PERSONAL WORKERS' LEAD EXPOSURE DURING INDOOR LEAD-BASED PAINT ABATEMENT

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ABSTRACT

This study addresses personal exposures of lead abatement workers. Personal monitoring of workers' lead exposure was performed during lead-based paint (LBP) abatement of wooden surfaces in a room size environmental chamber. Short-term task-specific lead exposures were determined for dry scraping, dry non-HEPA machine sanding, and wet scraping. Lead exposures were also monitored for different work practices during the final cleaning work task immediately after the required 1-hour waiting period following active LBP removal. The personal monitoring of workers was performed with the Button Personal Inhalable Aerosol Sampler operated at 4 Lpm and the standard closed-face 37-mm cassette at 2 Lpm. The sampling efficiency curve of the Button Sampler at its flow rate is close to the ACGIH/CEN/ISO inhalable particles sampling efficiency convention, while the more common 37-mm cassette at its commonly-used flow rate is not.

The 90% upper confidence levels of short-term worker lead exposures (measured with the Button Sampler) for all of the investigated active LBP removal methods exceeded the half-facepiece air purifying respirator protection level of 500 $\mu g/m^3$ at least by a factor of 5.

The two samplers were compared by correlation analysis which indicated up to 50% higher lead concentrations when measured using the Button Sampler as compared with that measured using the 37-mm cassette. The regression coefficients ranged from 1.08 for final wet cleaning to 1.50 for dry scraping. Microscopic analyses of the samples for all the above-mentioned work tasks showed that the sampler regression coefficients were higher for work tasks with higher percentages of large (> 20 μm) inhalable particles.

Because large airborne particles may penetrate through a respirator's faceseal leak less readily than submicron particles, the half-facepiece respirator's work protection factor is likely to be sufficient for worker's protection during majority of LBP abatement work tasks. Additional studies on the lead concentrations inside face masks should be performed to clarify the situation.

Keywords: lead exposure, personal monitoring, lead abatement, cleaning procedures, airborne particles, respirator protection

INTRODUCTION

According to the latest estimates by the Department of Housing and Urban Development (HUD), about 38 million occupied housing units in the U.S, in which children are permitted to live, contain some lead-based paint (LBP).[1] Many of these homes require lead abatement. Based on Occupational Safety and Health Administration (OSHA) data, about 45,000 abatement workers have been exposed to lead annually while performing lead abatement activity.[2] As national efforts to reduce residential lead hazards have progressed, the number of workers exposed to lead during lead abatement may have increased. To address the lead exposure of lead abatement workers the classification of lead exposure levels during typical lead abatement work tasks was performed.[3] It was reported that the workers' lead exposure during typical lead abatement tasks has considerable variability for individual contractors as well as for abated housing units. This finding has resulted in the OSHA standard requirement for employers to perform air sampling representative of a full work shift for each specific job classification in each new work site.[4] Thus, the sampling of airborne leaded particulates became a routine lead abatement procedure.

According to the American Conference of Governmental Industrial Hygienists (ACGIH) criteria for personal inhalable aerosol sampling, the samplers' efficiency curves are expected to fit the international ACGIH / European Standards Committee (CEN)/International Standard Organization (ISO) convention.[5-7] The 37-mm closed-face cassette, which has been widely used in occupational environments for many years to provide data on the average weighted lead mass concentration, has a sampling efficiency curve that do not fit this convention.[8-9] The deviation of this cassette's sampling efficiency from the international convention is especially pronounced in the particle size range of 20

to 100 μm. In this size range, the sampling efficiency of the 37-mm closed-face cassette ranges between 5% to 20%, while the ACGIH/ISO/CEN inhalable convention ranges from 50 to 65%. Thus, the workers' exposure assessments performed using data obtained with the 37-mm cassette may underestimate the actual exposure. In recent years, several new samplers have been developed with sampling efficiencies close to the ACGIH/ISO/CEN inhalable convention. One of them, the Button Personal Inhalable Aerosol Sampler (SKC Inc., Eighty Four, PA) has several additional desirable features, such as a good filter collection uniformity, low sensitivity of the sampling efficiency to wind velocity and direction, and low intersample variability.[10-13] The sampling inlet of the Button Sampler is a curved shell with numerous orifices of about 380 μm diameter. Due to its inlet design, the filter in the Button Sampler is protected from very large particles that are projected from the lead abatement removal process toward the sampler, especially those whose sizes significantly exceed the 100 μm upper limit of the conventional inhalability range.[5] The Button Sampler has been shown to be suitable for personal aerosol monitoring in abrasive blasting environments contaminated with heavy metal particles of high concentrations and broad particle size ranges.[14]

During lead abatement, utilization of a personal aerosol sampler with sampling efficiency characteristics close to the ACGIH/CEN/ISO inhalable convention will result in a more accurate assessment of the workers' exposure to inhalable leaded particulates. In this study, the workers' lead exposures during lead abatement were measured with the Button Personal Inhalable Aerosol Sampler. The 37-mm cassette was used in parallel. Short-term task-specific workers' exposures were determined during various LBP abatement activities (wet scraping, dry scraping, dry machine sanding). Personal monitoring of workers' lead exposures was also performed for various final cleaning practices.

MATERIALS AND METHODS

Lead Abatement Procedures

The study was performed in the environmental test chamber [15] at the Department of Environmental Health of the University of Cincinnati. The dimensions of the chamber (L × W × H = 3.78 m × 2.44 m × 2.64 m, total volume of about 24.3 m^3) represent the size of a typical residential room. The chamber is separated from the surrounding laboratory area by an air lock room that prevents the contamination of the laboratory air during entry into the chamber. The interior chamber walls are drywalls painted with lead-free paint. All gaps and cracks in the chamber were sealed. The ventilation system, equipped with HEPA air-purifying units, was used for air cleaning the chamber interior before the experiments. During the lead-based paint abatement experiments the air exchange rate was equal to zero.

Wooden doors covered with LBP were used for paint removal in the study. The doors were obtained from lead abatement sites in the Cincinnati area. Both sides of each door were characterized for lead content by X-ray fluorescence (XRF) using a NITON-700 instrument (NITON Inc., Bedford, Mass.). Only doors with XRF readings higher than 1 mg/cm^2, the U.S. federal government lead-based paint level, [16] were chosen for the study. Overall, 12 doors with XRF readings ranging from 1.3 to 30.0 mg/cm^2 were used for active abatement in the test chamber.

The study addressed task-specific workers' lead exposure during various lead abatement activities, such as active paint removal (referred to as "active abatement") and final cleaning. The active abatement methods utilized in the study included dry scraping, wet scraping, and dry sanding. The final cleaning

procedure included debris sweeping from protective plastic sheeting (6-mil polyethylene), as well as folding and removal of the plastic sheeting followed by a HEPA vacuum / wet wash / HEPA vacuum cycle. The final cleaning procedure was separated from active abatement by a waiting period of 1 hour that allowed settling of coarse aerosol particles, thus reducing the airborne dust concentration before the cleaning began (as recommended by HUD [17]).

It is acknowledged that HUD does not recommend the dry scraping method for lead abatement and prohibits it use in certain federally-owned and -assisted housing.[18] The utilization of dry scraping is permitted by HUD in such housing only for limited areas within 1 ft from electrical outlets. As LBP removal from these relatively small areas can produce rather high airborne lead concentration levels, dry scraping was addressed in the study. HUD recommends and requires for work covered under its regulation that dry machine sanding be performed using HEPA-filter-equipped sanders. As failure of proper use of a HEPA sander (e.g., resulting from a clogged vacuum hose or overloaded filter) may result in high lead aerosolization, dry machine sanding was also included in the study.

Two scrapers, one with a 2 ½ inch and another with a 3 inch scraping blade, were utilized for scraping (Red Devil Inc., Union, N.J.). Sanders (model 7447, Black and Decker Inc., Towson, Md.) with sanding belts (3" x 21", medium 80, 3M Inc., St. Paul, Minn.) were utilized for sanding.

Two wet scraping techniques were employed in the study. The first is a water spray technique in which the LBP painted surfaces are wetted with water mist generated by a plant sprayer (Zep Manufacturing Co., Cartersville, Ga). A wet sponge (Spontex Professional, Spontex Inc., Columbia, Tenn.) was applied to water painted surfaces in the second technique.

Only wet mopping of the floor was performed for the wet washing part of final cleaning. The walls were not wet washed. This followed the HUD-permitted practice in dwellings with wall finish that may be damaged by water.

Different work practices were applied during the cleaning and removal of protective plastic sheeting, before the HUD-recommended HEPA vacuum / wet wash / HEPA vacuum cycle was implemented. These practices included: (i) cleaning of the plastic sheeting through wet sweeping with watering of the settled dust prior to sweeping; (ii) dry sweeping with no watering of the settled dust; (iii) no sweeping (the plastic was folded without prior cleaning). In separate series of experiments, the wet debris sweeping and plastic removal was followed only by HEPA vacuuming (wet mopping of the floor was omitted). For experiments the with above-described variations in the cleaning procedure, only dry active abatement methods were utilized. This assured that the generated leaded dust was dry so that the highest plausible level of airborne lead was achieved during active abatement and final cleaning ("worst case scenario" from the exposure assessment stand point). For experiments with wet active abatement, the full HUD-recommended final cleaning procedure (with wet sweeping) was utilized.

The lead abatement activities were performed in the chamber by two workers at the same time. Intense abatement of limited surface areas of the doors (range: from 4 to 18 ft^2 or 0.4 to 1.7 m^2) allowed us to achieve the highest reasonable airborne lead concentration [15] for each specific abatement method utilized in the study. Thus, the active abatement time ranged from 5 to 20 minutes depending on the initial surface conditions of the door being abated. The overall duration of final cleaning depended on the length of the specific cleaning tasks incorporated in the experimental procedure. Since wet washing was omitted in some selected experiments, the total time that workers spent inside the chamber during final cleaning ranged from 57 to 78 minutes. A total of 24 lead abatement

experiments with different combinations of paint removal and cleaning work practices was conducted in the study.

During the experiments the workers (investigators), trained on standard industrial hygiene and safety procedures, used personal protective equipment. The study was approved by the Institutional Review Board of the University of Cincinnati.

Sampling and Analysis of Leaded Dust

The workers' exposure to aerosolized lead was monitored separately for the active abatement part and the final cleaning part, using a 25-mm Button Personal Inhalable Aerosol Sampler and a 37-mm 2-piece closed-face cassette (SKC Inc., Eighty Four, PA). Each worker wore one Button Sampler and one 37-mm closed-face cassette placed in the worker's breathing zone on the left and right side of the chest. The side of each specific sampler location was chosen randomly before each test. The first set of samplers was used during active abatement, the second during the final cleaning. The sampling flow rate through the Button Sampler was 4 Lpm, while the 37-mm cassette was operated at 2 Lpm, as recommended by their manufacturer. Each sampler was run by a battery-operated pump (224-PCXR8, SKC Inc., Eighty Four, PA). Mixed cellulose ester (MCE) collection filters (SKC Inc., Eighty Four, PA) were used for both types of personal samplers. The filter material was chosen to allow for different analyses to be performed after the sampling. One set of MCE filters was used for chemical lead analysis (these filters were fully digested in acid). The other set of MCE filters was made transparent through exposure to acetone vapor for further microscopic particle counting.

The filters obtained from the samplers worn by the first worker were analyzed using Flame Atomic Absorption Spectrometry (FAAS, NIOSH Method

7082) [19] to determine the concentration of airborne lead. The air sampling for lead exposure assessment was performed during the entire duration of a work task. It ranged from 5 to 20 minutes for paint removal and from 57 to 78 minutes for cleaning.

The filters from the personal samplers worn by the second worker were used for microscopic particle analyses. After having observed that the filters exposed during the entire 5-20 min active abatement time were overloaded with particles (thus making microscopic counting impossible), the monitoring time for the second worker was reduced to two minutes of active abatement activity. As the final cleaning consists of several different procedures, the same approach of reducing the sampling time was not applied. That approach would have eliminated some parts of the cleaning procedure and would have made the sample non-representative. Thus, the sampling during final cleaning was performed in the same time fashion by both workers. The 37-mm cassette filters were overloaded in the center area during active abatement, even for short-term sampling, as well as during final cleaning. This prevented us from performing a meaningful particle count on these filters. Thus, only the 25-mm filters of the Button Sampler were used for determining microscopic particle counts. The microscopic analysis (Labophot-2, Nikon, Japan) classified the sampled aerosol particles by fifteen size ranges. Seven of them covered particle size range from about 1 to 20 μm, five covered the range from 20 to about 100 μm, and the last three covered the range from 100 to 200 μm. In the first part of the analysis, microscopic particle counting (magnification of 1000) were performed in three microscopic fields of about 190 μm diameter located in the area near the left filter edge, near the right filter edge, and at the filter center. If the number of particles in these three areas was less than 400, the counting was continued in other peripheral areas until the count reached 400 particles. Generally, the counting

area for this first part of the analysis was less than 0.01% of the total filter area. In the second part of the analysis, the particle counting was performed in an area larger than 5% of the filter surface area. However, only particles larger or equal to the maximal size observed in the first part of the analysis were counted. The magnification for the second part of analysis was 400 or 1000, depending on the particle size range addressed. Finally, the entire filter surface was scanned under the microscope (with magnification of 100) to assure that particles larger than the maximal size detected in the second part of the analysis were not present on a filter surface.

The resulting particle size distributions were transformed to cumulative particulate lead mass distributions. This mathematical transformation was performed under the assumption that all sampled particles are ideal spheres and have the same density and lead mass concentration.[15]

RESULTS AND DISCUSSION

Lead Mass Concentration during Active Abatement

Table 1 presents the geometric means of the lead mass concentrations and their geometric standard deviations, as measured with the Button Sampler and the 37-mm standard filter cassette for three LBP removal methods: dry scraping, wet scraping, and dry machine sanding. Because wet scraping by sponge or spray wetting generated airborne lead dust of the same mass concentration range, the data on wet scraping are combined into one category. As seen, the geometric means of the lead mass concentrations for the dry lead abatement methods are about ten times higher than those for the wet method. The concentrations obtained for dry abatement appear to be of the same level as the highest ones previously reported in the literature for similar work tasks (5,800 $\mu g/m^3$ [20]). For wet scraping, the airborne lead concentration observed in this study is more than

thirty times higher than the previously reported levels (for example, 24 $\mu g/m^3$ for a combination of wet scraping, HEPA vacuuming and mopping [20, 21]). The higher concentrations measured in this study can be attributed to the higher lead percentages in the abated paint (XRF ranged from 1.1 up to 30.0 mg/cm^2). The choice of abated objects (wood doors in our study; unspecified surfaces in the other studies [20, 21]) may also have contributed to the higher values of measured lead exposures. It is also important to recognize that complete LBP removal versus surface preparation for painting requiring removal of only loose and peeling LBP results in different levels of lead exposure for the workers.[21, 22] That difference might be as high as 200 times (28 $\mu g/m^3$ vs. 5,800 $\mu g/m^3$).[21] It has been reported [23] the existence of correlation between workers' lead exposure and the proportion of LBP removed from abated areas. This suggests that removing the large proportion of LBP from a painted surface is likely to produce high exposure levels regardless of the lead surface concentration (for lead content higher than 1 mg/cm^2).[23] In our study we performed the total removal of LBP. It has also been observed [21] that the usage of extension poles on scrapers may contribute to decrease in the lead exposures of workers. In our study, scraping was performed very close to the workers' breathing zones; extension poles were not used.

During active abatement, the lead concentrations measured in this study with the Button Sampler were higher than those measured with the 37-mm cassette. The correlation between the lead mass concentrations obtained with the Button Sampler and those obtained with the 37-mm cassette is presented in Figure 1. The different symbols represent different lead abatement methods: dry scraping, dry sanding, and wet scraping. The airborne lead concentration range of up to 2,500 $\mu g/m^3$ (all wet scraping data are well inside this range) is inserted in the top left hand corner of Figure 1. The straight line represents the correlation

for all investigated active abatement methods. The regression slope, k, is 1.34. The regression coefficient, r^2, is 0.83. The slopes and regression coefficients for specific lead abatement methods were : k = 1.50, r^2 = 0.95 for dry scraping; k = 1.18, r^2 = 0.52 for dry sanding; k = 1.17, r^2 = 0.62 for wet scraping. The dry scraping abatement method has the best (highest) regression coefficient and the highest slope.

Lead Mass Concentration during Final Cleaning

Table 2 presents the geometric means and geometric standard deviations of the lead mass concentrations measured with the Button Sampler and the 37-mm standard cassette for the different work practices during final cleaning. The last row in Table 2 represents final cleaning after wet scraping. In this case, the geometric means of the lead mass concentrations measured with the Button Sampler as well as with the 37-mm cassette (23 and 22 $\mu g/m^3$, respectively) are lower than the Permissible Exposure Limit (PEL) for lead of 50 $\mu g/m^3$. The range of measured lead exposures was 3 to 47 $\mu g/m^3$ for the Button Sampler and 4 to 43 $\mu g/m^3$ for the 37-mm cassette. While the geometric means of the airborne lead concentrations during final cleaning (with wet engineering control) measured in our study are about ten times higher than reported in the literature [17, 20] (2.1 $\mu g/m^3$), the measured range of exposures is about the same (0.9 to 36 $\mu g/m^3$). In our study, final cleaning was performed immediately after a one-hour waiting period following active abatement at the highest plausible lead aerosol concentrations. In the field, lead abatement may be performed during more than one day in several adjacent units, and final cleaning may be performed in several units simultaneously on the last work day. The waiting period in that case is different for each specific unit and may be considerably longer than 1 hour. Thus,

our study represents the most conservative approach to worker exposure during final cleaning.

When final cleaning was performed after wet scraping and consisted of wet debris sweeping in combination with a HEPA vacuuming / wet wash / HEPA vacuuming cycle (the last row in Table 2), the workers' lead exposure during final cleaning was the lowest of all the work practices investigated in this study (geometric mean of airborne lead concentration was 23 $\mu g/m^3$ as measured with the Button Sampler). In contrast, the highest level of airborne lead concentration was observed when dry debris sweeping was performed during final cleaning after dry active abatement. For that case (first row in Table 2) the concentrations measured with the Button Sampler were in the range of 144 to 634 $\mu g/m^3$ with a geometric mean of 318 $\mu g/m^3$. For all cleaning practices that included wet sweeping, the difference between Button Sampler and 37-mm cassette data was minimal.

The fourth row in Table 2 presents data for final cleaning with wet engineering control performed after dry active abatement. This simulates the case of lead hazard control utilizing dry scraping applied to areas around electrical outlets. The workers' exposure for this combination of abatement practices was about four times that for wet engineering control applied during both final cleaning and active abatement. The increased exposure is attributed to the higher overall lead concentration for dry active abatement and, correspondingly, to the higher airborne lead concentration throughout the period of final cleaning. During the one-hour waiting time preceding the final cleaning, the concentrations of airborne leaded particles decrease exponentially.[15] Thus, the airborne lead concentration at the beginning of final cleaning after dry active abatement is higher than after wet active abatement. That difference in aerosol concentration

remained throughout all final cleaning procedures. It resulted in the highest overall workers' exposure during final cleaning after dry active abatement.

The other final cleaning data obtained in our study represent variations of work practice, including some procedures that are not recommended. Our experiment was designed to be able to identify the specific cleaning task responsible for the highest level of dust reaerosolization during final cleaning. Comparison of the data with and without dry sweeping before plastic folding (first and second row in Table 2) indicates that dry sweeping by itself is a significant generator of airborne dust (318 vs. 139 $\mu g/m^3$, as measured with the Button Sampler). Spraying of dust with water before sweeping resulted in a decreased geometrical mean lead exposure (90 $\mu g/m^3$, as measured with the Button Sampler; see the fourth row of Table 2). The increase in the geometric standard deviation up to 4.7 in this case indicates a high variability of exposure. While spraying the dust with water always resulted in lower lead exposure compared to the case of dry sweeping, the lead concentration was as high as 388 $\mu g/m^3$ in one experiment with wet dust sweeping. This probably resulted from reaerosolization of leaded dust while applying water spay to dry dust piles. The data on lead exposures for different final cleaning work practices indicate that the safest work practice is achieved through wet engineering control during both procedures: LBP active removal and final cleaning.

Figure 2 shows the correlation between lead mass concentration data obtained during final cleaning with the Button Sampler versus the 37-mm cassette. The lead concentration range up to 50 $\mu g/m^3$ where all final cleaning after wet scraping data are located is shown in an insert in the top left hand corner of Figure 2. As seen, the concentrations measured with the Button Sampler are higher than those measured with the 37-mm cassette. The straight line in Figure 2 represents the correlation ($k = 1.25$, $r^2 = 0.94$) for all experimental data. For final

cleaning with wet engineering control after wet scraping (the work practice recommended by HUD), the correlation between the Button Sampler and 37-mm cassette data has a slope of 1.08 ($r^2 = 0.97$). For that work practice the Button Sampler and 37-mm cassette data are practically the same.

Cumulative Lead Mass Distributions during Active Abatement

Figure 3 presents cumulative lead mass distributions during active abatement, calculated from the particle size distributions determined by microscopic analysis of Button Sampler filters. It was previously found [15] that for particles larger than 1 μm, aerosolized during LBP abatement, the relative variation of the lead mass percentage in airborne particulate did not exceed 25%. In the previous study,[15] the sampling of dust was performed with a seven stage Andersen Cascade Impactor (Andersen Instruments Inc., Smyrna, Ga.). The upper stage of that device collected all airborne particles larger than 7.4 μm. In that study, no difference was observed for lead mass percentage for particles in the 4.7 - 7.4 μm size range versus particles with sizes >7.4 μm, while the variation in lead concentration for particles in the range of 1.1 to 7.4 μm was about 25%. Thus, it is estimated - with approximately 25% accuracy - that the lead-based paint dust in the inhalable size range (up to 100 μm) of the present study may be characterized by the same lead concentration. As a result, the data presented in Figure 3 were calculated from the particle size distributions with the assumption that all particles are spherical, have the same density and lead mass concentration. Figure 3 shows that the median mass size (the particle size corresponding to 50% of the cumulative mass) increased from about 15 μm for wet scraping to about 25 μm for the dry abatement methods. For the wet scraping methods, about 40% of the airborne particle mass was in the size range larger than 20 μm. For dry scraping, more than 70% of the airborne lead mass was in that size range. This

indicates that wet engineering controls during active abatement more effectively suppress the aerosolization of large inhalable particles. While the geometric mean of the lead mass concentration during wet scraping abatement is approximately $1/7^{th}$ that during dry scraping (Table 1), the aerosolization of large inhalable particles (> 20 μm) during wet active abatement is about $1/12^{th}$ that during dry abatement. For small inhalable particles (< 20 μm) the dust aerosolization during wet active abatement is only $1/3^{rd}$ that during dry abatement. Thus, the particle size distribution is significantly different for wet versus dry scraping abatement methods with respect to large inhalable particles.

The data in Figure 3 indicate that some particles larger than 100 μm (the upper limit of inhalable size range) were also sampled with the Button Sampler. However, for all investigated LBP abatement methods the mass of particles lager than 100 μm did not exceed 5% of the total mass collected by the Button Sampler. Thus, the bias in the sampled mass, resulting from particles larger than 100 μm, may be responsible for an error of only up to 5%. The Button Sampler has a higher sampling efficiency than the 37-mm cassette for large inhalable particles. The Button Sampler's efficiency curve more closely matches that of the international convention for inhalable particles.[8] It has, therefore, been concluded that the lead mass measurements during active lead-based paint abatement with the Button Sampler are more precise than those with the 37-mm cassette (the concentration data with the Button Sampler were higher than those measured with the 37-mm cassette). In environments with large inhalable aerosol particles, the Button Sampler appears more accurate than the 37-mm cassette. The information presented in Figure 3 explains why the sampler's regression slope value for dry scraping (see Figure 1) was the highest (k = 1.5) of all the abatement methods. During dry scraping abatement, a higher percentage of large inhalable

particles was aerosolized, and the Button Sampler sampled these large inhalable particles more efficiently than the 37-mm cassette.

Cumulative Lead Mass Distributions during Final Cleaning

Figure 4 presents cumulative lead mass distributions during final cleaning, calculated from particle size distributions determined by microscopic analysis of the Button Sampler filters. The same assumptions were made as for the data presented in Figure 3. The data presented in Figure 4 were obtained while implementing the entire HUD-recommended final cleaning procedure: the debris was wetted and swept, the plastic sheets were wetted and folded, after that the HEPA vacuuming / wet wash / HEPA vacuuming cycle was applied. In the present study, the HUD-recommended final cleaning was performed after completing various methods of active abatement (dry sanding and scraping, and wet scraping using the sponge or spray wetting technique). As seen, the experimentally determined curve for final cleaning after sponge wet scraping is very close to the one for final cleaning after spray wet scraping. Similarly, the curve for final cleaning after dry sanding is close to the one for cleaning after dry scraping. The data in Figure 4 indicate that the median mass size is about 7 μm for final cleaning after wet scraping and about 10 μm for cleaning after implementation of dry abatement methods.

During the final cleaning after wet scraping abatement about 85% of the lead mass was contained in particles smaller than 15 μm. This is the highest percentage among all of the analyzed experimental conditions. For particles smaller than 15 μm, the Button Sampler and the 37-mm cassette have essentially the same sampling efficiency.[8] This explains why the regression slope ($k = 1.08$) for final cleaning after wet scraping was closer to 1 than the slopes found for other experimental conditions investigated in the study.

Several particles larger than 100 μm were observed on the filters sampled during final cleaning. While the lead airborne concentration during final cleaning was less than 1/20th that during active abatement, the percentage of particles larger than 100 μm was higher for final cleaning than for active abatement. In some samples collected during final cleaning, up to 10% of the sampled mass resulted from particles >100 μm . However, for final cleaning performed after wet active abatement, the particles larger than 100 μm contributed less than 1% of the total mass. Particles of 100 μm diameter (with unit density) gravitationally settle at a velocity of about 26 cm/s, i. e., in typical room these particles are eliminated from indoor air within seconds. Thus, the presence of these large particles during final cleaning performed after the required 1 hour waiting time indicates that they aerosolized during final cleaning itself.

The cleaning work task responsible for the aerosolization of large particles was identified in a separate set of experiments in which different sweeping procedures were performed after dry abatement. These included wet and dry dust sweeping techniques and the absence of sweeping. With the exception of this modification, the other parts of the final cleaning procedure were identical and included the standard HEPA vacuuming / wet wash / HEPA vacuuming cycle. Comparison of the particle size distributions obtained through microscopic analysis indicates that the count of particle larger than 40 μm decreased by 2/3rd when sweeping was not included during final cleaning as compared to the case when the sweeping was performed. Particles larger than 80 μm were not observed through microscopic analysis after experiments that excluded sweeping, while in experiments with sweeping after dry abatement, particles up to 180 μm were detected. This finding is supported by the increase in aerosol concentration during the sweeping work task, measured with a real-time direct reading optical particle counter sampling the air in the central area of the chamber.[24] The

particles larger than 40 μm contributed up to 15% of all the mass sampled during final cleaning. The overall time for sweeping was less than 5 minutes, which is approximately one twelfth of the time for the final cleaning procedure. As the majority of the particles larger than 40 μm were sampled during the short sweeping work task, the workers' lead exposure during sweeping is more than twice the exposure averaged over the entire final cleaning cycle. This indicates that sweeping is the most hazardous part of the final cleaning procedure.

Workers' Lead Exposure during Lead Abatement

In general, worker lead exposures during lead-based paint abatement are highly variable. Personal lead exposures can vary significantly even among workers in the same job category and work area. Therefore, OSHA recommends air sampling at work sites for each contractor (however, it is not necessary for the same contractor to perform air sampling on every job, if the work is similar). At the same time, based on the exposures measured for the majority of investigated cases, HUD recommends for initial work planning the "residential lead hazard control assumed exposures for OSHA's task-related triggers",[17] adapted from the OSHA interim final rule for lead in the construction industry (29 CFR 1926.62).[4] For example, this classification determines manual scraping of lead-based paint as a work task with potential exposure from 50 to 500 $\mu g/m^3$. A half-facepiece air purifying respirator (APR) with an assigned protection factor (APF) of 10 should be sufficient for the protection from that exposure level.

The American Conference of Governmental Industrial Hygienists (ACGIH) recommends excursion limits for those Threshold Limit Value - Time-Weighted Averages (TLV-TWAs) that do not have Short-Term Exposure Limits (lead is that type of substance): "...excursions in worker exposure level may exceed 3 times the TLV-TWA for no more than a total of 30 minutes during a

workday, and under no circumstances should they exceed 5 times the TLV-TWA, provided that the TLV-TWA is not exceeded".[5] Thus, the short-term exposures (less than 30 min) during active abatement in this study should be compared to a value of 5 times the respirator protection level. For the air monitoring results obtained during final cleaning (the sampling time was about 1 hour), the airborne lead concentrations may be extrapolated to the entire work shift and analyzed against 8 hour exposures. Thus, the standard respirator protection level should be used for lead exposure analyses during final cleaning.

Figure 5 presents the short-term exposures measured with the Button Sampler during active abatement and final cleaning exposures with the sample time equal to the length of the work task (typically more than 1 hour). The 90% confidence interval for the measured exposures is marked by error bars. Thus, the upper values of the 90% confidence interval represent exposure levels which are expected not to be exceeded in 95 % of the cases for each specific abatement activity. The respirators' protection levels are marked as dashed horizontal lines. They are 500 $\mu g/m^3$ (50 $\mu g/m^3$ TLV-TWA x 10 APF) for the half-mask respirator and 2,500 $\mu g/m^3$ (50 $\mu g/m^3$ TLV-TWA x 50 APF) for the full-facepiece APR and powered air purifying respirators (PAPR) [4, 25], respectively.

The average exposures observed in this study for dry scraping and dry non-HEPA sanding are very close to each other (while they are placed in different lead exposure categories in the OSHA task-related triggers). The geometric mean of short-term lead exposures during dry scraping is more than ten times the protection level of a half-facepiece APR and more than twice the protection level of a full-facepiece APR and PAPR. The geometric mean of short-term lead exposures during dry sanding is more than three times the protection level of full-facepiece respirators. The upper 90% confidence levels of exposures for both methods are more than ten times higher than the full-facepiece respirator

protection level. As the short-term exposure should never exceed five times of the TVL-TWA concentration, the data obtained in this study on workers' short-term exposures during dry scraping and dry non-HEPA sanding indicate that the 5 times protection level of a full-facepiece PAPR may be exceeded for short times during dry active abatement. These data may be an argument for the prohibition of dry scraping during lead abatement or the strict limitation of its use for a small specified area per dwelling unit.

For wet scraping, the geometric mean of the lead mass concentration was only slightly higher than the protection level of a half-facepiece APR. But the upper 90% confidence level is more than five times higher than the protection level of a half-facepiece APR. The upper 90% confidence level does not exceed 3 times the protection level of a full-facepiece APR or PAPR.

This study shows that variations of workers' lead exposure during lead-based paint abatement may be so high that the workers' protection should not be solely based on the 8-hour TWA airborne lead concentration values. Thus, it is suggested that, in addition to determining the 8-hour TLV-TWA values, the short-term personal exposure be monitored during the most intense periods of lead abatement.

The authors believe that real time monitoring of the aerosol concentration at lead abatement sites is the simplest way to identify and estimate abnormally high levels of workers' short-term lead exposure. Based on conservative assumptions about the density of airborne particles and the lead percentage in these particles [26] it is possible to use the real-time data on airborne dust mass for estimations of short-term lead exposures.

For final cleaning with dust wetting before sweeping and plastic removal after wet scraping, the observed lead exposures (see Figure 5) were relatively low (the 90% confidence level is only about twice higher than the lead TLV-TWA), well below the protection level of a half-facepiece APR. For final cleaning with

implementation of the HUD-recommended wetting procedures after dry paint removal, the 90% upper confidence level was twice the protection level of a half-facepiece APR. Dry dust generated during dry active abatement may cause higher workers' exposures not only during that activity, but also later during cleaning, even if wet engineering control is applied during cleanup. Strict limitation of the area that may be abated by dry scraping would result in a decrease of the amount of airborne and settled leaded dust during abatement.

The above discussion is based on the respirator protection factor assigned on the basis of fit tests with sub-micron test particles.[25] However, the aerosol particles in the size range from 10 to 100 μm are less penetrating than the submicron particles. While an occasional particle in this size range may penetrate through faceseal leak, none will penetrate through the filter material.[27] As the majority of exposure during active lead abatement is due to particles larger than 10 μm (Figures 3 and 4), worker protection with a half-mask APR is likely to be sufficient for the majority of lead-based paint abatement work tasks. This suggests future experiments which measure the aerosol concentrations inside and outside the respirator mask during the performance of lead abatement tasks to clarify the situation.

CONCLUSIONS

Air monitoring during lead-based paint abatement was performed in this study with two types of personal samplers. The Button Sampler, which relatively well follows the ACGIH/CEN/ISO personal sampler inhalable particles sampling efficiency convention, consistently indicated higher values of exposure than the standard closed-face 37-mm cassette. For active abatement, airborne particles > 20 μm contributed up to 70% of the total lead mass (as sampled by the Button Sampler). The airborne lead concentrations measured with the Button Sampler

were up to 50% higher than measured with the standard 37-mm cassette. For air monitoring during final cleaning the samplers' regression coefficient had a lower value (k = 1.25) than for air monitoring during active abatement (k = 1.34). For final cleaning with utilization of wet engineering control, the difference between the samplers' data was only about 8 %. Overall, the Button Sampler proved to be a better monitor for the determination of the workers' lead exposures, because it samples the broad particle size distributions during LBP abatement more efficiently, especially large inhalable particles.

This study suggests that in addition to 8-hour TWA lead exposure measurements short-term exposure measurements be considered as well during the most intense periods of lead-based active abatement. The geometric means of short-term workers' exposures during wet scraping, dry scraping, and non-HEPA machine sanding were 820, 5,860, and 8,330 $\mu g/m^3$, respectively. For dry scraping and non-HEPA machine sanding, the estimated exposure values were more than five times (ACGIH recommended absolute excursion limit on short-term exposures) higher than the half-facepiece APRs protection level of 500 $\mu g/m^3$. The 90% upper confidence level for wet scraping also exceeded the half facepiece APR protection level more than five times, leaving at least 5% of wet scraping abatements beyond the assigned protection.

During final cleaning with wet engineering control after dry active abatement, the observed exposures were about four times higher than those for final cleaning with wet sweeping after wet scraping active abatement. However, when wet sweeping was implemented during final cleaning after dry active abatement, the variations in exposure were very high (geometric standard deviation of 4.7 was observed). It put the upper 90% lead exposure confidence level higher than the protection level for half-facepiece air purifying respirators. Microscopic analysis of the collected samples identified leaded dust sweeping as

the most hazardous task of final cleaning (with the level of lead exposure about twice higher than the exposure average during the entire final cleaning procedure).

This study stresses the need for addressing the short-term exposures during the most intense periods of lead abatement, which may be several times higher than the 8-hour average lead exposures. As the majority of lead exposure during active abatement came from large airborne particles, current respirator protection standards may be quite sufficient, since the large particles do not penetrate through the filter material and may only occasionally infiltrate through a faceseal leak, depending on respirator wear.

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Table 1. Lead mass concentrations for different work practices during active abatement

Active abatement work task	Total number of experiments	Measured lead mass concentration[a], $\mu g/m^3$	
		Button Sampler	37-mm Cassette
Wet Scraping (sponge & spray methods)[b]	6	820 (2.24)	530 (2.88)
Dry Scraping	10	5,860 (3.64)	3,550 (3.47)
Dry non-HEPA Sanding	8	8,330 (1.87)	6,300 (2.06)

[a] geometric mean (geometric standard deviation)
[b] abatement method recommended by HUD

Table 2. Lead mass concentrations for different work practices during final cleaning

Abatement work task	Total number of experiments	Measured lead mass concentration[a], $\mu g/m^3$	
		Button Sampler	37-mm Cassette
Dry sweeping of debris followed by HEPA / wet mopping / HEPA cycle (after dry scraping and dry sanding)	4	318 (2.03)	239 (1.79)
No sweeping before HEPA / wet mopping / HEPA cycle (after dry scraping and dry sanding)	4	139 (1.49)	81 (2.79)
Wet sweeping of debris followed by HEPA vacuuming without wet mopping (after dry scraping and dry sanding)	4	179 (1.35)	175 (1.31)
Wet sweeping of debris followed by HEPA / wet mopping / HEPA cycle (after dry scraping and dry sanding)	4	90 (4.72)	82 (4.7)
Wet sweeping of debris followed by HEPA / wet mopping / HEPA cycle (after wet scraping)[b]	6	23 (2.60)	22 (2.35)

[a] geometric mean (geometric standard deviation)
[b] work practice recommended by HUD

FIGURE CAPTIONS

Figure 1. Lead mass concentration correlation between measurements performed with the Button Sampler and the 37-mm closed-face cassette for different active lead-based paint abatement methods.

Figure 2. Lead mass concentration correlation between measurements performed with the Button Sampler and the 37-mm closed-face cassette during final cleaning for different active abatement methods.

Figure 3. Cumulative lead mass distributions, as measured with the Button Sampler for different methods of active lead-based paint abatement.

Figure 4. Cumulative lead mass distributions, as measured with the Button Sampler during final cleaning for different active abatement methods.

Figure 5. Protection levels of different respirator types and airborne lead concentrations for different lead-based paint abatement work tasks. The error bars represent control exposure levels, which are expected not to be exceeded in 95 % of the specific abatement activities: A) dry scraping; B) dry sanding; C) wet scraping; D) wet final cleaning after dry active abatement; E) wet final cleaning after wet active abatement.

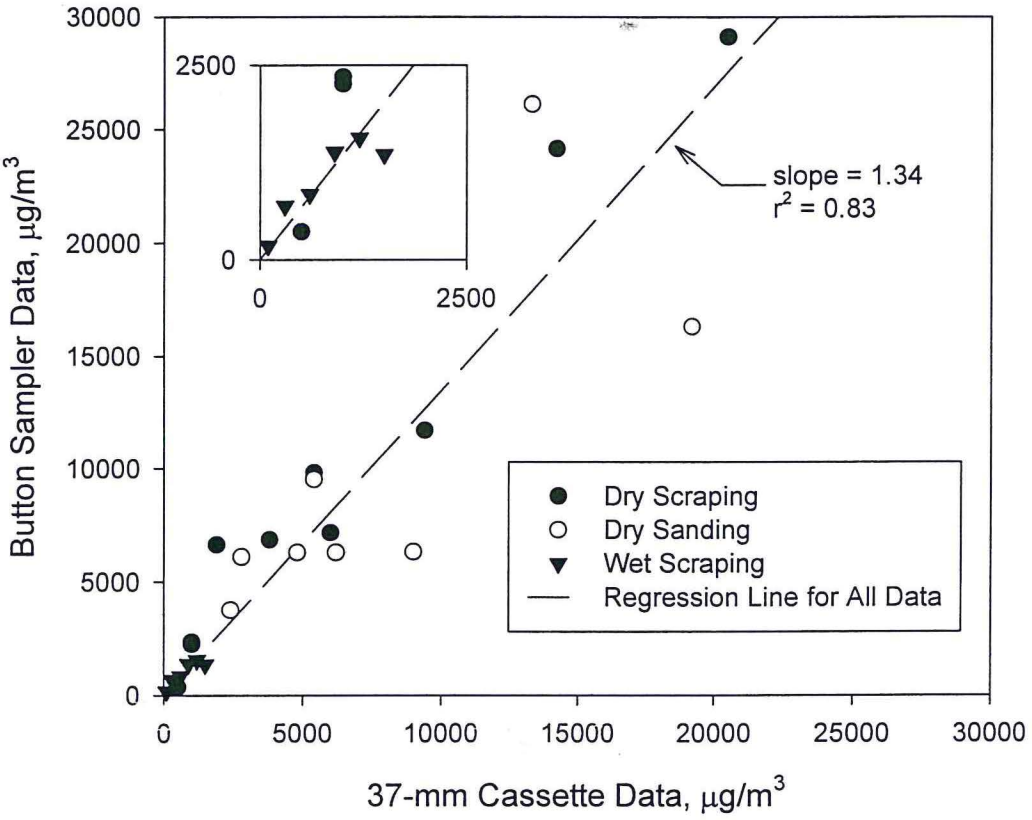

Figure 1. Lead mass concentration correlation between measurements performed with the Button Sampler and the 37-mm closed-face cassette for different active lead-based paint abatement methods.

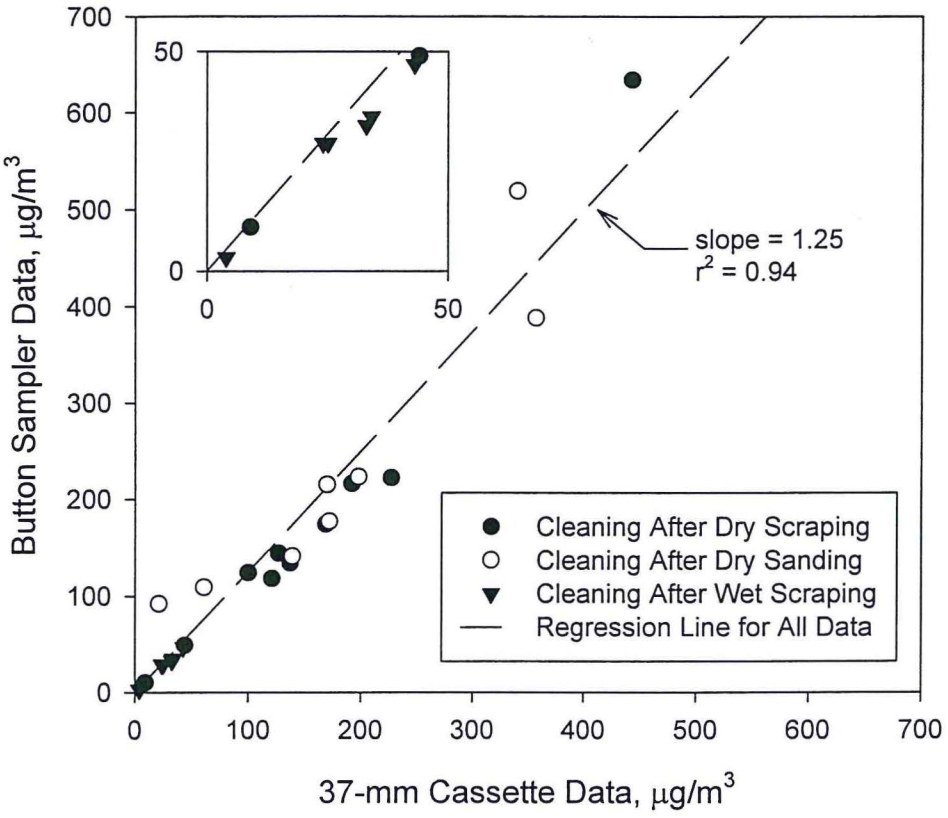

Figure 2. Lead mass concentration correlation between measurements performed with the Button Sampler and the 37-mm closed-face cassette during final cleaning for different active abatement methods.

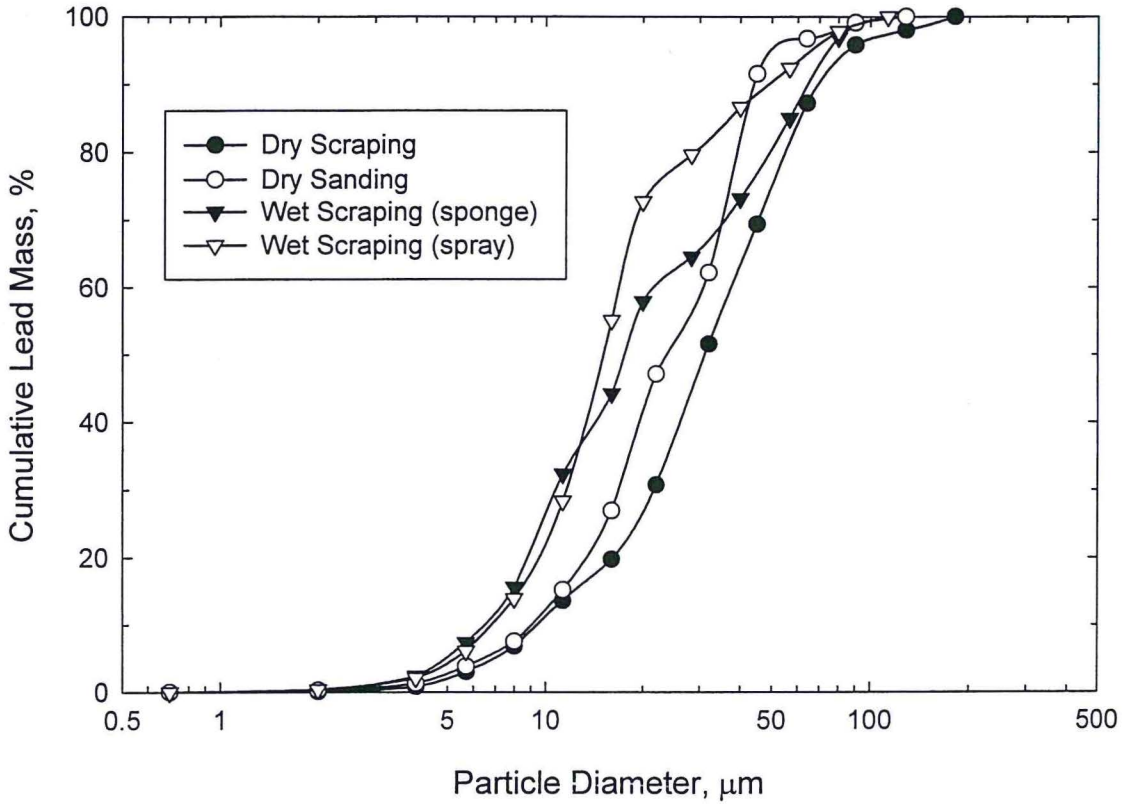

Figure 3. Cumulative lead mass distributions, as measured with the Button Sampler for different methods of active lead-based paint abatement.

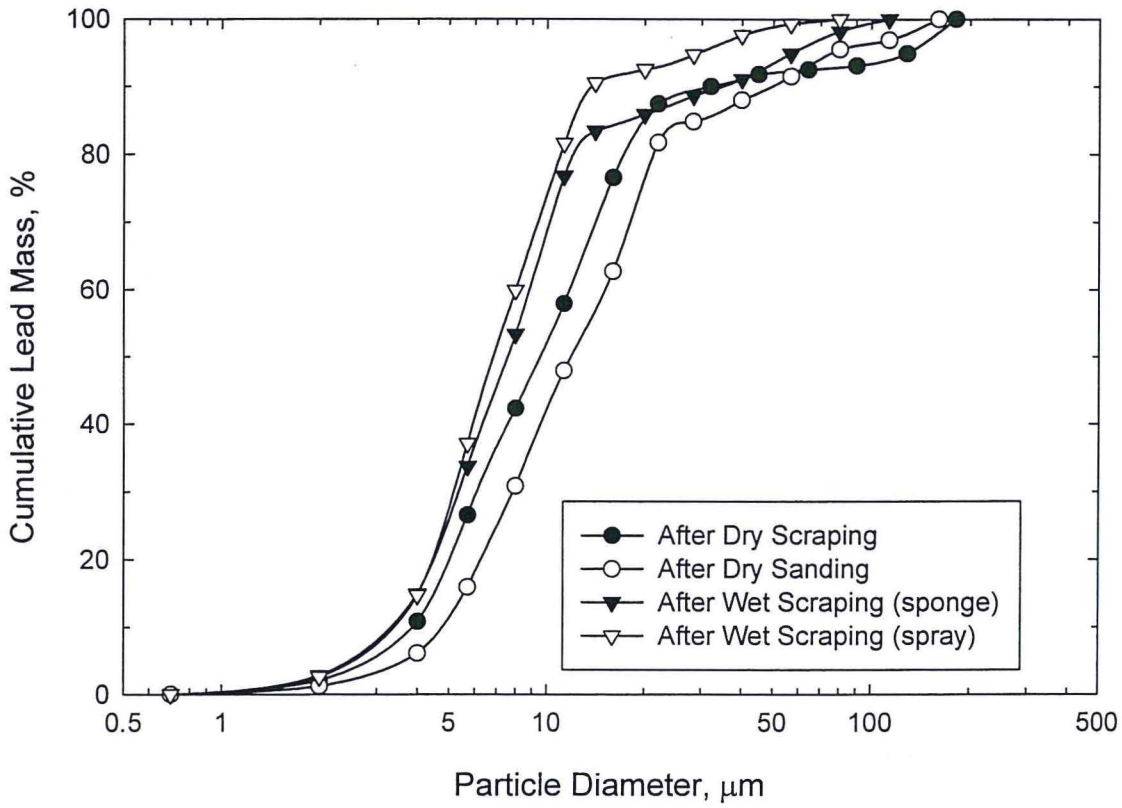

Figure 4. Cumulative lead mass distributions, as measured with the Button Sampler during final cleaning for different active abatement methods.

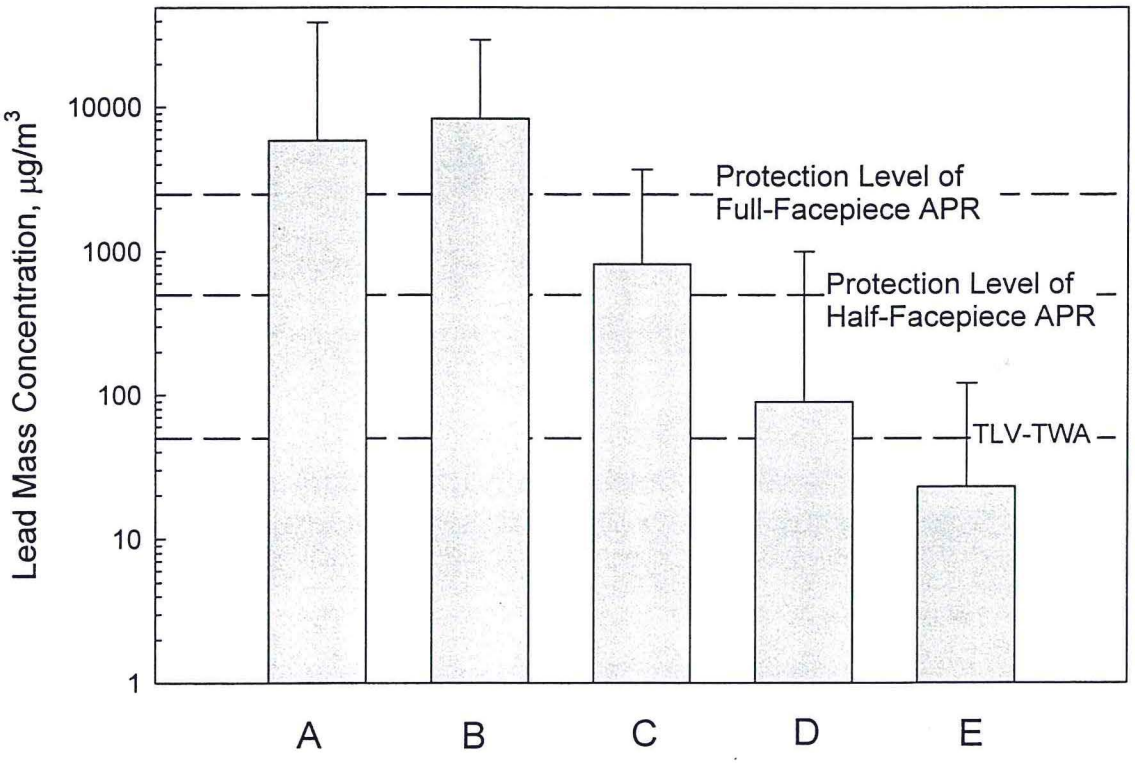

Figure 5. Protection levels of different respirator types and airborne lead concentrations for different lead-based paint abatement work tasks. The error bars represent exposure levels, which are expected not to be exceeded in 95% of the specific abatement activities: A) dry scraping; B) dry sanding; C) wet scraping; D) wet final cleaning after dry active abatement; E) wet final cleaning after wet active abatement.