes (powdered clay) or end of day (wet clay).
How do you wash your skin after you work with clay?	Soap and water.
Do you treat your skin with anything in particular after working with clay?	Lotion.

Table A-8. Subject 8

Question	Answer
Approximately how many hours per week do you work with clay?	20 hours.
Approximately how many weeks per year?	52 weeks.
How long have you been doing clay work with this level of intensity?	6 years.
What type of clay artwork do you do?	Large clay sculpture. Rolling out slabs, cut and bend them and then press them together.
What types of clothing do you wear while you work?	Pants or shorts, short sleeves or tank tops, sneakers or sandals.
What areas of skin typically are exposed to the clay while you work?	Arms, neck, hands, calves, and shins.
Do you correlate any skin health issues with how much you work with clay? If yes, what?	Dryness and cracking.
In relation to the time you complete working with clay, when do you wash parts of your body that have been exposed to clay?	Hands: 5 minutes. Face and legs: 4–24 hours.
How do you wash your skin after you work with clay?	Soap and water or just water.
Do you treat your skin with anything in particular after working with clay?	Lotion.

APPENDIX B

EVALUATION OF CLAY DUST INHALATION

The methodology used to evaluate the dose of clay dust and associated dioxin received via inhalation is discussed in this appendix. The appendix is divided into four sections: clay dust size distribution, particle inhalability, respiratory deposition of clay dust, and delivered dose estimates.

B.1. CLAY DUST SIZE DISTRIBUTION

As discussed in the main body of this report, the size distribution of clay dust was measured using a Delron® cascade impactor and a Climet® during regular daily activities in the art studio. The Climet® optically determines particle concentration for six size bins with the associated physical particle diameter (d_p) of 0.3–0.5, 0.5–1, 1–2.5, 2.5–5, 5–10, and >10 μm. Aerodynamic particle diameter (D_{ae}) can be estimated for the Climet®'s size bins by assuming that the airborne clay dust has a density of 2.6 g/cm^3, similar to that of bulk clay.[1] Using this approach, a clay particle with a d_p of 10 μm has a D_{ae} of 16 μm. The Delron® cascade impactor fractionates particles directly, based on their D_{ae}, into the seven ranges of <0.5, 0.5–2, 2–4, 4–8, 8–16, 16–32, and >32 μm.

During normal artisan activities (Subjects 1–8), 64 $\pm$ 9% (mean $\pm$ SD) of the aerosol is associated with particles having a D_{ae} > 16 μm based on average Climet® data. Based on average impactor data, 63 $\pm$ 13% of the aerosol is associated with a D_{ae} > 16 μm (Subjects 1–8). The particle size distributions to which the artisans were exposed was assumed to be log-normally distributed.[2] The cascade impactor data were selected for estimating particle size distributions for the following reasons: (1) the impactor measures particle size based on the aerodynamic behavior of particles, whereas the Climet® uses light scattering to estimate a physical particle size; (2) the impactor affords a better characterization of the large particles than does the Climet® because it contains an additional size bin of 16–32 μm; and (3) particle deposition in the respiratory tract is a function of D_{ae}. Thus, uncertainty in estimates of respiratory deposition is reduced by the direct measurement of D_{ae} by the impactor. The clay

[1] $D_{ae} = d_p$ {(clay density * Cc(d_p))/(H_2O density * Cc(D_{ae}))}$^{0.5}$, where: Cc(d_p) and Cc(D_{ae}) are the Cunningham slip correction factor for the physical and aerodynamic particle size, respectively. For more information, the reader is referred to ICRP (1994), page 239.

[2] For more information about particle sizing and the log-normal distribution, the reader is referred to Hinds (1999).

dust size distribution was not estimated for runs where two or more of the impactor stages were below the nondetect level.

When engaged in normal artisan activities, the mass median aerodynamic diameter (MMAD) of clay dust to which artisans were exposed ranged from 13 to 45 µm. Table B-1 provides a characterization of clay dust exposures for each subject. Figure B-1 illustrates a log-probability plot of a typical (i.e., near the average MMAD) clay dust particle size distribution and a background sample from the studio. The prevalence of fewer large particles in the background aerosol can be explained easily, based on particle-settling velocities. The settling velocities for the D_{ae} of 1-, 10-, and 20-µm particles are 3.5×10^{-3}, 0.3, and 1.2 cm/s, respectively. Due to their rapidly settling velocities, large particles ($D_{ae} > 10$ µm) are maintained in the air only by active generation or resuspension from surfaces. The substantive presence of large particles (52% of mass associated with a $D_{ae} > 10$ µm) in the background sample is suggestive of particle resuspension due to movement (e.g., walking and setting up sampling equipment in the studio).

Table B-1. Clay dust size distribution and concentration during normal activities

Subject	Size distribution[a]		Total concentration (mg/m^3)
	MMAD (µm)	σ_g	
1	26.9	3.9	0.35
2	44.6	4.8	0.47
3	18.5	4.3	0.99
4	NA	NA	0.37
5	NA	NA	0.13
6	20.2	3.0	0.61
7	13.0	3.6	0.51
8	26.7	3.3	0.64
Mean $\pm$ SD	25.0 $\pm$ 11	3.8 $\pm$ 0.7	0.51 $\pm$ 0.25

[a] The aerosol size distribution is described in terms of the mass median aerodynamic diameter (MMAD) and geometric standard deviation (σ_g).

NA = not available.

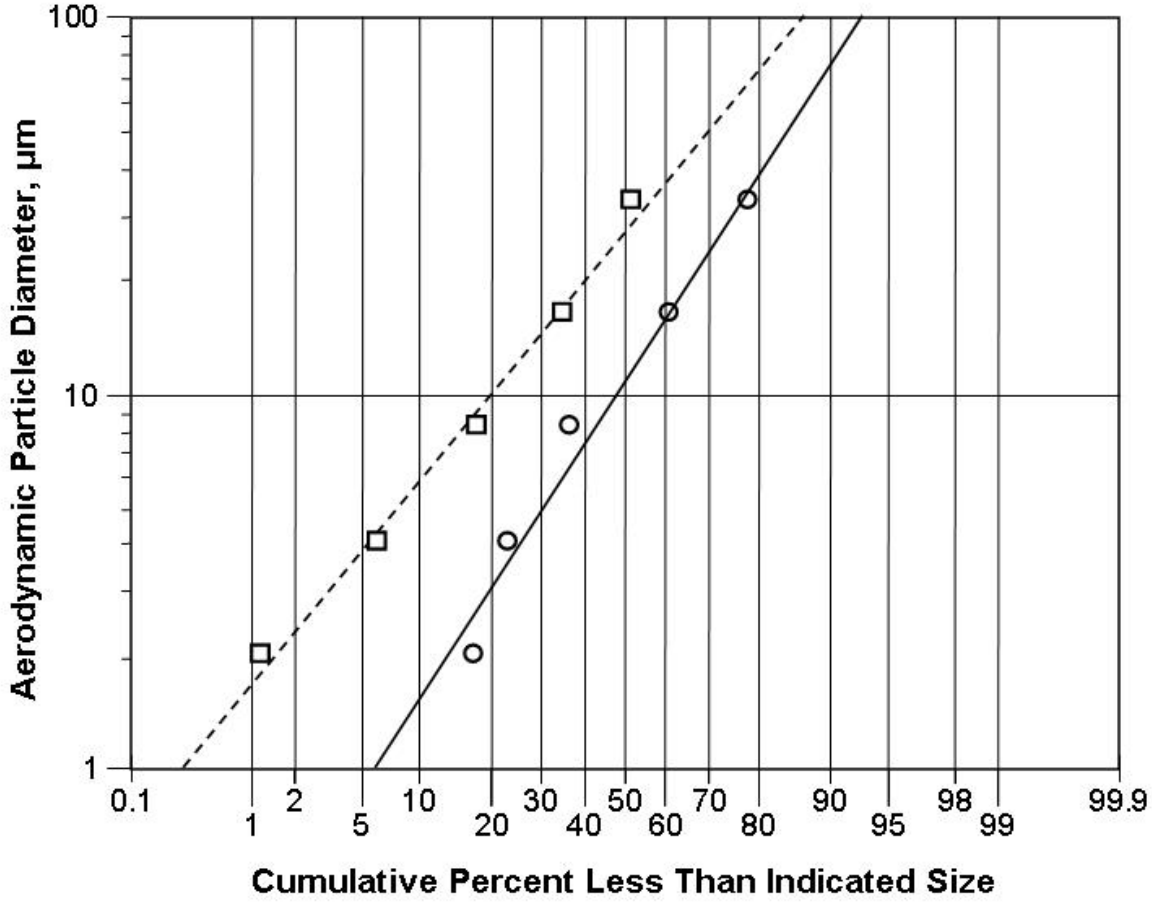

Figure B-1. Clay dust particle size distribution during normal artisan activities from analysis of cascade impactor data. Illustrated are the data for Subject 8 (□) and a background sample when work was not being done in the studio (○). The dashed and solid lines illustrate the log-normal distribution for these respective data. The mass median aerodynamic diameter (MMAD) of clay dust was 27 µm (σ_g = 3.3) for Subject 8, whereas the background sample had an MMAD of 11 µm (σ_g = 4.6).

Data were also available for two subjects during specific activities (i.e., when sculpting and using a pottery wheel) (see Table B-2). During pottery wheel operations, an average MMAD of 33 µm with a geometric standard deviation (σ_g) of 5.4 was observed. A dog was present during two of the sculpting runs. The MMAD with the dog present was 21 µm versus only 16 µm without the dog. The shift toward larger particles when the dog was present appears to be consistent with particle resuspension due to the dog's movement around the studio.

Table B-2. Clay dust size distribution and concentration during specific activities

Subject		Size distribution[a]		Total concentration (mg/m^3)
		MMAD (μm)	σ_g	
Subject 9 (Pottery wheel)	Run 1	33.7	6.2	0.049
	Run 2	NA	NA	0.046
	Run 3	24.8	4.3	0.102
	Run 4	NA	NA	0.073
	Run 5	39.3	5.6	0.152
Mean ± SD		32.6 ± 7.3	5.4 ± 0.9	0.085 ± 0.044
Subject 10[b] (Sculpting work)	Run 1	21.2	3.9	0.48
	Run 2	20.4	3.2	0.24
	Run 3	16.0	3.5	0.24

[a] The aerosol size distribution is described in terms of the mass median aerodynamic diameter (MMAD) and geometric standard deviation (σ_g).
[b] A dog was present during Runs 1 and 2 but not during Run 3. Therefore, these three runs were not averaged as was done in the case of the pottery wheel work.

NA = not available

B.2. PARTICLE INHALABILITY

For a given particle size, inhalability is the ratio of the particle concentration that enters the respiratory tract through the nose or mouth to the concentration of these particles in the ambient air. Inhalability depends mainly on particle size (i.e., D_{ae}), route of breathing, wind speed, and a person's orientation with respect to wind direction. Wind speeds in the art studio were assumed to be 0.3 m/s or less (Baldwin and Maynard, 1998). The artisans were presumed to move about the studio such that their orientation was random with respect to wind direction.

The clay dust aerosol present under normal activities in the art studio was observed to have an average MMAD of 25 μm and σ_g of 3.8. Hence, 50% (on average, by mass) of the airborne clay dust is composed of particles having a D_{ae} of ≥25 μm, a size that is generally considered to be unable to penetrate the thorax (ACGIH, 2004). These large particles (D_{ae} ≥25 μm), if inhaled, will deposit almost completely and exclusively in the extrathoracic (ET) airways. Thus, determining inhalability is key to estimating the delivered dose of these

large particles. For smaller particles, inhalability still describes the fraction of airborne particles that may enter the respiratory tract and thereby the availability of these particles for deposition in the lung.

Only limited data are available on the inhalability of particles from calm air (wind speeds of 0.3 m/s and less). Inhalability from calm air depends on the route of breathing. Logistic functions describing particle inhalability during nasal [$P(I_N)$] and oral [$P(I_O)$] breathing are given by Ménache et al. (1995) and Brown (2005):

$$P(I_N) = 1 - \frac{1}{1 + \exp(10.32 - 3.114 \ln(D_{ae}))} \quad \text{(B-1)}$$

$$P(I_O) = \frac{1.44}{1 + 0.44 \exp(0.0195\, D_{ae})} \quad \text{(B-2)}$$

Note that these equations depend only on aerodynamic particle diameter, D_{ae}. Given by Eq. B-1, $P(I_N)$ begins a rapid decline from 0.95 at D_{ae} = 11 μm, to 0.5 at D_{ae} = 27.5 μm, and 0.1 at D_{ae} = 56 μm. Eq. B-2 predicts a slow decline in $P(I_O)$ from 0.95 at D_{ae} = 8 μm, to 0.5 at D_{ae} = 74 μm, and 0.1 at D_{ae} = 175 μm.

Figure B-2 illustrates particle inhalability predicted by Eqs. B-1 and B-2 (shown by solid lines) along with relevant experimental data. Based on high wind speeds (1–8 m/s), the American Conference of Governmental Industrial Hygienists (ACGIH) inhalability criterion is also illustrated (shown by dashed lines) for comparative purposes. Eq. B-1 for $P(I_N)$ describes the experimental nasal inhalability data well with an r^2 of 0.86 (model sum of squares divided by the total corrected sum of squares). A negative r^2 is obtained for the fit of the ACGIH (2004) criterion to these data.[3] Equation B-2 describes the experimental oral inhalability data with an r^2 of 0.69, whereas the ACGIH criterion fit with an r^2 of 0.32.

B.3. RESPIRATORY DEPOSITION OF CLAY DUST

Inhaled particles may be either exhaled or deposited in the ET, tracheobronchial (TB), or pulmonary (PU) airways. The deposition of particles in the respiratory tract depends primarily

[3]An r^2 is calculated as the model sum of squares (MSS) divided by the total corrected sum of squares (TSS). The MSS equals the TSS minus the residual sum of squares (RSS). In typical linear regressions, when a model is fitted to a data set, the resulting r^2 must be non-negative because the least square fitting procedure assures RSS $\leq$ TSS. When r^2 is computed on excluded data, i.e., data not used to fit the model, the RSS can exceed the TSS. In this case, r^2 (which is not the square of r) can be negative, indicating that the mean of the data is a better predictor than the model.

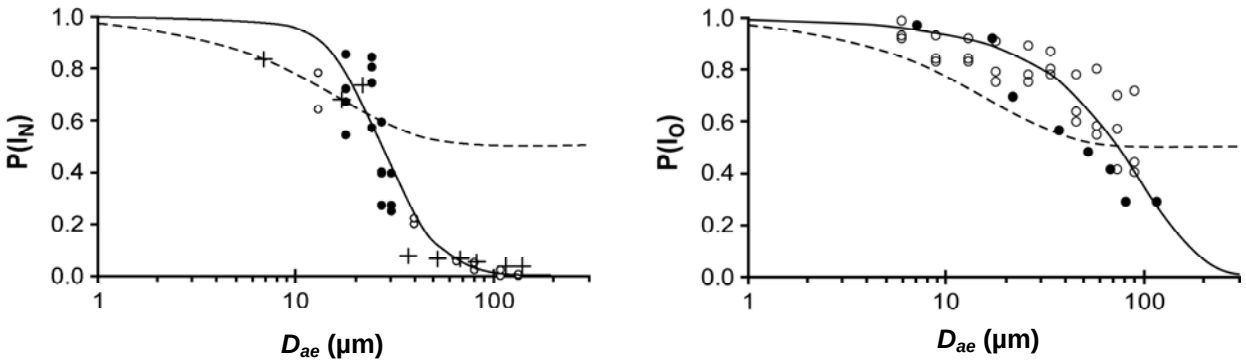

Figure B-2. Particle inhalability from calm air for nasal [$P(I_N)$] and oral [$P(I_O)$] breathing as a function of aerodynamic particle diameter (D_{ae}). Left panel [── Eq. B-1, ● Breysse and Swift (1990), + Hinds et al. (1998), ○ Hsu and Swift (1999), - - - ACGIH (2004)]. Right panel [── Eq. B-2, ○ Aitken et al. (1999), ● Kennedy and Hinds (2002), - - - ACGIH (2004)].

Table B-3. Breathing patterns used in particle deposition calculations[a]

Activity		Males	Females
Sitting	V_T (mL) f (min^{-1})	750 12	464 14
Light exercise	V_T (mL) f (min^{-1})	1,250 20	992 21

[a] Source: ICRP (1994), Table 8.

on inhaled particle size (i.e., D_{ae}), route of breathing (through the nose or mouth), tidal volume (V_T), and breathing frequency (f). Reference respiratory values for males and females were adopted from the International Commission on Radiological Protection (ICRP, 1994). In addition to breathing patterns (see Table B-3) necessary for deposition calculations, males and females were assumed to have a functional residual capacity of 3,300 mL and 2,680 mL, respectively. The majority (70%) of the subjects were female; only Subjects 1, 2, and 5 were male.

Particle deposition in the respiratory tract was predicted using the publicly available Multiple Path Particle Dosimetry (MPPD) model.[4] The MPPD model was developed by the

[4] The MPPD program is available on request from the CIIT Centers for Health Research (<asgharian@ciit.org>).

CIIT Centers for Health Research (CIIT), United States, in collaboration with the National Institute of Public Health and the Environment (RIVM), the Netherlands, and the Ministry of Housing, Spatial Planning and the Environment, the Netherlands. The MPPD model may be used to predict the deposition in the human respiratory tract for particles between 0.01 and 20 μm in diameter. In the lung, the model considers deposition by the mechanisms of impaction, sedimentation, and diffusion. Additional model details are available elsewhere (de Winter-Sorkina and Cassee, 2002). For the size of the clay dust, only impaction and sedimentation are of concern.

Using the MPPD model, deposition was predicted for the ET, TB, and PU regions of the respiratory tract. Particle deposition was estimated individually for oral and nasal breathing. During oral breathing, deposition in the TB airways did not always reach zero by a D_{ae} of 20 μm (the upper limit for the MPPD model). For $D_{ae} > 20$ μm, deposition in the TB airways was estimated by a best fit polynomial (3rd or 4th degree) determined using CurveExpert 1.3 (112B Crossgate St., Starkville, MS 39759). This polynomial function was fitted to TB deposition fractions for D_{ae} from 10 to 20 μm. The predicted ET deposition during oral breathing for a $D_{ae} > 20$ μm was taken as one minus the TB deposition fraction for oral breathing. For nasal breathing, these additional steps were unnecessary because TB deposition was well under 1% at a D_{ae} of 20 μm.

External to the MPPD model, all of the predicted deposition fractions were corrected for particle inhalability using Eqs. B-1 and B-2. The current version of MPPD model offers an inhalability correction for nasal breathing only. For a given D_{ae}, an inhalability corrected deposition fraction is the product of the uncorrected deposition fraction and the predicted inhalability for that D_{ae}. Unless otherwise specified, all mention of particle deposition fractions in the main body of this report and subsequently in this appendix refer explicitly to inhalability corrected deposition fractions.

The deposition fraction (DF_r) of an aerosol in a region of the respiratory tract is the integral of the deposition fractions across all particle sizes in the aerosol:

$$DF_r(MMAD, \sigma_g) = \int_0^\infty DF_r(d_i)\ \rho(d_i)\ \delta d_i \qquad \text{(B-3)}$$

where

$DF_r(d_i)$ = the deposition fraction in region, r, of particles having an aerodynamic diameter of d_i

$\rho(d_i)$ = the mass fraction associated with the interval δd_i

The total deposition fraction for the respiratory tract is the sum of DF_r for the ET, TB, and PU regions. Eq. B-3 can be approximated by summing the particle deposition fractions at known intervals or percentiles of the particle size distribution. Here, the interval of 1% was used and the approximation is

$$DF_r(MMAD, \sigma_g) \approx \frac{1}{100} \sum_{P=0.01}^{0.99} DF_r(d_i) \tag{B-4}$$

where

$DF_r(d_i)$ = the deposition fraction in region, r, of particles having an aerodynamic diameter d_i (the particle size associated with a given percentile, P, of the size distribution).

For a log-normal distribution, d_i is given by

$$d_i = MMAD\, \sigma_g^{z(P)} \tag{B-5}$$

where

$z(P)$ = the normal standard deviate for a given probability

Table B-4 provides the predicted regional deposition fractions for the clay dust in the respiratory tract of each subject for oral and nasal breathing at two activity levels. These deposition fraction estimates were based on each subject's measured aerosol exposure size distribution (see Tables B-1 and B-2). Subjects 4 and 5 lacked aerosol size distribution data and were assumed exposed to an aerosol with an MMAD of 25 μm and σ_g of 3.8, this being the average for artisans during normal activities (see Table B-1). The deposition fraction estimates for Subject 10 were based on Run 3, when the dog was not present in the studio.

B.4. DELIVERED DOSE ESTIMATES

The rate of particle deposition in a region of the respiratory tract may be expressed as:

$$\dot{D}_r(t) = C(t)\, f(t)\, V_T(t)\, DF_r(t) \qquad \text{(B-6)}$$

where

$\dot{D}_r$ = the rate of deposition per unit time in region r
C = the exposure concentration
f = breathing frequency
V_T = tidal volume
DF_r = the deposition fraction in region r

Note that all of the variables in Eq. B-6 may vary with time. The dose to a respiratory region is determined by integrating Eq. B-6 over the exposure duration.

Table B-4. Regional deposition fractions (corrected for inhalability) for clay dust in the respiratory tract

Subject	Sitting						Light exercise					
	Nasal breathing			Oral breathing			Nasal breathing			Oral breathing		
	ET	TB	PU	ET	TB	PU	ET	TB	PU	ET	TB	PU
1	0.441	0.015	0.022	0.473	0.082	0.058	0.473	0.006	0.011	0.516	0.060	0.052
2	0.336	0.011	0.016	0.412	0.059	0.042	0.360	0.004	0.008	0.442	0.044	0.037
3	0.472	0.028	0.033	0.431	0.104	0.067	0.531	0.010	0.020	0.486	0.074	0.075
4	0.447	0.021	0.022	0.471	0.091	0.050	0.487	0.007	0.013	0.521	0.064	0.056
5	0.458	0.016	0.023	0.479	0.086	0.061	0.492	0.006	0.011	0.523	0.063	0.054
6	0.526	0.023	0.022	0.521	0.108	0.053	0.566	0.007	0.012	0.581	0.075	0.059
7	0.549	0.035	0.041	0.432	0.128	0.085	0.622	0.013	0.025	0.498	0.090	0.095
8	0.451	0.018	0.017	0.507	0.087	0.041	0.483	0.005	0.010	0.557	0.061	0.046
9	0.368	0.020	0.023	0.396	0.077	0.047	0.410	0.007	0.014	0.437	0.054	0.053
10	0.533	0.030	0.033	0.462	0.118	0.072	0.593	0.010	0.020	0.525	0.083	0.081

ET = extrathoracic; PU = pulmonary; TB = tracheobronchial.

By assuming that aerosol characteristics and an individual's activity levels are fairly constant over discrete periods of time, the dose to a respiratory region may be approximated by:

$$D_r = 0.06 \sum_{j=1}^{n} (V_T f)_j \, (CT)_j \, [F_m DF_{m,r} + F_N DF_{N,r}]_j \qquad \text{(B-7)}$$

where

D_r	= the dose (μg) to region r of the respiratory tract
V_T and f	= tidal volume (mL) and breathing frequency (min^{-1}) for a specified activity j
C and T	= exposure concentration (mg/m^3) and duration (hr) during activity j
F_m and F_N	= the fraction of a breath entering the respiratory tract through the mouth and nose, respectively, during activity *j*
$DF_{m,r}$ and $DF_{N,r}$	= the deposition fraction for oral and nasal breathing, respectively, in region *r* of the respiratory tract while performing activity *j*
Constant 0.06	= a unit conversion parameter

As expressed, an "activity" in Eq. B-7 could be associated with changes in exposure concentration, the particle size distribution, and/or an individual's exertion level. For simplicity, only two exertion levels (sitting and light exercise) and a single particle size distribution (see Tables B-1 and B-2) were considered for each subject.

The fraction of flow through the mouth (F_m in Eq. B-7) increases with activity level and varies between individuals. For the two activity levels considered here, most people (87%) will breathe through their nose (Niinimaa et al., 1981). Hence, for these people, $F_m = 0$ and $F_N = 1$ in Eq. B-7. However, 13% of people will be oronasal breathers even at rest, i.e., they will breathe simultaneously through the nose and mouth (Niinimaa et al., 1981). This latter group is commonly referred to in the literature as "mouth breathers" (e.g., ICRP, 1994). Derived from Niinimaa et al. (1981), the fraction of air respired through the mouth (F_m) is well described by a modified exponential function in the form of

$$F_m = \alpha \exp\left(\frac{\gamma}{\dot{V}_e}\right) \qquad \text{(B-8)}$$

where

$\dot{V}_e$ = minute ventilation
α = 0.748
γ = −7.09 (r^2 = 0.997) in mouth breathers for $10 \leq \dot{V}_e \leq 80$ L/min
γ = −18.3 (r^2 = 0.998) in normal augmenters for $35.3 \leq \dot{V}_e \leq 80$ L/min
For $\dot{V}_e < 35.3$ L/min, normal augmenters breathe entirely through the nose, i.e., $F_m = 0$.
F_N is one minus F_m regardless of the activity.

Table B-5 gives the estimated clay dust doses to regions of the respiratory tract for each subject during nasal and oronasal breathing. Estimates are for a 4-hour exposure assuming that the exposed individual spent 50% of his or her time sitting and 50% engaged in light exercise. For oronasal breathing in Table B-5, there is a small positive bias in ET doses and a corresponding negative bias in TB doses calculated by Eq. B-7. In other words, this method of calculating ET and TB doses shifts the pattern of deposition toward the head relative to the real-life pattern of deposition. This shift occurs due to deposition being calculated at a higher airflow rate through the nose and mouth than actually occurs during oronasal breathing. The deposition calculations presumed that all inhaled airflow was through the nose or mouth. In reality, inhaled air is partitioned between the nose and the mouth, and the actual flows (for sitting and light exercise) are roughly half of that used in the deposition calculations. For breathing by a single route (nasal or oral), changing activity from sitting to light exercise approximately triples flow rates but only slightly increases ET deposition and modestly decreases TB deposition (see Table B-4). The effect of using Eq. B-7 for calculating doses during oronasal breathing should similarly affect the pattern of deposition. Ultimately, particles deposited in the ET and TB regions will typically be cleared to the throat and swallowed within 24 to 48 hours postdeposition (ICRP, 1994). Hence, the exact site of deposition (i.e., ET versus TB) is of little significance because both regions effectively contribute to ingested doses.

Table B-5. Regional doses (µg) of clay dust in the respiratory tract[a]

Subject	Nasal breathing			Oronasal breathing		
	ET	TB	PU	ET	TB	PU
1	664	12	20	693	53	48
2	678	11	19	757	52	47
3	1,677	47	75	1,612	143	154
4	580	13	19	598	45	41
5	256	4.6	7.7	264	21	19
6	1,114	22	29	1,126	85	70
7	1,011	30	49	917	90	100
8	997	18	24	1,067	72	57
9	110	2.9	4.5	114	8.8	9.2
10	455	12	18	431	39	39
Mean	754	17	27	758	61	58
SD	460	13	21	445	39	42

[a] Doses calculated by Eq. B-7 as described in the text.

ET = extrathoracic; PU = pulmonary; TB = tracheobronchial.

Table B-6 provides estimates of the dioxin absorption in each subject for nasal and oronasal breathing. Particles deposited in the ET and TB regions clear rapidly (within 1–2 days) to the throat and are swallowed. The absorption of dioxin from particles deposited within the ET and TB regions was treated as if the particles had been ingested. Dose estimates for oronasal breathing are slightly more conservative from a safety or risk perspective than presuming nasal breathing. However, nasal breathing may be considered as representative of the majority of the population (87%). Oronasal breathing is thought to represent 13% of healthy individuals (Niinimaa et al., 1981). In contrast to healthy subjects, Chadha et al. (1987) found that the majority (11 of 12) of patients with asthma or allergic rhinitis breathe oronasally even at rest. On average across all the subjects, dioxin doses are about 1.2 times greater for oronasal than for nasal breathing.

Table B-6. Estimates of dioxin absorption[a] (pg TEQ)

Subject	Nasal breathing			Oronasal breathing		
	ET and TB[b]	PU[c]	Total	ET and TB[b]	PU[c]	Total
1	0.033	0.003	0.035	0.036	0.006	0.043
2	0.034	0.003	0.036	0.039	0.006	0.045
3	0.084	0.010	0.094	0.085	0.020	0.105
4	0.029	0.002	0.031	0.031	0.005	0.037
5	0.013	0.001	0.014	0.014	0.002	0.016
6	0.055	0.004	0.059	0.059	0.009	0.068
7	0.051	0.006	0.057	0.049	0.013	0.062
8	0.049	0.003	0.052	0.055	0.007	0.063
9	0.005	0.001	0.006	0.006	0.001	0.007
10	0.023	0.002	0.025	0.023	0.005	0.028
Mean	0.038	0.004	0.041	0.040	0.007	0.047
SD	0.023	0.003	0.026	0.023	0.006	0.029

[a] Dioxin concentration was assumed to be 162 pg toxic equivalent (TEQ) per gram clay.
[b] Absorption fraction of 0.3 assumed, extrathoracic (ET) and tracheobronchial (TB) rapidly clear into the gastrointestinal tract.
[c] Absorption fraction of 0.8 assumed, due to slow clearance from pulmonary (PU) region.

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APPENDIX C

SEM AND EDS DATA BY SUBJECT

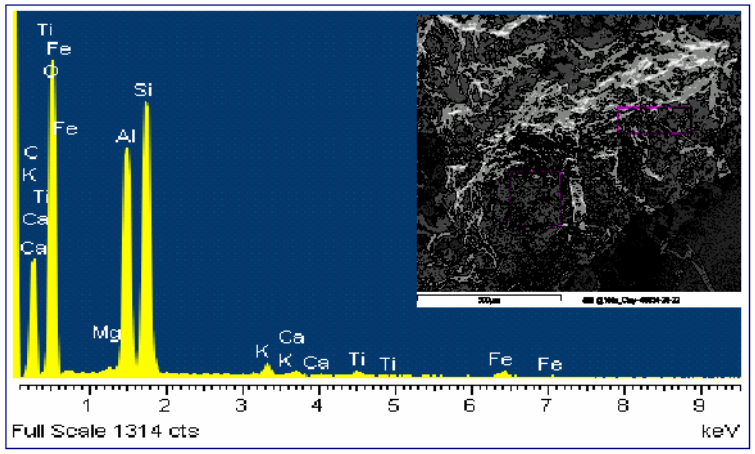

Figure C-1a. Sample of clay used by Subject 1.

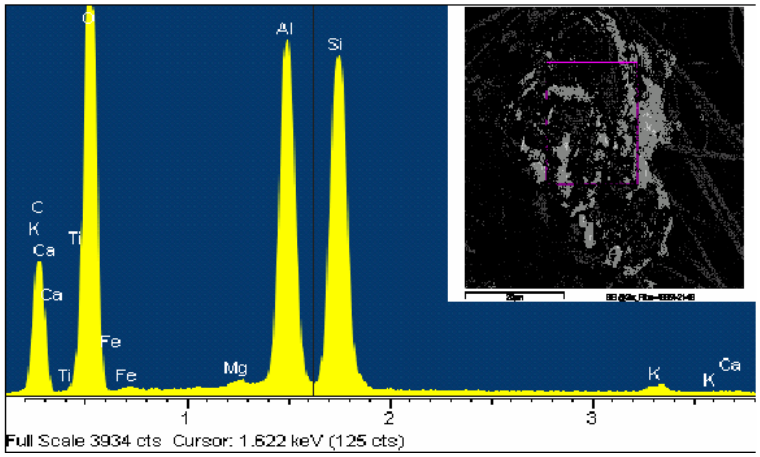

Figure C-1b. Clay particles on Subject 1's Respicon Filter.

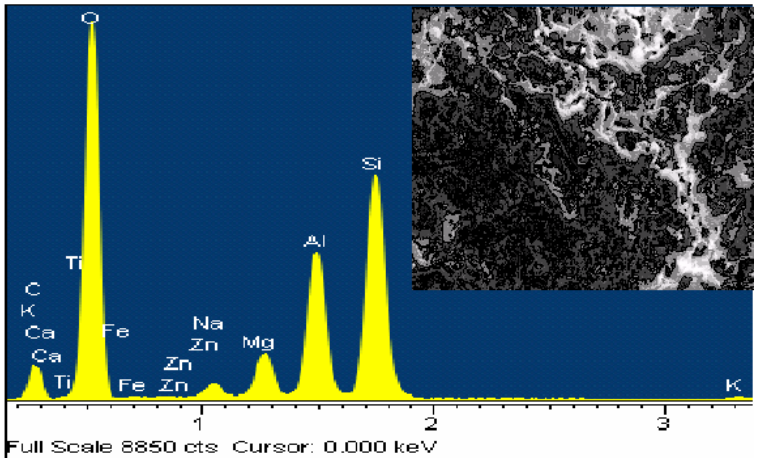

Figure C-2a. Sample of clay used by Subject 2.

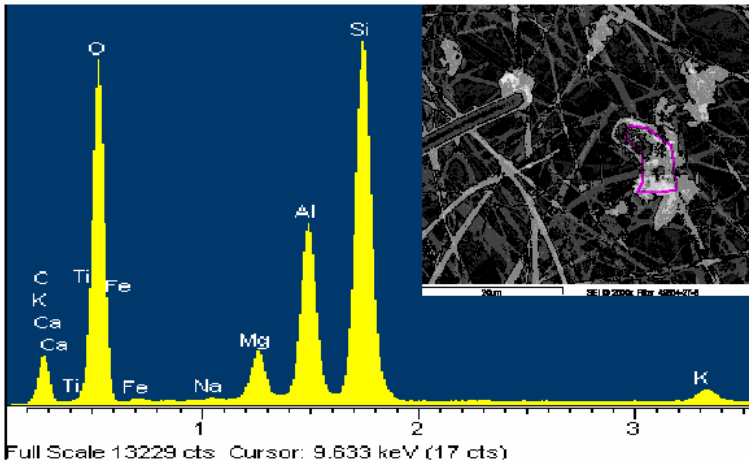

Figure C-2b. Clay particles on Subject 2's Respicon Filter.

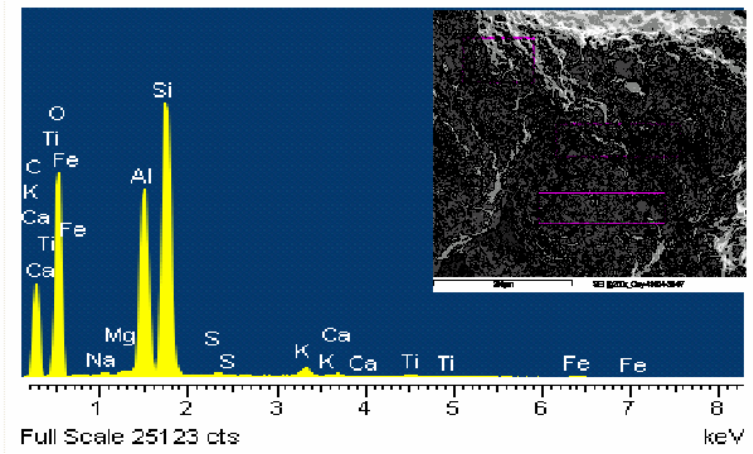

Figure C-3a. Sample of clay used by Subject 3.

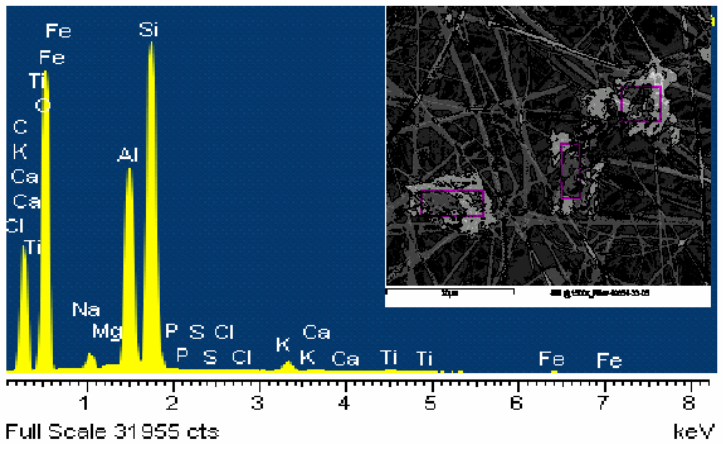

Figure C-3b. Clay particles on Subject 3's Respicon Filter.

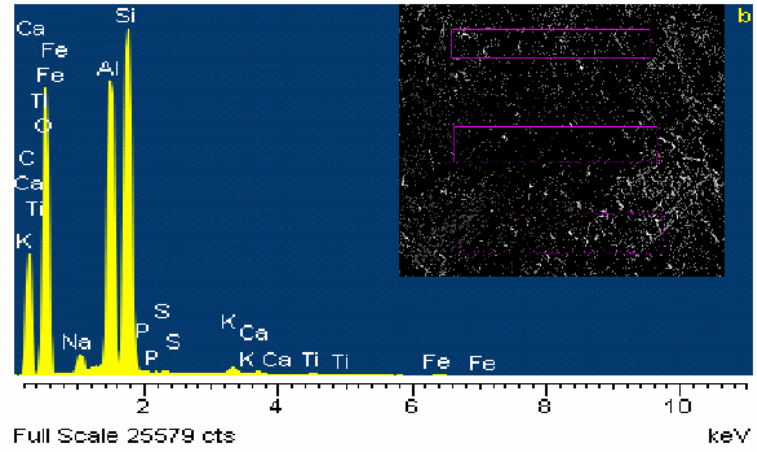

Figure C-4a. Sample of clay used by Subject 4.

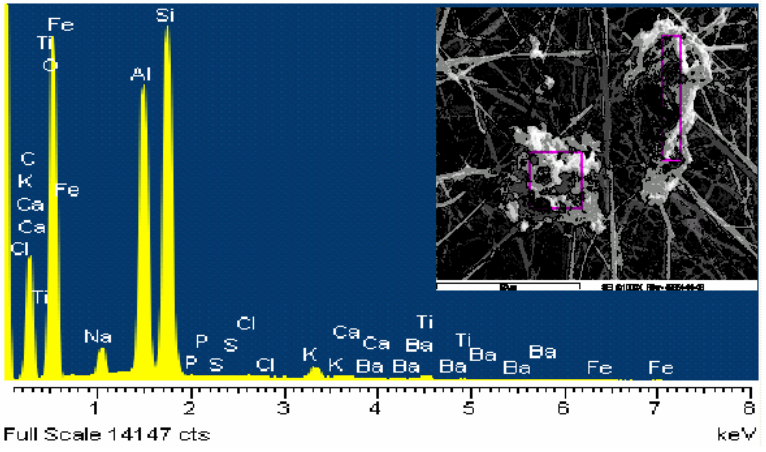

Figure C-4b. Clay particles on Subject 4's Respicon Filter.

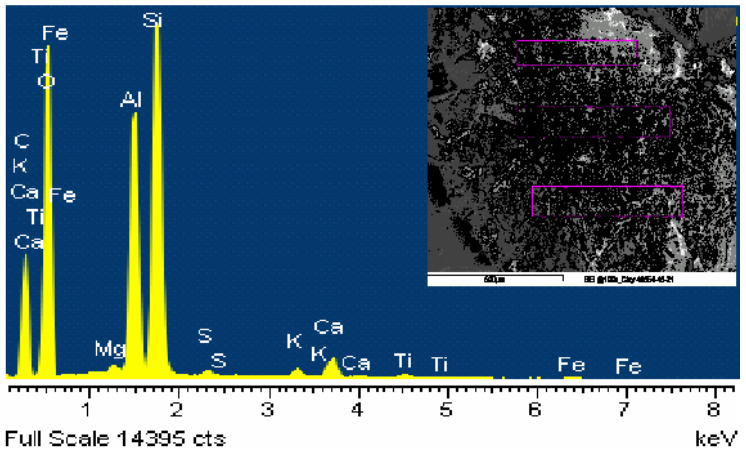

Figure C-5a. Sample of clay used by Subject 5.

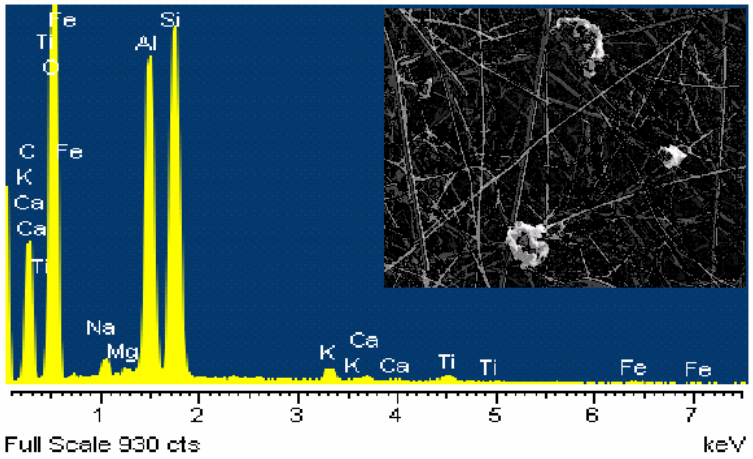

Figure C-5b. Clay particles on Subject 5's Respicon Filter.

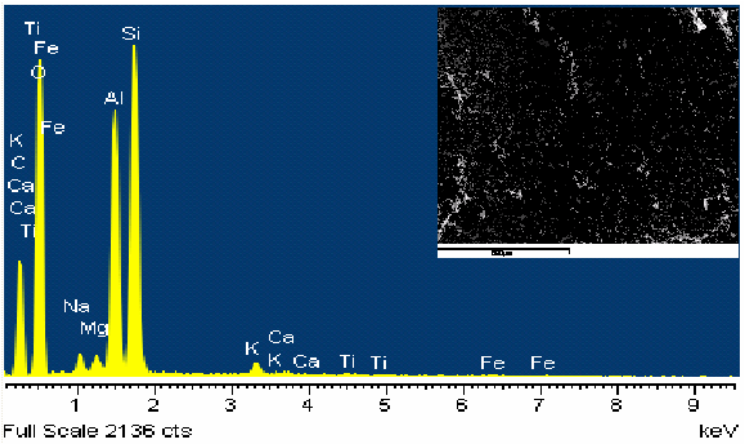

Figure C-6a. Sample of clay used by Subject 6.

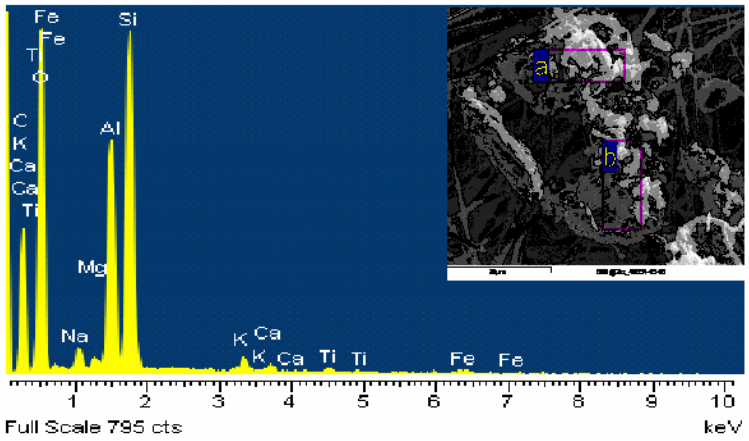

Figure C-6b. Clay particles on Subject 6's Respicon Filter.

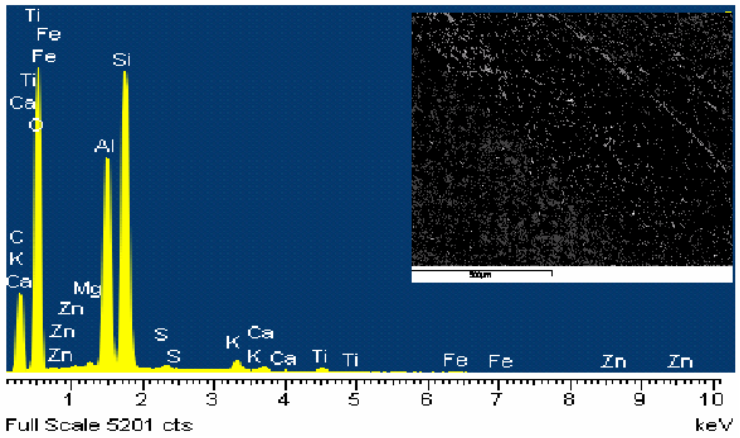

Figure C-7a. Sample of clay used by Subject 7.

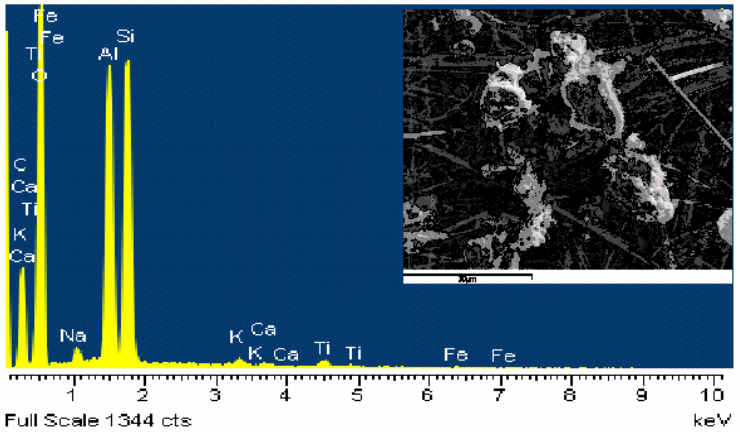

Figure C-7b. Clay particles on Subject 7's Respicon Filter.

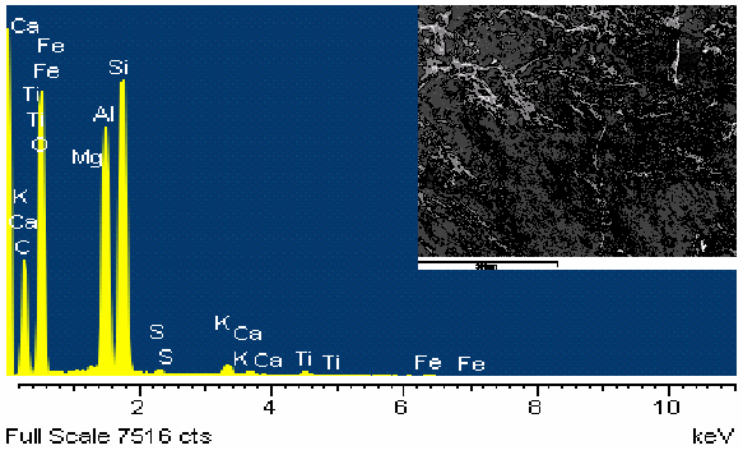

Figure C-8a. Sample of clay used by Subject 8.

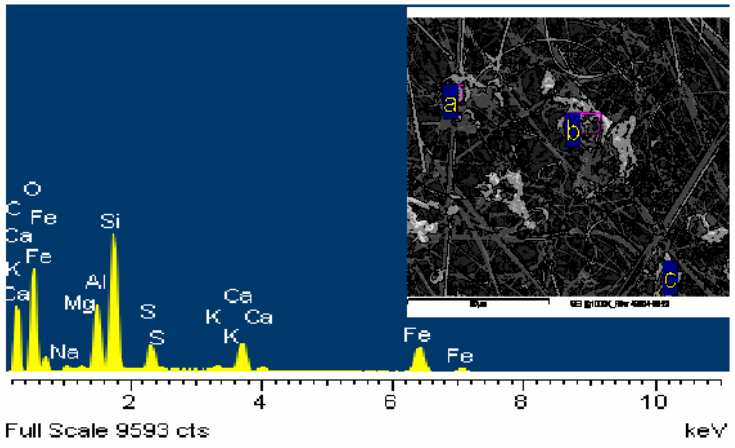

Figure C-8b. Clay particles on Subject 8's Respicon Filter.

APPENDIX D

ALTERNATIVE METHOD FOR ESTIMATING DERMAL ABSORPTION

This document uses the fraction absorbed approach to estimate dermal absorption, which is the method recommended in current U.S. Environmental Protection Agency guidance (U.S. EPA, 2004, 1992). The discussion below presents an alternative approach using a more mechanistic model.

Kissel et al. (2007) present a flux based model for estimating an upper limit of dermal absorption from soil:

$$AbsDose = C_{soil,0} L A\left[1 - \exp\left(-t\,(J_{multi} / C_{multi})\;(C_{multi,sat} / C_{soil,sat}) / L\right)\right] \qquad \text{(D-1)}$$

where

$AbsDose$ = absorbed dose (pg)
$C_{soil,0}$ = concentration of dioxin in soil at t = 0 (pg mg^{-1})
L = soil load on exposed skin (mg cm^{-2})
A = area of skin exposed (cm^2)
t = exposure time (hr)
J_{multi} = flux rate of chemical through skin from multi layer experiment (ng cm^{-2} hr)
C_{multi} = concentration of chemical in soil used in multi layer experiment (ng mg^{-1})
$C_{multi,sat}$ = saturation concentration of chemical in soil used in multi layer experiment (ng mg^{-1})
$C_{soil,sat}$ = saturation concentration of chemical in soil used in exposure scenario (ng mg^{-1})

This equation was derived from a mass balance of the chemical on the soil and assumes that the flux is proportional to the concentration. The model uses the exponential term to represent the decline in absorption rate that occurs over time as the contaminant is depleted from the soil.

Kissel et al. (2007) suggest estimating the ratio of the saturated soil concentrations on the basis of the ratio of organic carbon concentration in the soil used in the experiment to the organic carbon concentration in the soil used in the exposure scenario. As discussed in Section 5, this report derives the dermal absorption properties of dioxin from Roy et al. (2008), who measured dermal absorption of tetrachlorodibenzo-*p*-dioxin (TCDD) in soil with an organic carbon content of 0.45% and applied at supermonolayer coverage (monolayer estimated as 3 mg/cm^2 and amount applied was 6 mg/cm^2). Since the carbon content of the soil used in the Roy et al. tests was essentially identical to that of the clay, this ratio is one and it drops out of the equation.

If the amount of dioxin absorbed is less than about 10% of the original amount on the skin, then Eq. D-1 can be approximated as

$$AbsDose = C_{soil,0}\ A\ t\ (J_{multi} / C_{multi}) \quad \text{(D-2)}$$

For purposes of comparing this approach to the absorption fraction method, Eq. D-2 was applied to exposure scenario for Subject 2. The exposure conditions for Subject 2 were as follows:

$C_{soil,0}$ = 162 pg g^{-1} = 0.162 pg mg^{-1}
A = 970 cm^2
T = 4 hr

The 4-hour average flux rate from Roy et al. (2008) was calculated as follows:

$$J_{multi} = AF\ C_{soil}\ L / t \quad \text{(D-3)}$$

where

AF = Absorption Fraction = 0.0027 (for 4 hr, includes amount in skin)
C_{soil} = 1 ng mg^{-1}
L = 6 mg cm^{-2}
t = 4 hr

This yields a flux estimate of 0.004 ng cm^{-2} hr^{-1}. The experiment was conducted at 1 ppm or 1 ng mg^{-1}. Thus, the term (J_{multi}/C_{multi}) in Eq. D-2 is equal to 0.004 mg cm^{-2} hr^{-1}. Substituting into Eq. D-2, the absorbed dose is calculated as 2.5 pg which is higher than the value reported in Table 9 (0.77 pg) based on the fraction absorbed approach. Note that the amount of dioxin in the monolayer can be estimated as 79 pg (0.162 pg mg^{-1} × 0.5 mg cm^{-2} × 970 cm^2). This means that the absorbed dose is less than 10% of the applied dose and Eq. D-2 is approximately equivalent to Eq. D-1.

The Kissel et al. model is conceptually different from the absorption fraction method in that it assumes that the fluxes measured in the supporting experiment (and normalized by concentration) can be applied to the exposure scenario of concern. Whereas, the absorption fraction method assumes that the absorption fraction measured in the supporting experiment can be applied to the exposure scenario of concern. In the present document, the absorption fraction method is refined by adjusting the experimentally derived absorption fraction on the assumption that the absorption occurs exclusively from the monolayer and applying this to the monolayer (or actual soil load on skin if less than monolayer) in the exposure scenario of concern. The flux based approach has a stronger scientific basis and has the advantage that it is less dependent on

uncertain monolayer calculations. Additionally, in the form presented by Kissel et al., it can account for reductions in flux rate as the chemical is depleted from the soil. Accordingly, this approach has significant advantages over the absorption fraction method and is likely to become the preferred approach in the future. Further research is recommended for the continued development and validation of this promising approach.

REFERENCES FOR APPENDIX D

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Roy, TA; Hammerstrom, K; Schaum, J. (2008) Percutaneous absorption of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) from soil. J Toxicol Environ Health, Part A (Accepted).

U.S. EPA (Environmental Protection Agency). (1992) Dermal exposure assessment: principles and applications. Office of Science Policy, Office of Research and Development, Washington, DC; EPA/600/8-91/011B. Available online at http://www.epa.gov/osa/spc.

U.S. EPA (Environmental Protection Agency). (2004) Risk assessment guidance for Superfund. Vol. I: human health evaluation manual (part E, supplemental guidance for dermal risk assessment). Office of Superfund Remediation and Technology Innovation, Washington, DC; EPA/540/R/99/005. Available online at http://www.epa.gov/superfund/programs/risk/ragse/index.htm.

APPENDIX E

SKIN RINSING DATA

Table E-1. Weight of clay rinsed from skin of each subject during each individual skin rinse (g)

Subject	Rinse 1	Rinse 2	Rinse 3
1	0.321	NA[a]	0.773
2	2.957	2.804	0.083
3	0.558	0.427	0.333
4	0.139	0.126	0.18
5	2.908	1.919	3.042
6	9.893	12.522	10.319
7	0.158	0.149	0.313
8	0.443	1.018	2.618

[a] Sample lost during analysis.

NA = not available.

Table E-2. Residual clay (mg)

Subject	Right Hand	Left Hand	Arms	Legs	Feet	Face
Subject 9 Wheel	9,750	11,243	398.55	509.80	214.40	16.70
	1,874	2,352	790.25	596.25	144.00	0.00
	4,059	4,270	388.60	1,276.70	267.20	4.35
	1,536	2,845	5,005.35	958.50	220.65	9.60
	1,367	3,426	8,630.60	273.95	2,991.50	524.60
Subject 10 Sculpture	70	14	33.50	8.40	17.40	0.00
	83	65	58.50	42.85	42.65	9.80
	74	98	131.80	9.20	14.10	25.70

APPENDIX F

PICTURES OF ARTISANS PRIOR TO SKIN RINSE PROCEDURE

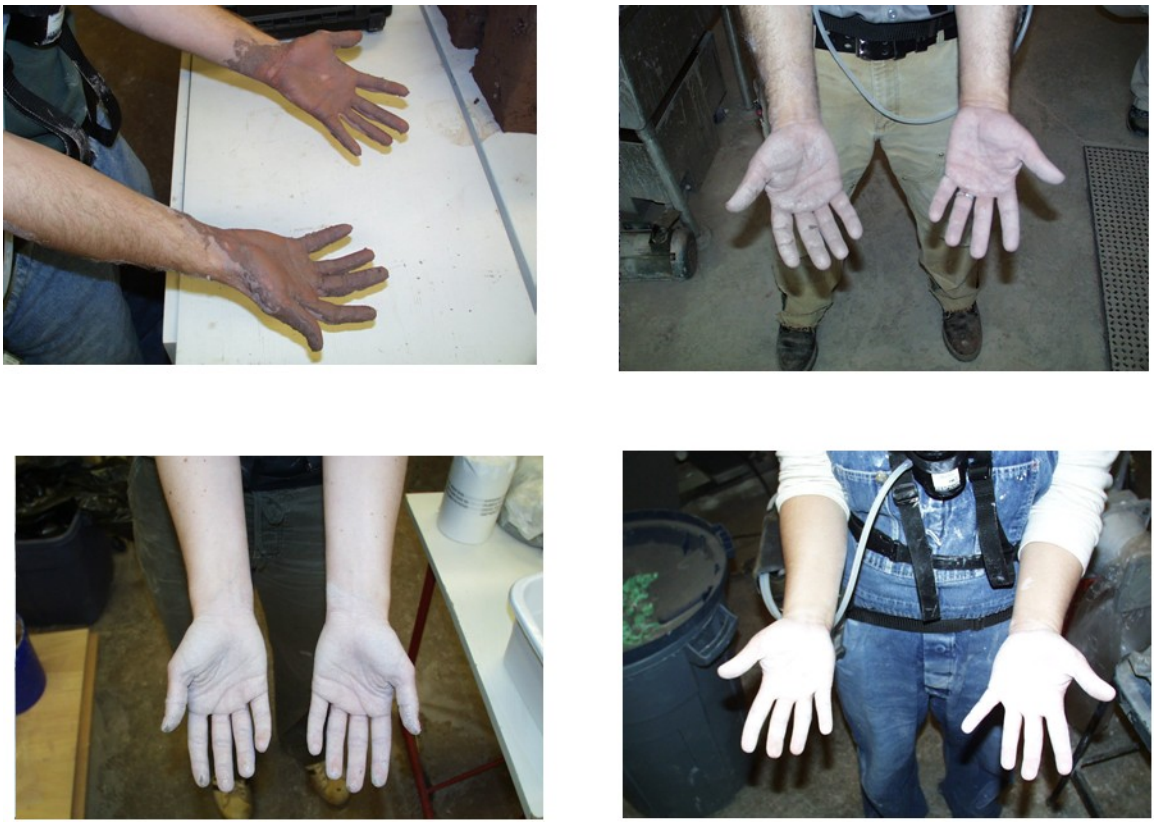


Figure F-1. Subjects 1–4.

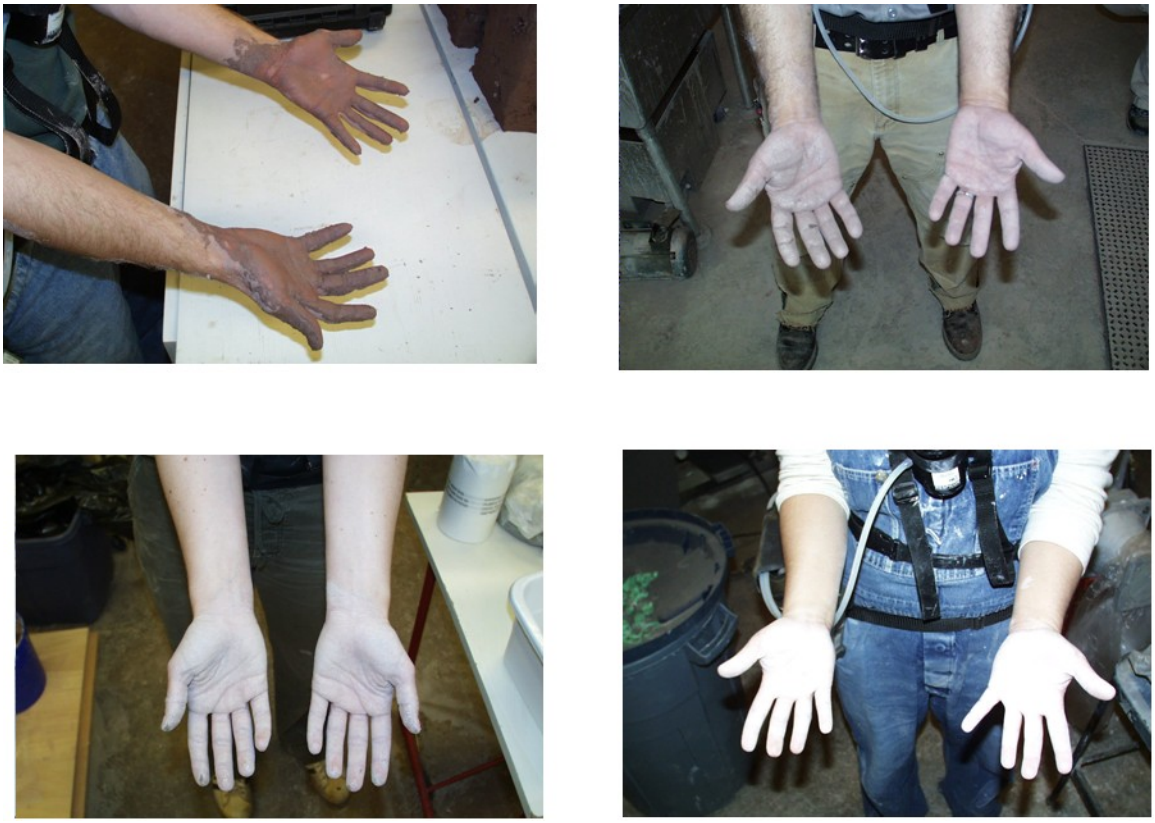


Figure F-2. Subjects 5–8.

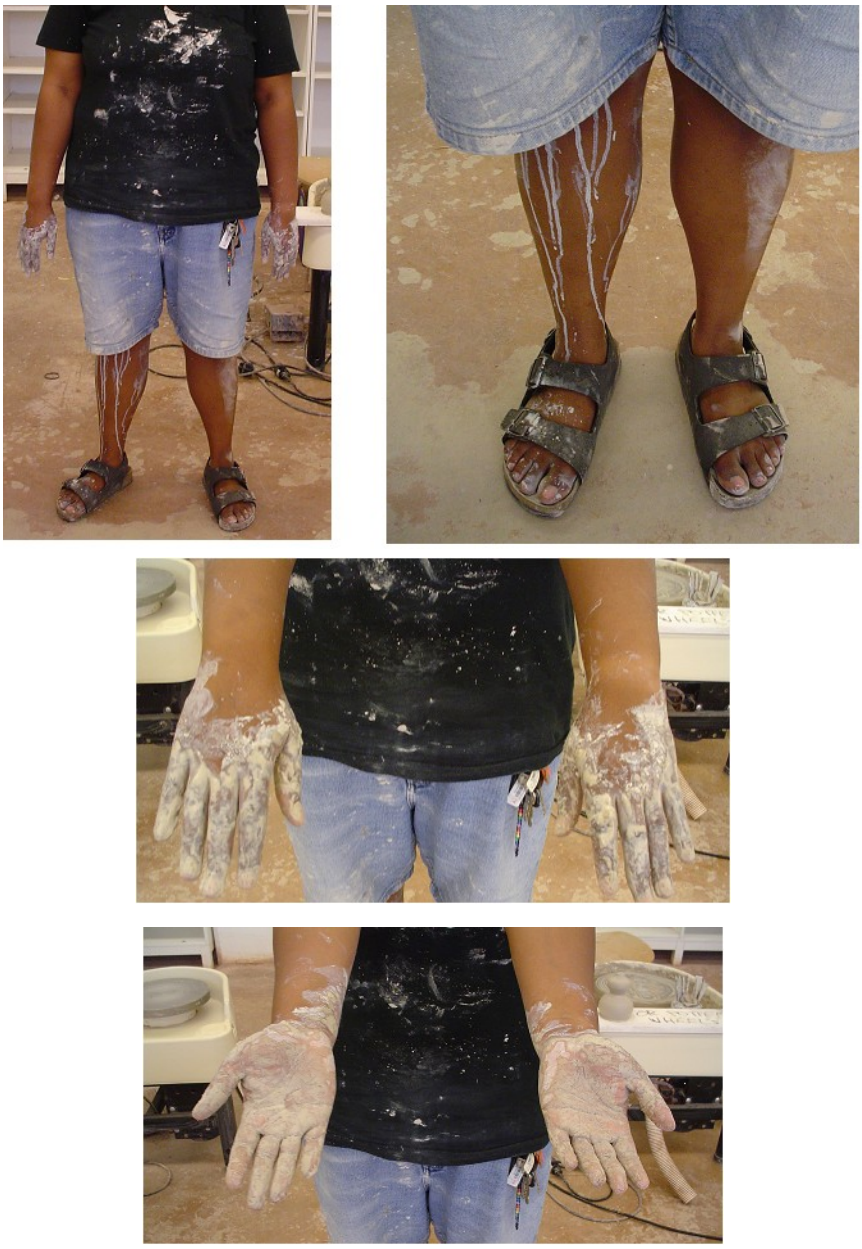


Figure F-3. Subject 9.

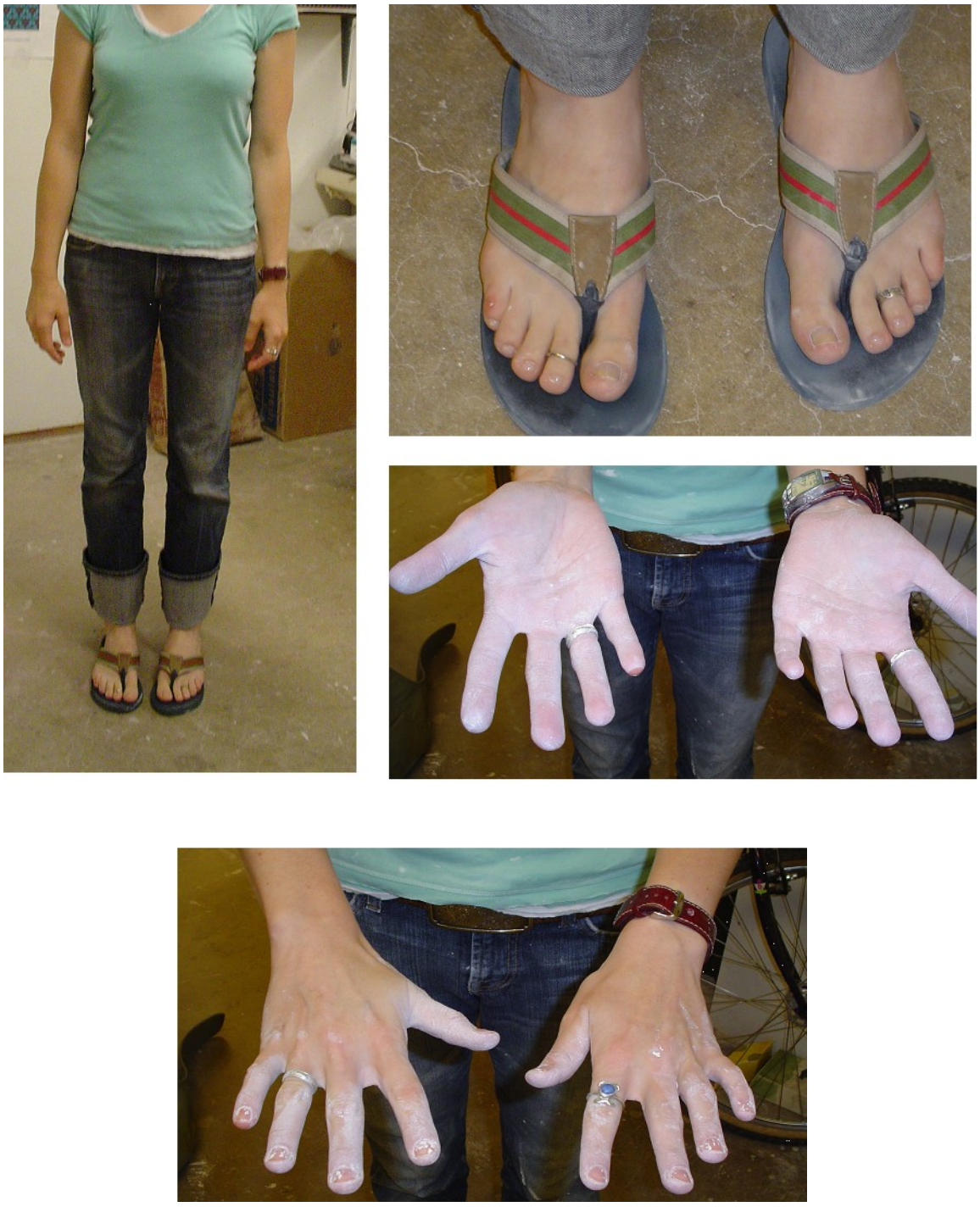
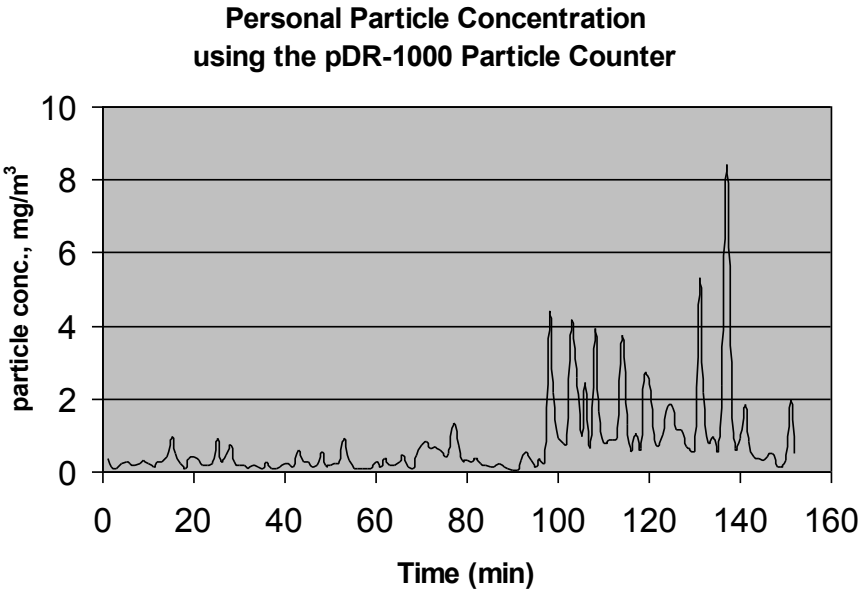


Figure F-4. Subject 10.

APPENDIX G

REAL-TIME PARTICLE CONCENTRATION DATA



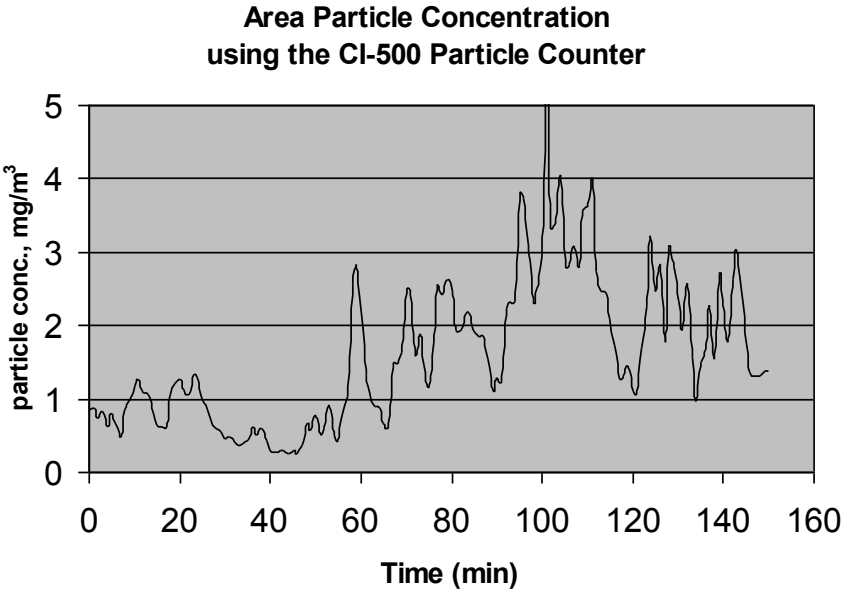
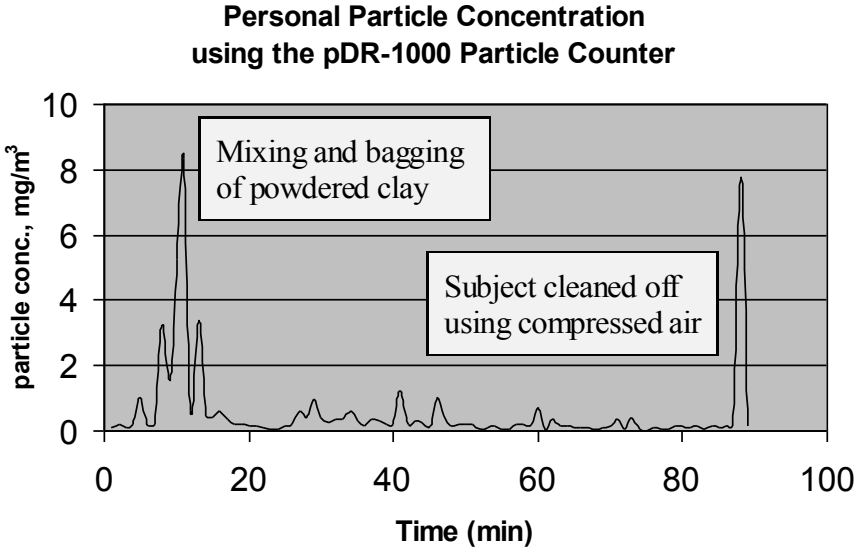


Figure G-1. Subject 1.



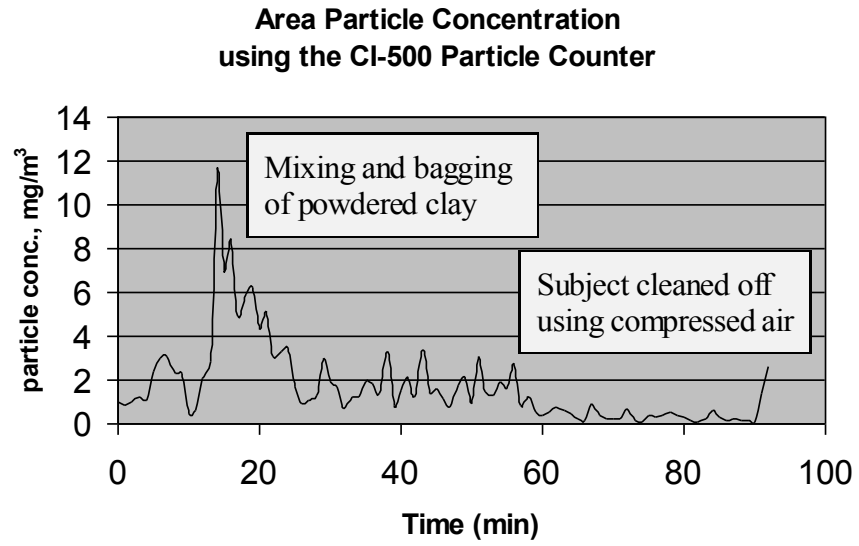
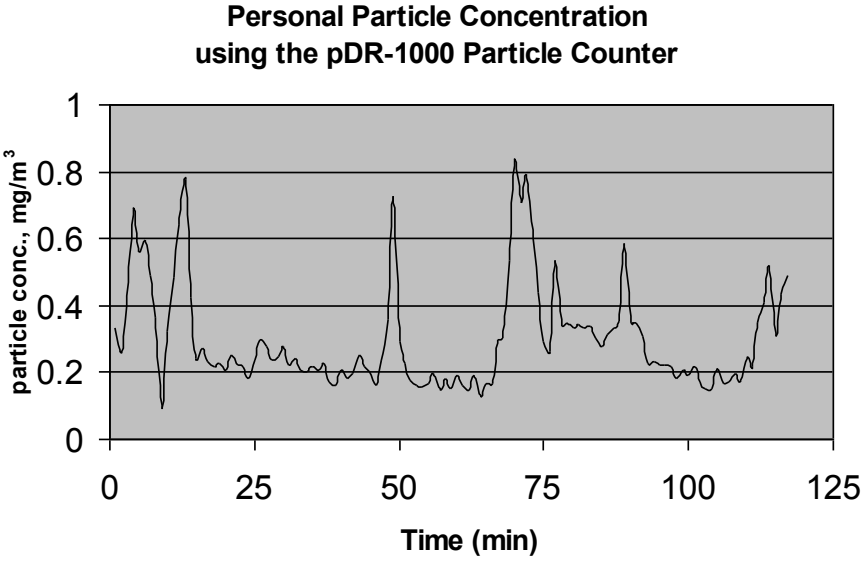


Figure G-2. Subject 2.



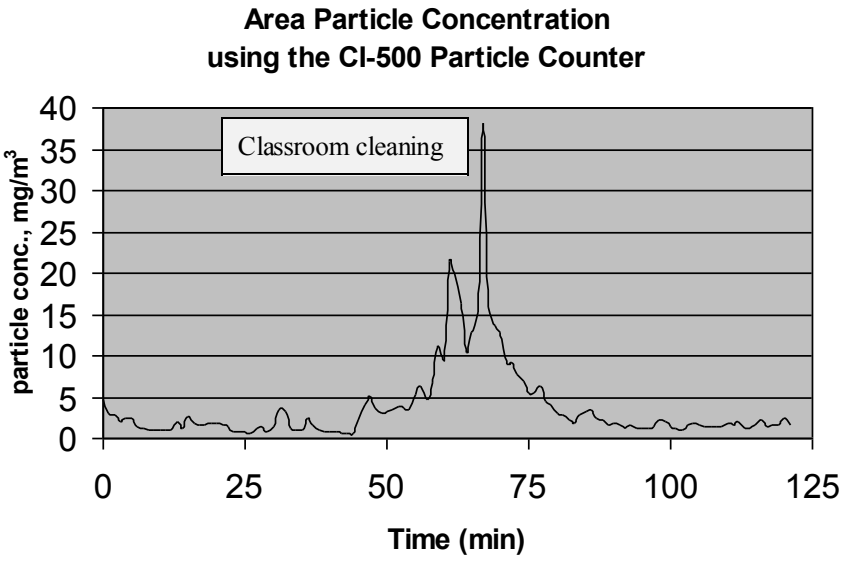


Figure G-3. Subject 3.

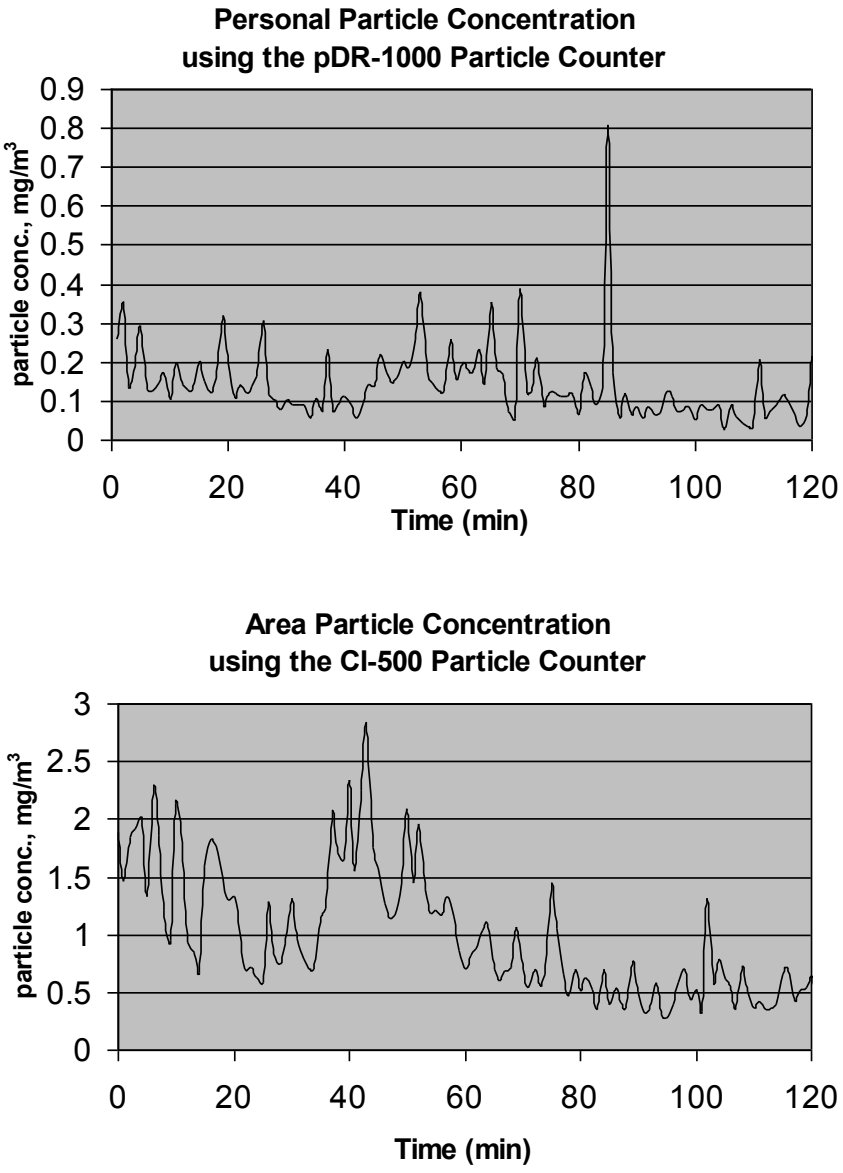
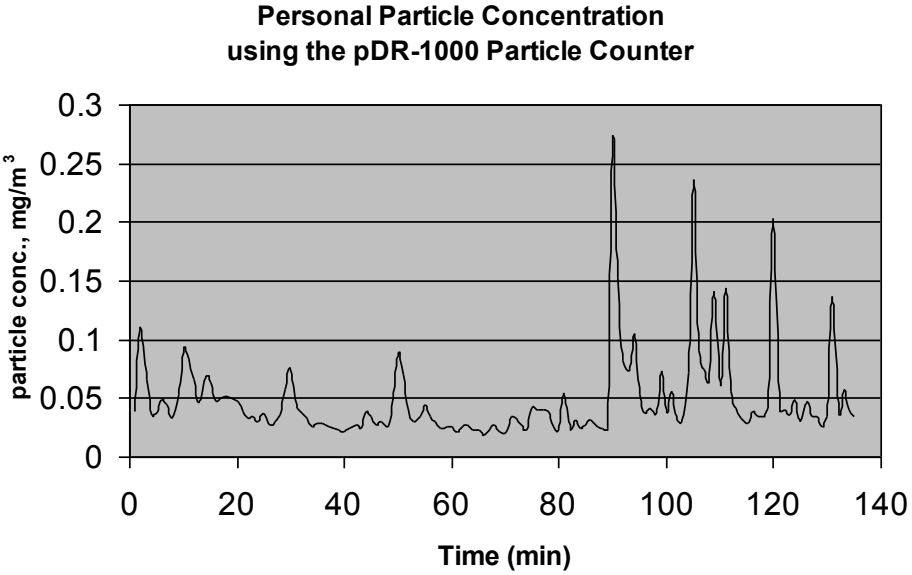


Figure G-4. Subject 4.



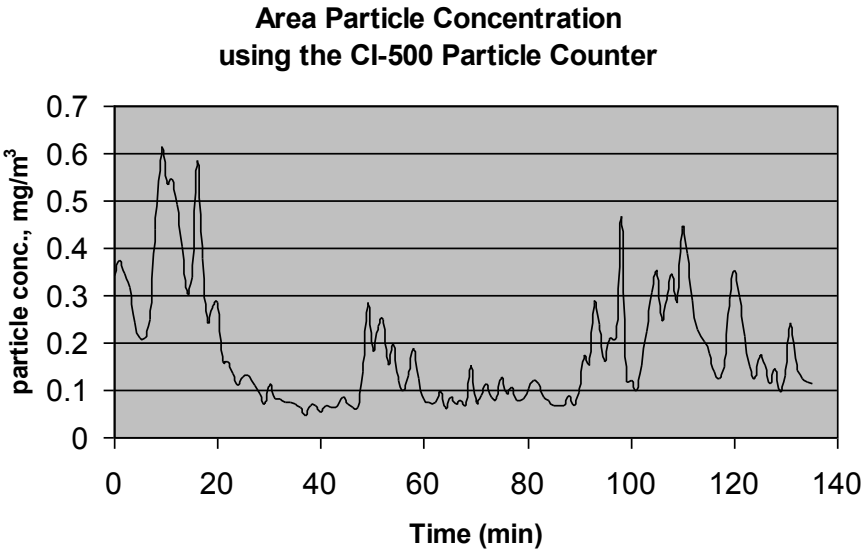


Figure G-5. Subject 5.

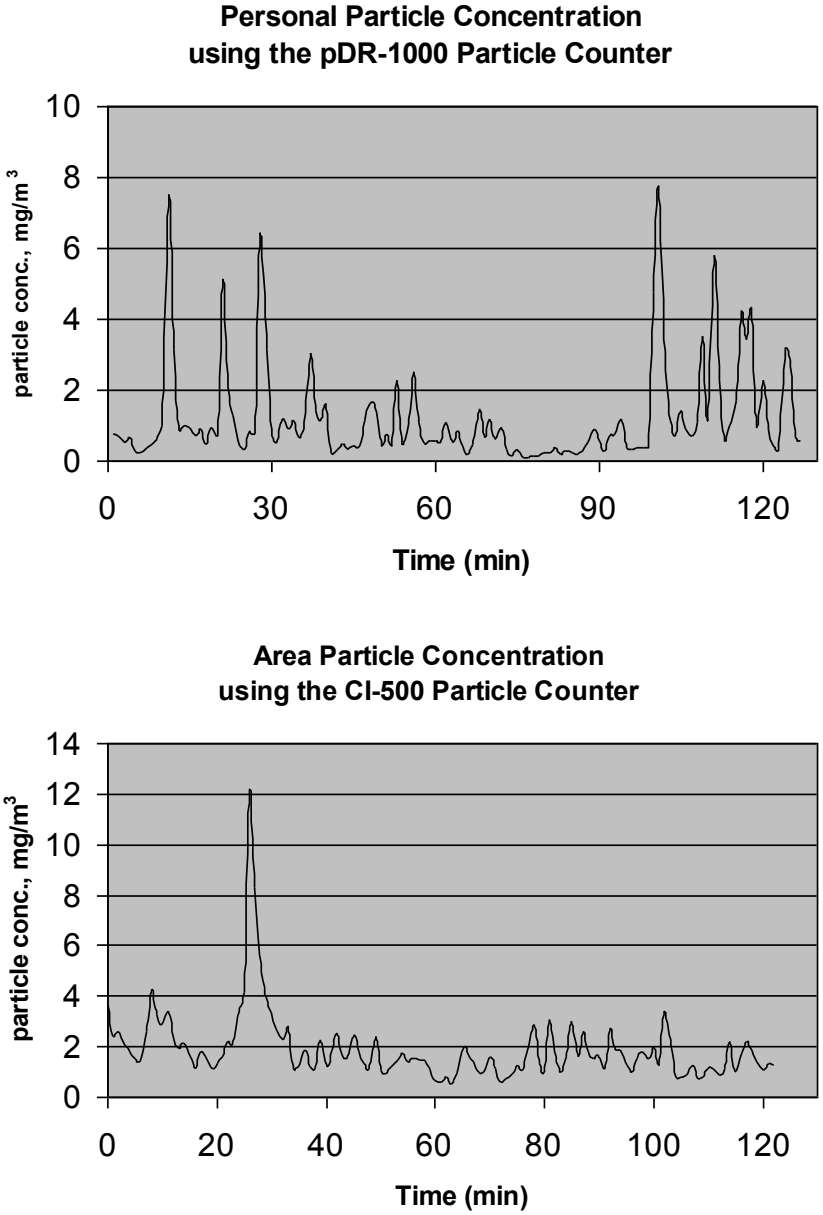
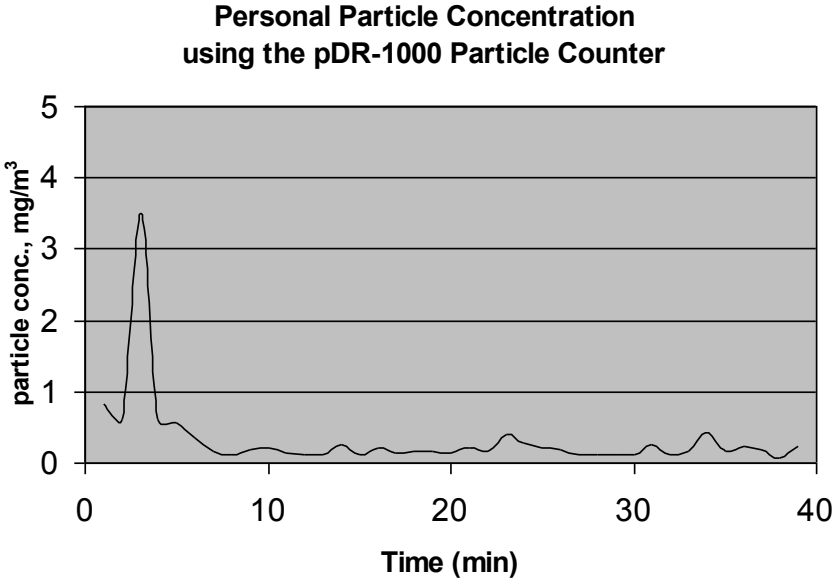


Figure G-6. Subject 6.



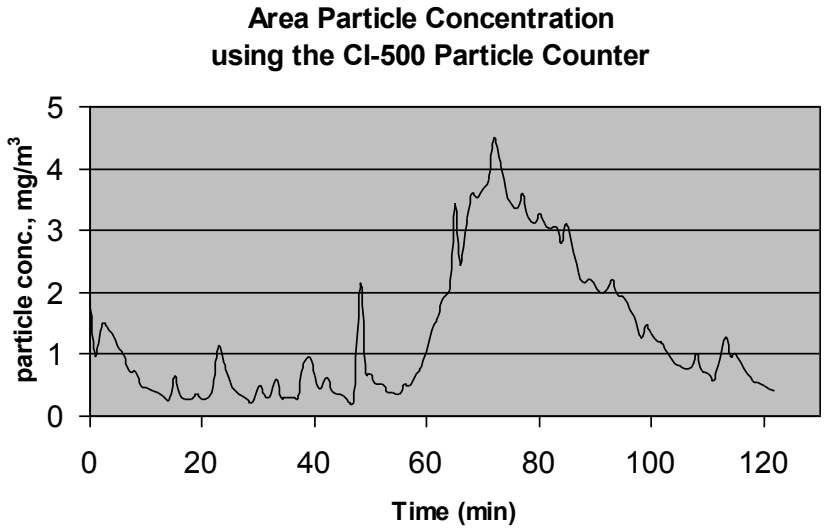
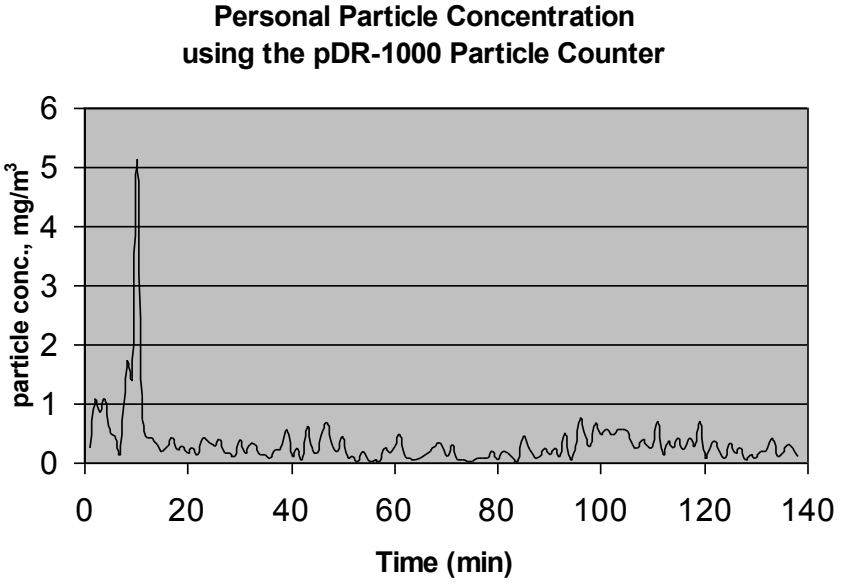


Figure G-7. Subject 7.



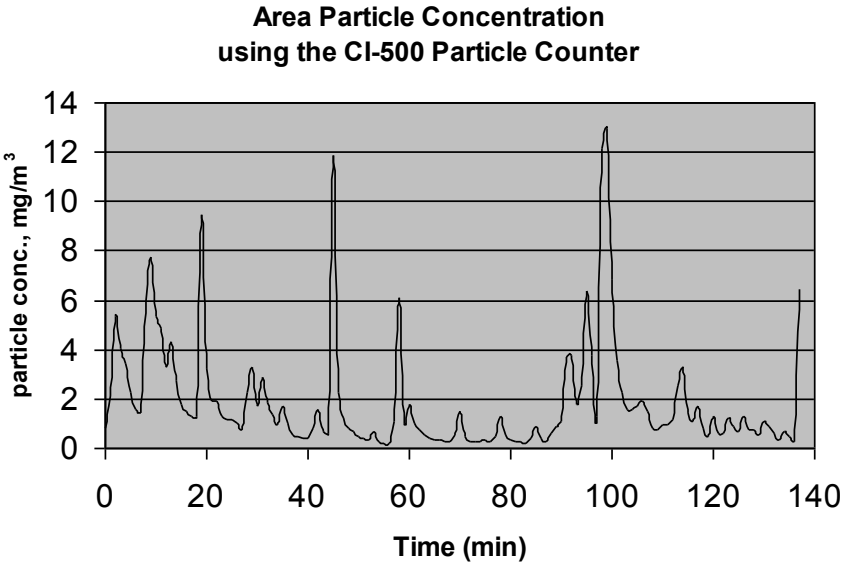


Figure G-8. Subject 8.

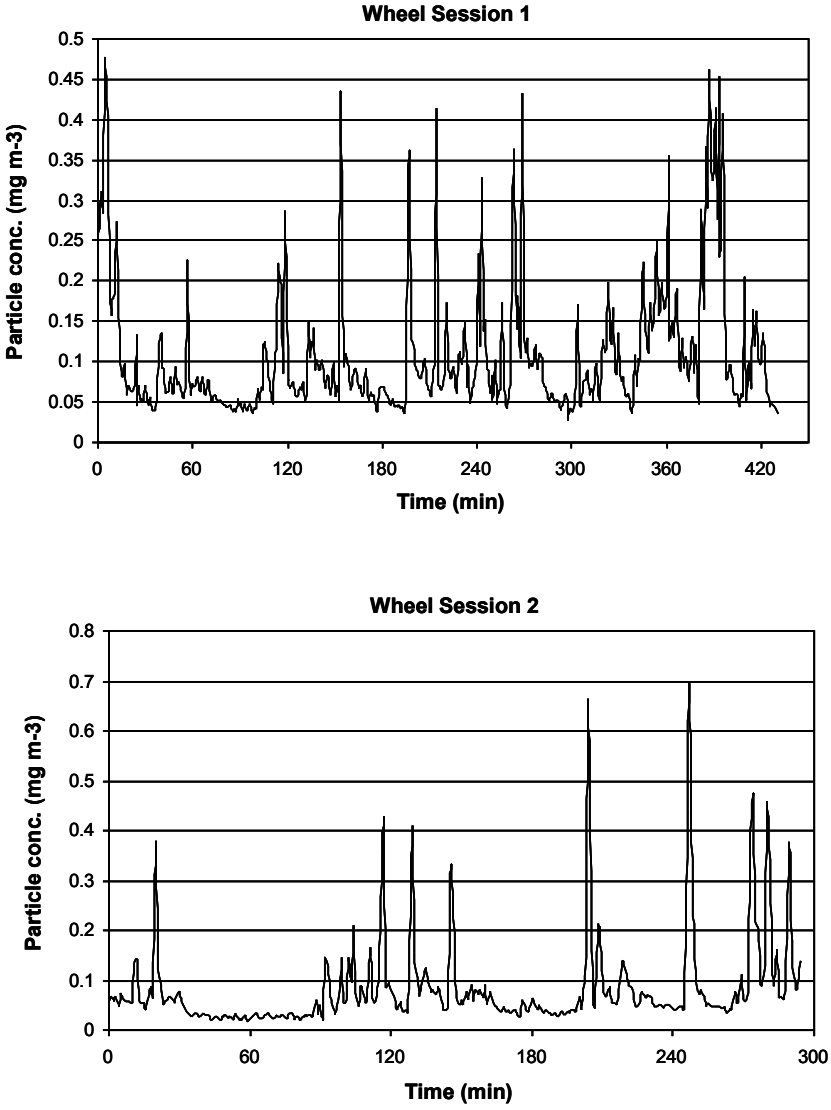
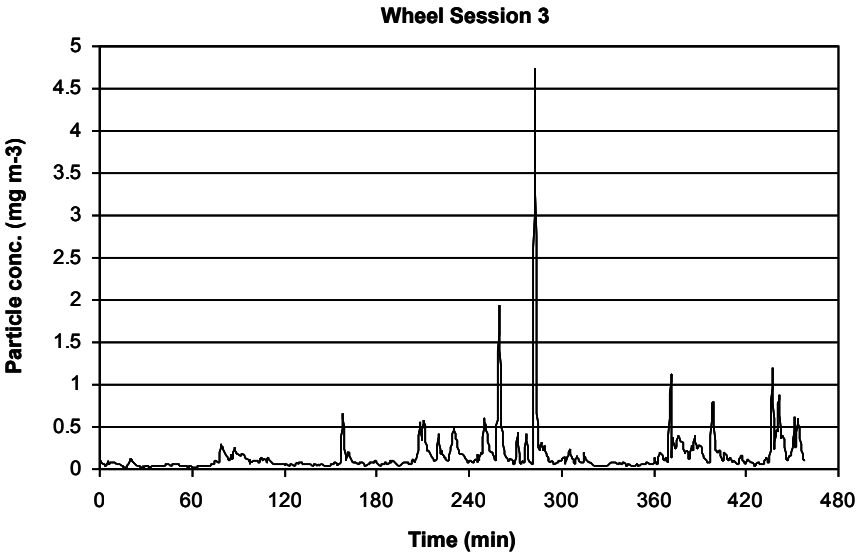


Figure G-9. Subject 9.



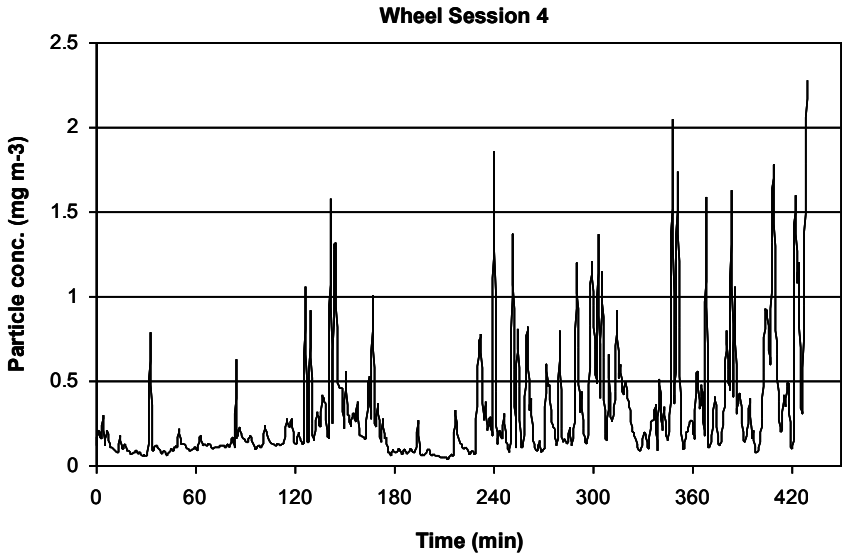


Figure G-9. continued.

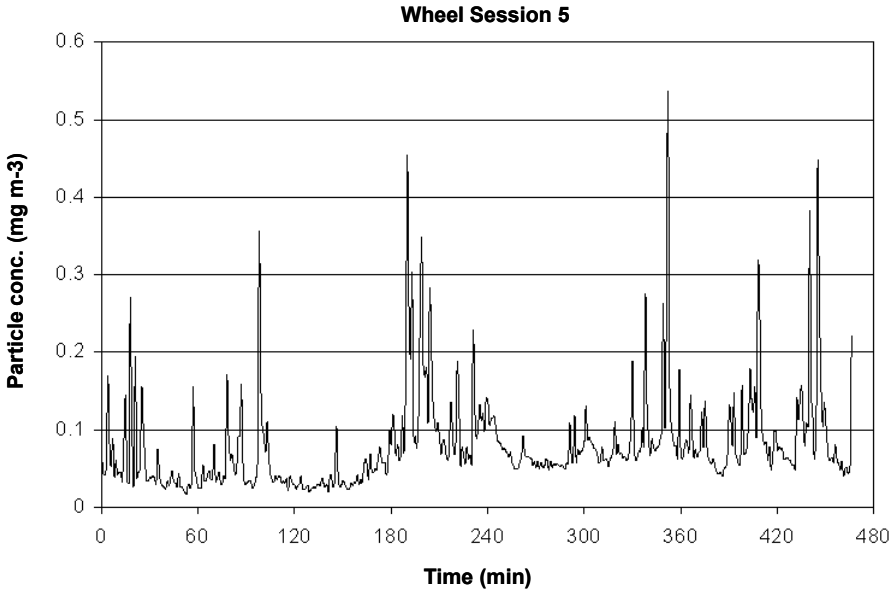


Figure G-9. continued.

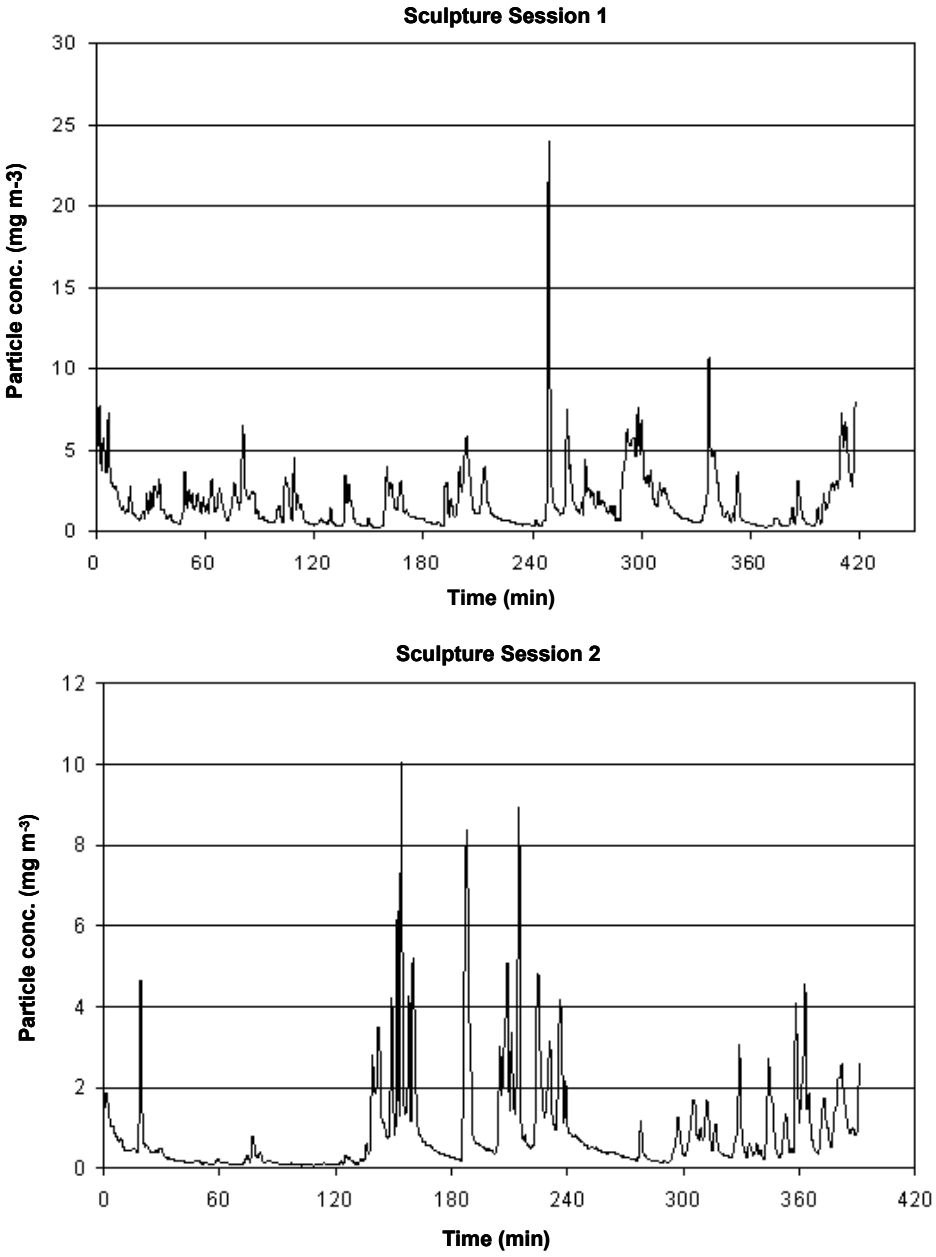
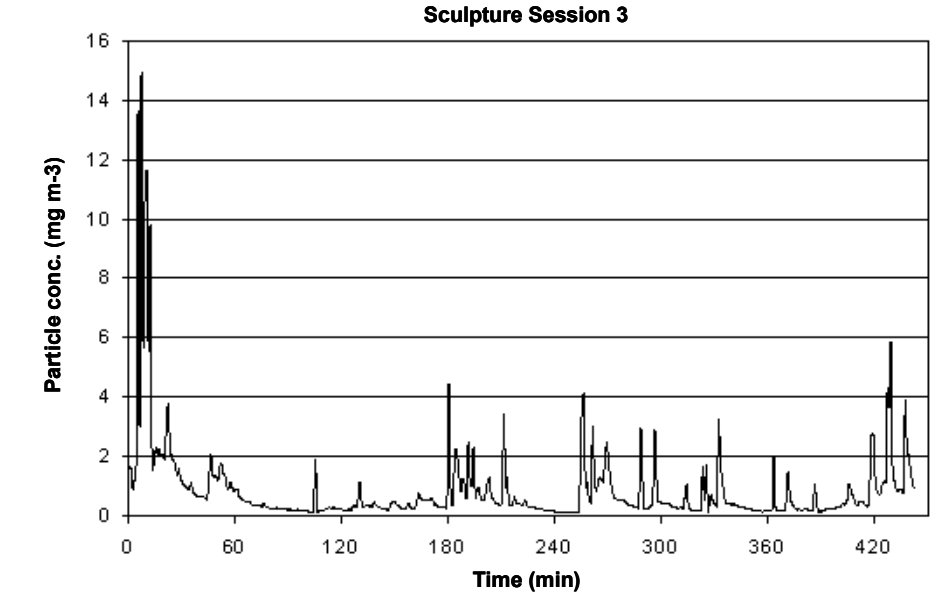


Figure G-10. Subject 10.



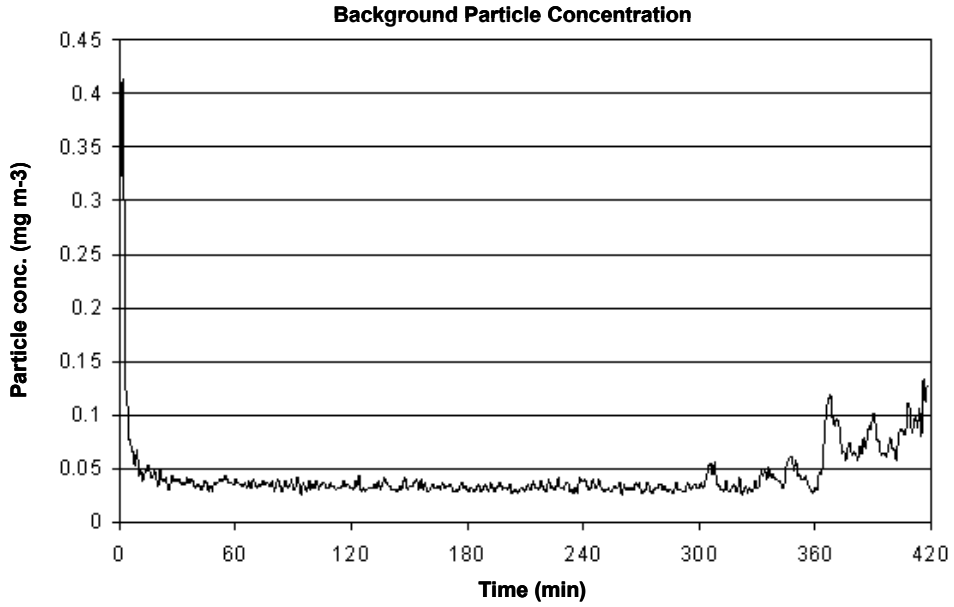


Figure G-10. continued.

APPENDIX H

RESPICON™, CASCADE IMPACTOR, PDR-1000, AND CLIMET® CI-500, DATA FOR EACH INDIVIDUAL SUBJECT

Table H-1. Concentration by particle diameter (µm) as measured by the Respicon™ Air Sampler (mg/m^3)[a, b]

Aerodynamic diameter	<4	4–10	10–100	Total
Subject 1	<DL	<DL	1.03	1.90
Subject 2	<DL	<DL	1.54	2.42
Subject 3	<DL	<DL	<DL	1.32
Subject 4	<DL	<DL	1.75	2.63
Subject 5	<DL	<DL	<DL	1.32
Subject 6	1.06	1.25	1.69	4.00
Subject 7	<DL	<DL	<DL	1.32
Subject 8	<DL	<DL	1.23	2.11
Background[c]	<DL	<DL	<DL	1.32

[a] DL (Detection Limit) = 0.878 mg/m^3.
[b] ½ DL was used in place of the <DL results for the purpose of calculating the total concentration.
[c] Based on measurements taken late at night when no students were present in building.

Table H-2. Concentration by particle diameter (µm) as measured by the Cascade Impactor Air Sampler (mg/m^3)[a, b]

Aerodynamic diameter	0.5–2	2.0–4.0	4.0–8.0	8.0–16	16–32	>32 µm	Total
Subject 1	<DL	0.02	0.06	0.02	0.06	0.18	0.35
Subject 2	<DL	0.04	0.03	0.05	0.02	0.31	0.47
Subject 3	0.06	0.08	0.19	0.15	0.13	0.39	0.99
Subject 4	<DL	<DL	0.03	0.05	0.05	0.22	0.37
Subject 5	<DL	<DL	<DL	<DL	<DL	0.10	0.13
Subject 6	<DL	0.04	0.08	0.14	0.10	0.23	0.61
Subject 7	0.04	0.05	0.11	0.12	0.06	0.15	0.51
Subject 8	<DL	0.03	0.07	0.11	0.10	0.31	0.64
Background[c]	<DL	<DL	<DL	<DL	0.017	0.085	0.13

[a] DL (Detection Limit) = 0.015 mg/m^3.
[b] ½ DL was used in place of the <DL results for the purpose of calculating the total concentration.
[c] Based on measurements taken late at night when no students were present in building.

Table H-3. Particle concentration as measured by the pDR-1000 Air Sampler (mg/m^3)

	Mean	Maximum	Minimum
Subject 1	0.75	8.42	0.047
Subject 2	0.57	8.33	0.016
Subject 3	0.30	0.84	0.093
Subject 4	0.14	0.81	0.027
Subject 5	0.049	0.27	0.019
Subject 6	1.22	7.70	0.078
Subject 7	0.32	3.51	0.080
Subject 8	0.34	5.14	0.015

Table H-4. Concentration by particle diameter (µm) as measured by the Climet CI-500 Air Sampler (mg/m^3)[a]

Physical diameter	0.3–0.5	0.5–1.0	1.0–2.5	2.5–5.0	5.0–10	>10.0	Total
Subject 1	0.001	0.005	0.026	0.222	0.560	1.499	2.313
Subject 2	0.001	0.002	0.016	0.166	0.535	1.747	2.467
Subject 3	0.002	0.009	0.058	0.411	1.214	3.756	5.450
Subject 4	0.002	0.003	0.013	0.124	0.323	0.964	1.429
Subject 5	0.008	0.002	0.003	0.025	0.055	0.167	0.260
Subject 6	0.011	0.006	0.029	0.260	0.679	1.746	2.731
Subject 7	0.005	0.010	0.054	0.377	0.631	0.817	1.895
Subject 8	0.006	0.004	0.021	0.186	0.578	1.878	2.672
Background[b]	0.009	0.005	0.002	0.010	0.010	0.019	0.055

[a] Concentration calculations assume particle density of 2.6 g/cm^3.
[b] Based on measurements taken late at night when no students were present in building.

Table H-5. Average concentrations by particle diameter ranges (µm) measured by the Cascade Impactor Air Sampler (mg/m^3)[a, b]

Aerodynamic diameter	0.5–2	2.0–4.0	4.0–8.0	8.0–16	16–32	>32	Total
Subject 9 Session 1	0.004	<DL	0.004	0.008	0.007	0.024	0.049
Subject 9 Session 2	<DL	<DL	0.005	0.007	0.008	0.024	0.046
Subject 9 Session 3	0.004	0.008	0.012	0.013	0.020	0.044	0.102
Subject 9 Session 4	<DL	<DL	0.004	0.005	0.009	0.053	0.073
Subject 9 Session 5	0.007	0.008	0.004	0.026	0.026	0.081	0.152
Subject 10 Session 1[c]	0.019	0.034	0.075	0.079	0.075	0.198	0.480
Subject 10 Session 2[c]	0.005	0.015	0.034	0.052	0.040	0.092	0.237
Subject 10 Session 3	0.011	0.018	0.047	0.054	0.032	0.079	0.241
Background[d]	0.004	<DL	0.003	0.006	0.004	0.005	0.023

[a] DL (Detection Limit) = 0.0025 mg/m^3.
[b] ½ DL was used in place of the <DL results for the purpose of calculating the total concentration.
[c] Concentration not adjusted for presence of dog.
[d] Based on measurements taken late at night when no students were present in building.

Table H-6. Concentration by particle diameter ranges (µm) measured by the Climet® CI-500 Air Sampler (mg/m^3)[a]

Physical diameter	0.3–0.5	0.5–1.0	1.0–2.5	2.5–5.0	5.0–10	>10.0	Total
Subject 9 Session 1	0.008	0.003	0.005	0.026	0.042	0.070	0.155
Subject 9 Session 2	0.010	0.005	0.003	0.014	0.027	0.058	0.117
Subject 9 Session 3	0.006	0.004	0.005	0.026	0.054	0.124	0.220
Subject 9 Session 4	0.012	0.007	0.011	0.055	0.113	0.240	0.439
Subject 9 Session 5	0.011	0.008	0.004	0.018	0.026	0.048	0.115
Subject 10 Session 1[b]	0.018	0.015	0.067	0.353	0.746	1.430	2.629
Subject 10 Session 2[b]	0.003	0.005	0.031	0.172	0.367	0.700	1.278
Subject 10 Session 3	0.006	0.008	0.039	0.181	0.341	0.656	1.231
Background[c]	0.012	0.009	0.003	0.011	0.012	0.016	0.064

[a] Concentration calculations assume particle density of 2.6 g/cm^3.
[b] Concentration not adjusted for presence of dog.
[c] Based on measurements taken late at night when no students were present in building.

APPENDIX I

MONTE CARLO CALCULATION OUTLINE

I.1. SELECT GENERAL EXPOSURE PARAMETERS

Dioxin concentration in clay (C) from distribution

Fraction ball clay in blend (F_{blend}) from distribution

Exposure duration (ED) from distribution

Select value for gender selector (0 to 0.5 means male, >0.5 to 1.0 means female)

Total body surface area males (SA) from distribution

Total body surface area females (SA) from distribution

I.2. COMPUTE DERMAL DOSE

Table I-1. Select value for clothing selector and determine fraction of body unclothed

Clothing Selector	Fraction Unclothed (FU)		
	FU_{arm}	FU_{leg}	FU_{feet}
0 to 0.2	0	0	0
0.2 to 0.8	0.67	0	0
0.8 to 0.9	0.67	0.67	0
0.9 to 1.0	0.67	0.67	1.0

Monolayer load (ML) = 0.5 mg/cm^2

Dermal absorption fraction for feet (DAF_{feet}) = 0.0226 (assumes 24-hour exposure)

Dermal absorption fraction for legs (DAF_{legs}) = 0.0226 (assumes 24-hour exposure)

Dermal absorption fraction for hands (DAF_{hand}) = (0.0005 ED^2 + 0.05 ED + 0.7692)/100

Dermal absorption fraction for arms (DAF_{arms}) = (0.0005 ED^2 + 0.05 ED + 0.7692)/100

Dermal absorption fraction for face (DAF_{face}) = (0.0005 ED^2 + 0.05 ED + 0.7692)/100

Select clay load on hand (L_{hand}) from distribution

Adjust L_{hand}: if $L_{hand} > ML$, then $L_{hand} = ML$, if $L_{hand} < ML$, then $L_{hand} = L_{hand}$.

Total hand surface area (SA_{hand}) = 0.052 SA
Dose to hand (D_{hand}) = ($C\ F_{blend}\ DAF_{hand}\ L_{hand}\ SA_{hand}$) 0.001

Select clay load on arm ($Larm$) from distribution
Adjust L_{arm}: if $L_{arm} > ML$, then $L_{arm} = ML$, if $L_{arm} < ML$, then $L_{arm} = L_{arm}$.
Total arm surface area (SA_{arm}) = 0.014 SA
Dose to arm (D_{arm}) = ($C\ F_{blend}\ DAF_{arm}\ L_{arm}\ SA_{arm}\ FU_{arm}$) 0.001

Select clay load on leg (L_{leg}) from distribution
Adjust L_{leg}: if $L_{leg} > ML$, then $L_{leg} = ML$, if $L_{leg} < ML$, then $L_{leg} = L_{leg}$.
Total hand surface area (SA_{leg}) = 0.318 SA
Dose to hand (D_{leg}) = ($C\ F_{blend}\ DAF_{leg}\ L_{leg}\ SA_{leg}\ FU_{leg}$) 0.001

Select clay load on feet (L_{feet}) from distribution
Adjust L_{feet}: if $L_{feet} > ML$, then $L_{feet} = ML$, if $L_{feet} < ML$, then $L_{feet} = L_{feet}$.
Total feet surface area (SA_{feet}) = 0.068 SA
Dose to feet (D_{feet}) = ($C\ F_{blend}\ DAF_{feet}\ L_{feet}\ SA_{feet}\ FU_{feet}$) 0.001

Select clay load on face (L_{face}) from distribution
Adjust L_{face}: if $L_{face} > ML$, then $L_{face} = ML$, if $L_{face} <$ ML, then $L_{face} = L_{face}$.
Total face surface area (SA_{face}) = 0.025 SA
Dose to face (D_{face}) = ($C\ F_{blend}\ DAF_{face}\ L_{face}\ SA_{face}$) 0.001

Total dermal dose (D_{der}) = $D_{hand} + D_{arm} + D_{leg} + D_{feet} + D_{face}$

I.3. COMPUTE INGESTION DOSE

Ingestion absorption fraction (F_{ing}) = 0.3
Clay load on food (L_{food}) from distribution
Clay load on beverage (L_{bev}) from distribution
Total ingestion dose (D_{ing}) = $C\ F_{blend}\ F_{ing}\ (L_{food} + L_{bev})$ 0.001

I.4. COMPUTE INHALATION DOSE

Particulate concentration in air (C_{air}) from distribution
Mass mean aerodynamic particle size (MMAD) from distribution
Geometric SD for particle distribution = 4

Select value for activity selector (*AS*) from distribution
Walk time = *AS ED*
Light exertion time (*LET*) = *ED* (1 – *AS*)

Table I-2. Set respiration parameters

	Slow walk		Light exertion	
	Female	**Male**	**Female**	**Male**
Tidal volume (*TV)* (mL)	464	750	992	1,250
Breathing frequency *F* (times/min)	14	12	21	20
Ventilation rate V_e (l pm)	*TV***F*/1,000 = 6.5	*TV***F*/1,000 = 9	*TV***F*/1,000 = 21	*TV***F*/1,000 = 25
Residual lung capacity (mL)	2,680	3,300	2,680	3,300

Select value for Breath Selector
0 to 0.13 means oralnasal breather, >0.13 to 1.0 means nasal breather

Compute regional doses using MPPD Subroutine (see below where D_n = dose to nose, D_m = dose to mouth, D_{tb} = dose to tracheal bronchial and D_{pu} = Dose to pulmonary)

Absorption fraction for nose, mouth, and TB = 0.3
Absorption fraction for PU = 0.8

Compute total inhalation dose (D_{inh}) = $0.3(D_n + D_m + D_{tb}) + 0.8D_{pu}$

I.5. COMPUTE TOTAL DOSE $(D_{TOTAL}) = D_{DER} + D_{ING} + D_{INH}$

MPPD Subroutine

MPPD (plus extrapolation curves for particles over 20 μm, see Appendix B) used to generate deposition fractions over a range particle sizes for each respiratory region and scenario based on breathing pattern, tidal volume, breathing frequency and residual lung capacity. The deposition fractions for each particle size (based on aerodynamic diameter or D_{ae}) are multiplied by the inhalation fraction:

Inhalation Fraction oral breather, $I_o = 1.44 / (1 + 0.44\exp(0.0195 D_{ae}))$
Inhalation Fraction nasal breather, $I_n = 1 - (1.0 / (1 + \exp(10.32 - 3.114\, l_n D_{ae}))$

This results in eight sets of MPPD outputs for deposition fractions in ET, TB, and PU (corrected for inhalation) which are stored in the spreadsheet:

Table I-3. Output categories for deposition fractions

	Slow Walk		**Light Exertion**	
	Nasal	**Oral**	**Nasal**	**Oral**
Male	1	2	3	4
Female	5	6	7	8

The particle size distribution is divided into 100 intervals and *DF* to each region is computed by summing the deposition fraction over each interval

Deposition to each region are calculated for slow walk and light exertion and then summed. For example, deposition to the nose, D_n is calculated as follows:

$D_n = C_{air}\,[V_t\, F\, ED\, DF_n]\text{light} + C_{air}\,[V_t\, F\, ED\, DF_n]\text{slow}$

APPENDIX J

MONTE CARLO SIMULATION RESULT GRAPHICS

Crystal Ball Report - Full
Simulation started on 7/23/2008 at 10:07:17
Simulation stopped on 7/23/2008 at 10:15:22

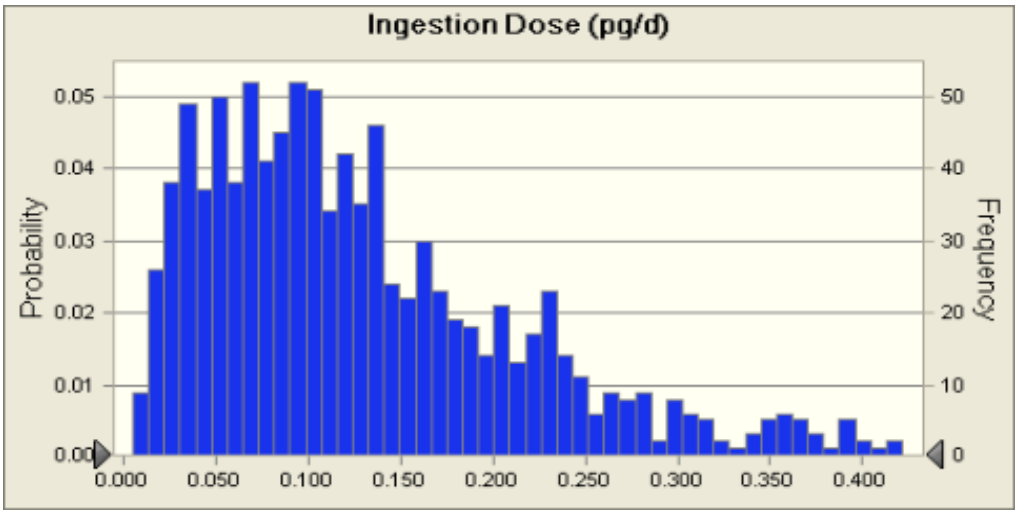
Run preferences:	
Number of trials run	1,000
Monte Carlo	
Random seed	
Precision control on	
Confidence level	95.00%
Run statistics:	
Total running time (sec)	485.46
Trials/second (average)	2
Random numbers per sec	37
Crystal Ball data:	
Assumptions	18
Correlations	0
Correlated groups	0
Decision variables	0
Forecasts	4

Forecasts

Worksheet: [VarDp-Dep monte6.xls]Monte

Forecast: Ingestion Dose (pg/d)

Summary:
Entire range is from 0.005 to 1.001
Base case is 0.058
After 1,000 trials, the std. error of the mean is 0.003



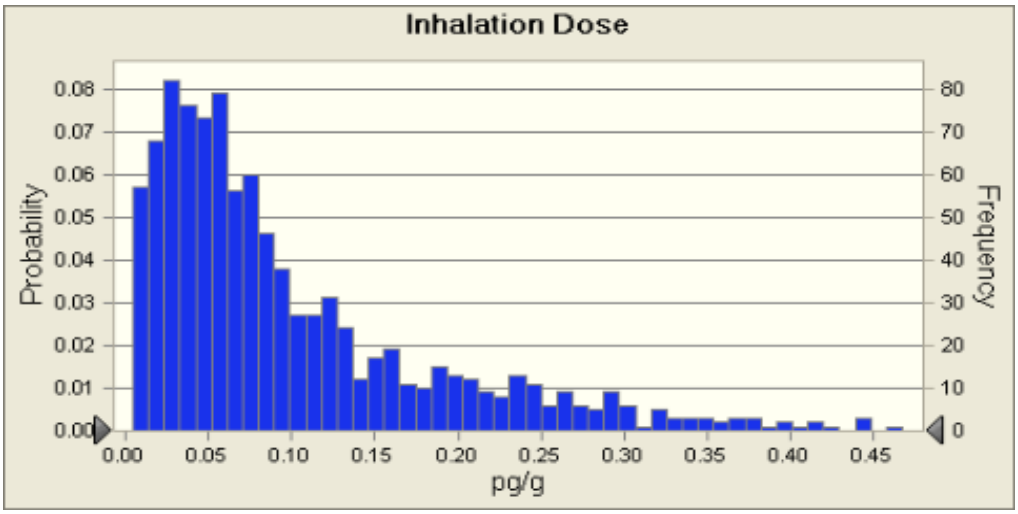
Statistics:	Forecast values
Trials	1,000
Mean	0.135
Median	0.110
Mode	---
Standard Deviation	0.102
Variance	0.010
Skewness	2.08
Kurtosis	11.29
Coeff. of Variability	0.76
Minimum	0.005
Maximum	1.001
Range Width	0.997
Mean Std. Error	0.003

Forecast: Ingestion Dose (pg/d) (cont'd)

Percentiles:	Forecast values
0%	0.005
10%	0.035
20%	0.053
30%	0.073
40%	0.092
50%	0.110
60%	0.133
70%	0.161
80%	0.202
90%	0.258
100%	1.001

Forecast: Inhalation Dose

Summary:
Entire range is from 0.00 to 1.12
Base case is 0.03
After 1,000 trials, the std. error of the mean is 0.00



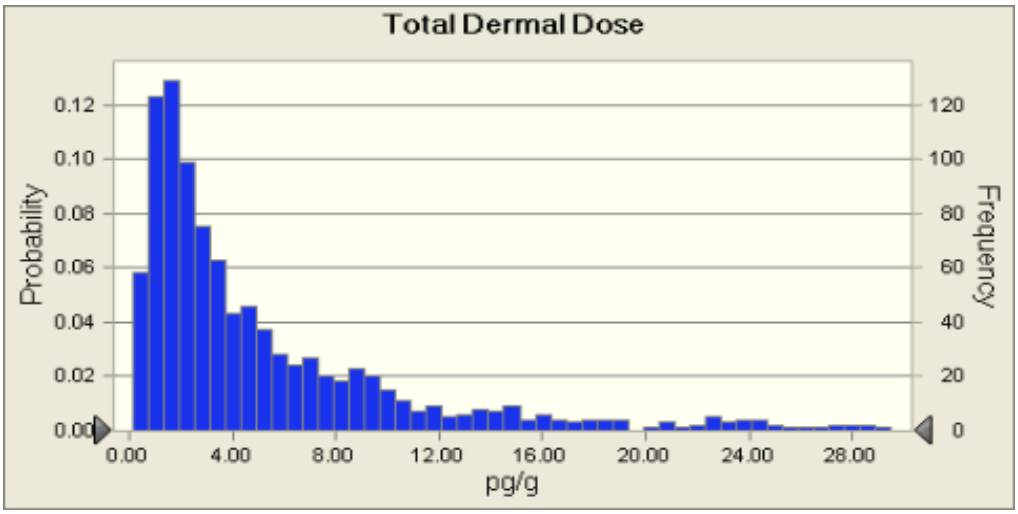
Statistics:	Forecast values
Trials	1,000
Mean	0.11
Median	0.07
Mode	---
Standard Deviation	0.13
Variance	0.02
Skewness	2.78
Kurtosis	14.10
Coeff. of Variability	1.10
Minimum	0.00
Maximum	1.12
Range Width	1.11
Mean Std. Error	0.00

Forecast: Inhalation Dose (cont'd)

Percentiles:	Forecast values
0%	0.00
10%	0.02
20%	0.03
30%	0.04
40%	0.06
50%	0.07
60%	0.09
70%	0.12
80%	0.17
90%	0.26
100%	1.12

Forecast: Total Dermal Dose

Summary:
Entire range is from 0.14 to 91.63
Base case is 3.32
After 1,000 trials, the std. error of the mean is 0.26



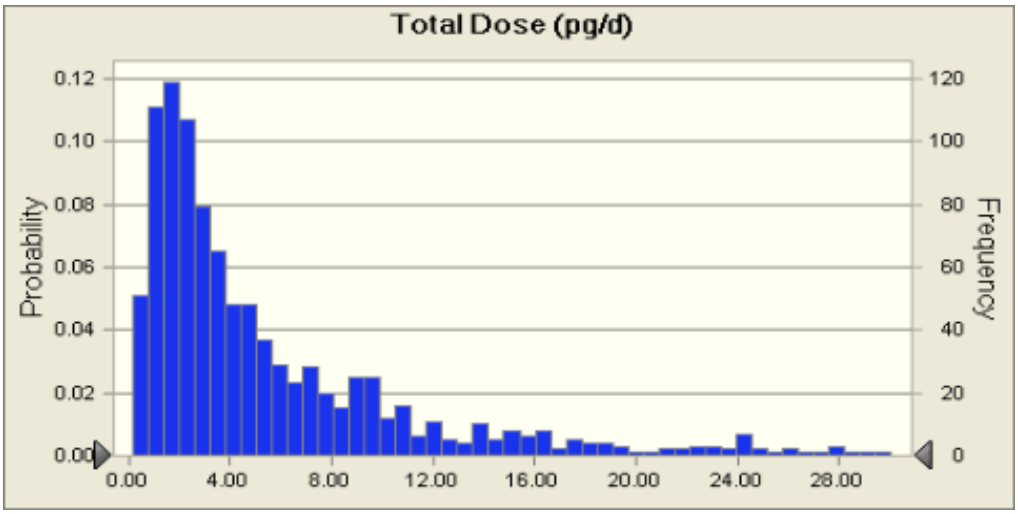
Statistics:	Forecast values
Trials	1,000
Mean	6.18
Median	3.23
Mode	---
Standard Deviation	8.32
Variance	69.30
Skewness	3.71
Kurtosis	23.60
Coeff. of Variability	1.35
Minimum	0.14
Maximum	91.63
Range Width	91.48
Mean Std. Error	0.26

Forecast: Total Dermal Dose (cont'd)

Percentiles:	Forecast values
0%	0.14
10%	0.96
20%	1.42
30%	1.90
40%	2.45
50%	3.23
60%	4.46
70%	6.07
80%	8.90
90%	14.42
100%	91.63

Forecast: Total Dose (pg/d)

Summary:
Entire range is from 0.17 to 92.39
Base case is 3.41
After 1,000 trials, the std. error of the mean is 0.27



Statistics:	Forecast values
Trials	1,000
Mean	6.43
Median	3.50
Mode	---
Standard Deviation	8.43
Variance	71.03
Skewness	3.67
Kurtosis	23.22
Coeff. of Variability	1.31
Minimum	0.17
Maximum	92.39
Range Width	92.22
Mean Std. Error	0.27

Forecast: Total Dose (pg/d) (cont'd)

Percentiles:	Forecast values
0%	0.17
10%	1.07
20%	1.55
30%	2.08
40%	2.73
50%	3.50
60%	4.69
70%	6.36
80%	9.15
90%	14.80
100%	92.39

End of Forecasts

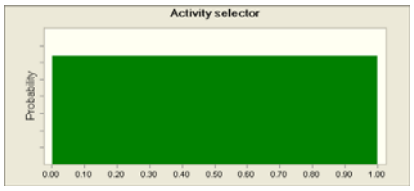
Assumptions

Worksheet: [VarDp-Dep monte6.xls]Monte

Assumption: Activity selector

Uniform distribution with parameters:

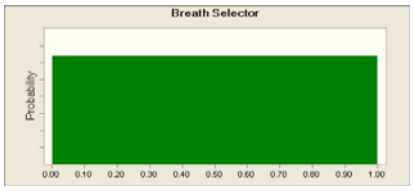
Minimum	0.00
Maximum	1.00



Assumption: Breath Selector

Uniform distribution with parameters:

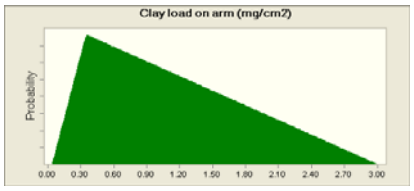
Minimum	0.00
Maximum	1.00



Assumption: Clay load on arm (mg/cm2)

Triangular distribution with parameters:

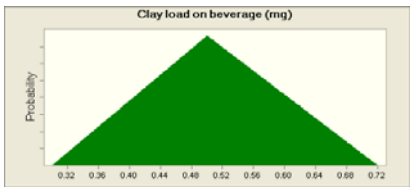
Minimum	0.04
Likeliest	0.35
Maximum	3.00



Assumption: Clay load on beverage (mg)

Triangular distribution with parameters:

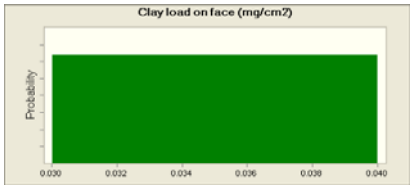
Minimum	0.30
Likeliest	0.50
Maximum	0.72



Assumption: Clay load on face (mg/cm2)

Uniform distribution with parameters:

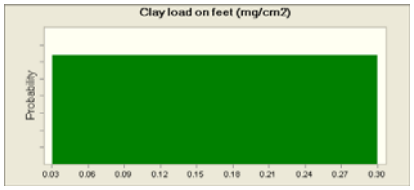
Minimum	0.030
Maximum	0.040



Assumption: Clay load on feet (mg/cm2)

Uniform distribution with parameters:

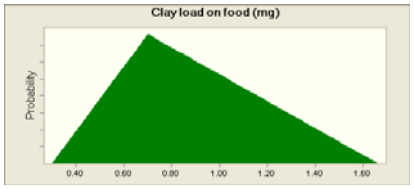
Minimum	0.03
Maximum	0.30



Assumption: Clay load on food (mg)

Triangular distribution with parameters:

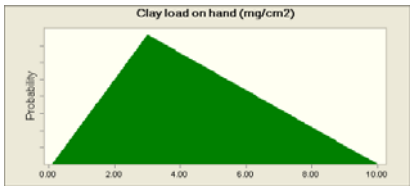
Minimum	0.30
Likeliest	0.70
Maximum	1.66



Assumption: Clay load on hand (mg/cm2)

Triangular distribution with parameters:

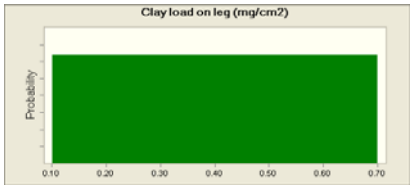
Minimum	0.10
Likeliest	3.00
Maximum	10.00



Assumption: Clay load on leg (mg/cm2)

Uniform distribution with parameters:

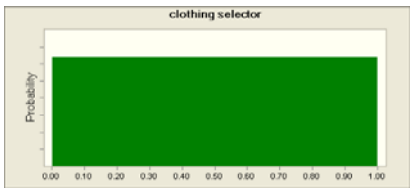
Minimum	0.10
Maximum	0.70



Assumption: clothing selector

Uniform distribution with parameters:

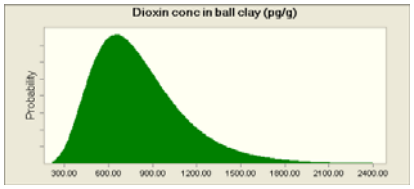
Minimum	0.00
Maximum	1.00



Assumption: Dioxin conc in ball clay (pg/g)

Lognormal distribution with parameters:

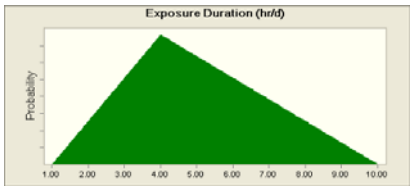
Mean	808.00
Std. Dev.	318.00



Assumption: Exposure Duration (hr/d)

Triangular distribution with parameters:

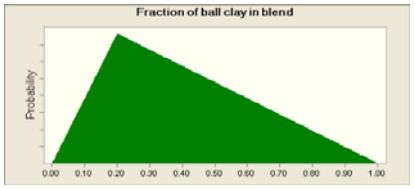
Minimum	1.00
Likeliest	4.00
Maximum	10.00



Assumption: Fraction of ball clay in blend

Triangular distribution with parameters:

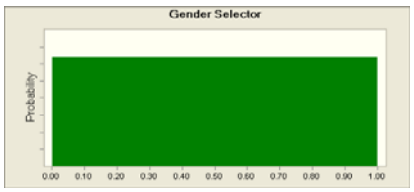
Minimum	0.00
Likeliest	0.20
Maximum	1.00



Assumption: Gender Selector

Uniform distribution with parameters:

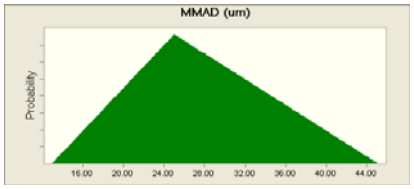
Minimum	0.00
Maximum	1.00



Assumption: MMAD (um)

Triangular distribution with parameters:

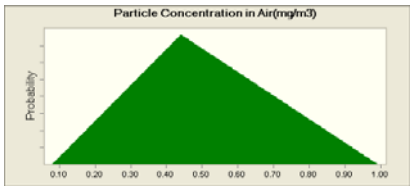
Minimum	13.00
Likeliest	25.00
Maximum	45.00



Assumption: Particle Concentration in Air(mg/m3)

Triangular distribution with parameters:

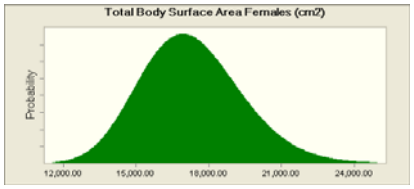
Minimum	0.08
Likeliest	0.44
Maximum	0.99



Assumption: Total Body Surface Area Females (cm2)

Lognormal distribution with parameters:

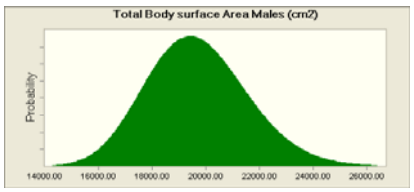
Mean	17,300.00
Std. Dev.	2,100.00



Assumption: Total Body surface Area Males (cm2)

Lognormal distribution with parameters:

Mean	19,700.00
Std. Dev.	1,900.00



End of Assumptions

EPA
United States
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Agency

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Office of Research and Development
Washington, DC 20460