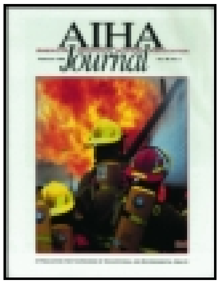

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Particle Settling After Lead-Based Paint Abatement Work and Clearance Waiting Period

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This study investigated the evolution of airborne particle concentration and size distribution following abatement work in a controlled environment utilizing direct real-time particle monitoring and used it to project potential lead loadings as those particles settle. An 860 ft^3 environmental test chamber with sophisticated ventilation and air purifying systems was built. Wooden doors with lead-based paint were dry sanded or scraped to generate the highest feasible airborne lead concentrations. Size-fractional airborne particle concentrations decreased exponentially with time in all tests, even with no air exchange, consistent with the stirred model of constantly mixed air, which predicts longer settling than for tranquil settling. Very low levels of air mixing generated by temperature gradients and initial room air turbulence affected particle settling. About 90% of airborne lead mass settled within 1 hour after active abatement, before final cleaning began. During the second waiting period of 1 hour, which followed cleaning of the floor, additional dust settled so that the additional potential lead loading from remaining airborne lead was less than 20 μg/ft^2. For this worst case scenario, the underestimate of the lead loading done by the clearance sampling did not exceed about 30%. For more realistic conditions, the underestimates are projected to be much lower than the new 40 μg/ft^2 Housing and Urban Development (HUD) clearance standards for floor dust lead. These results were obtained for the first waiting period (between the end of active abatement and the beginning of cleaning) of 1 hour, as recommended by HUD guidelines. Thus, this study demonstrates no need to increase either the first or second waiting period.

Keywords: abatement, clearance, concentration, dust, lead-based paint

It is estimated that American housing stock contains more than 3 million tons of lead in the form of lead based-paint.(1) Although the use of lead-based paint in residential environments was banned in 1978, about 60 million U.S. homes still contain leaded paint(2) that deteriorates and contaminates indoor surfaces. When ingested or inhaled, the leaded dust causes various health problems,(3) especially for children.(4–8) For this reason, hundreds of millions of dollars have been spent in the United States for lead abatement.(9) Clearance testing of lead dust loading on horizontal surfaces after lead-based paint abatement in most U.S. pre-1978 residences and child-occupied facilities is required as of March 1, 2000, nationwide.(10) Clearance testing also is required for specified interim control measures on certain federally owned and federally assisted housing as of September 15, 2000.(11)

A considerable amount of dust may become airborne during abatement work.(12) After lead-based paint abatement (e.g., removal, encapsulation or enclosure),(10) the dust is allowed to settle for a period of time before various cleaning procedures are undertaken.(13) This time is called here the first waiting period. After cleaning is completed, some time is allowed again for gravitational settling of the remaining dust. Following this second waiting period, visual inspection of the completeness of the work and a clearance test are performed on selected horizontal surfaces (floors, window sills, and/or window troughs).(13) The clearance test is a standard procedure designed to assess lead loading (mass/

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area concentration) levels on these surfaces after abatement; the loadings may be elevated if the dust is not properly cleaned up.[14,15] This clearance procedure, however, allows only the detection of leaded dust that has settled at the time of clearance sampling. Particles that are still airborne at that time may settle later and recontaminate the cleaned indoor surfaces. Therefore, an accurate assessment of accumulation of lead on horizontal surfaces during the second waiting period—between completion of cleanup and clearance—is especially important.

Issued in 1990, the U.S. Department of Housing and Urban Development (HUD) *Interim Guidelines for Hazard Identification and Abatement in Public and Indian Housing* recommended 24 hours as the minimum duration for each of the two waiting periods to allow sufficient settling of airborne lead-contaminated particles.[16] The current (1995) HUD *Guidelines for the Evaluation and Control of Lead-based Paint Hazards in Housing* (HUD guidelines) recommend 1 hour between active abatement and final cleanup and 1 hour between cleanup and clearance testing.[13] Referring to the second waiting period, the current HUD guidelines specifically indicate that "clearance dust sampling should be performed no sooner than 1 hour after completion of the final cleanup to permit airborne leaded dust to settle."[13] The rationale given for this revised recommendation is that "the additional amount of leaded dust that would settle onto floors after 1 hour is negligible."[13] This estimation is based on theoretical calculations of the gravitational settling velocity of 5 μm particles in a perfectly still environment (termed as "tranquil settling" [17,18]). However, the tranquil settling model may not describe particle motion in abatement sites adequately, because cracks and holes in walls and windows, temperature differentials between indoor surfaces, and other factors may cause air movement.

The goal of this study was to assess the effects of varying the second waiting period on potential surface lead loading. The strategy used in this study was to obtain experimental data on the time evolution of the airborne concentration of particles aerosolized during lead abatement in an indoor environment. The rate of decrease in airborne lead concentration was determined primarily for two paint removal methods (dry scraping and dry machine sanding) selected to produce high airborne dust levels.[19] Although wet scraping also was used in two selected tests for comparison purposes, most of the tests were conducted using dry paint removal methods without the normal dust control measures of wetting (for scraping) or high efficiency particulate air (HEPA) filtration local exhaust ventilation[13] (for sanding). This approach provided stringent experimentation conditions. The data on the changes in concentration of airborne particles were obtained with a direct-reading particle size spectrometer, whereas the lead mass fractions in specific particle size ranges were acquired through sampling by a cascade impactor, followed by atomic absorption analysis of lead. Based on these data, the effects of waiting periods on projected settled lead loadings were determined, leading to recommendations for waiting period needed between the end of cleanup and the start of clearance testing.

EXPERIMENTAL DESIGN AND MATERIALS

Test Chamber

Figure 1 is a schematic of the environmental test chamber designed and built for this study in the Department of Environmental Health at the University of Cincinnati. The dimensions of the chamber are L × W × H = 149″ × 96″ × 104″ ~ 3.78 m × 2.44 m × 2.64 m, with a total volume of about 860 ft^3 ~ 24.3 m^3 that represents the size of a typical residential room. An air lock room that separated the chamber from the surrounding laboratory area prevented contamination of the laboratory air during entry into the chamber.

The airflow was supplied to the chamber through a closed-loop ventilation system with HEPA air-purifying units. Each of the two air-purifying units consisted of a prefilter and a HEPA filtration unit (AstroCel® I Type D, American Air Filter International Inc., Louisville, Ken.). A high-pressure direct-drive blower (model 2C940, Dayton Inc., Niles, Ill.) with a maximum capacity of approximately 145 ft^3/min (4.11 m^3/min) was used in the system. Air was supplied through 4- and 3-inch pipes. A total of 19 slot gates (15 gates for the air supply and 4 gates for the air exhaust) were installed on the vertical walls of the test chamber. The left-side wall (air lock side) had six supply gates: three pairs at 12, 52, and 82 inches, respectively, above the floor. The right-side wall had nine gates: three at each of the same three heights. The back wall, on which an abated object was mounted, had no ventilation slots. The area near the back wall is labeled in Figure 1 as "work area." The wall opposite to the work area had four exhaust gates: two pairs at 24 and 79 inches above the floor. Each slot could be operated independently of the others in the open or closed position. This allowed operating the chamber using any possible combination of slots and thus creating various directions of air current in the chamber. The air exchange rate could be controlled from 0 to 10 air exchanges per hour. When using air ventilation, the pressure in the chamber is kept about 0.5 mm w.g. (5 Pa) below the pressure in the surrounding laboratory space.

The ventilation and air purifying system was evaluated by measuring the air velocities through the air supply gates and inside the air supply and exhaust pipes with a VelociCheck thermo-anemometer (TSI Inc., St. Paul, Minn.) and with pitot tubes (model 3T086, Dwyer Instrument, Inc., Michigan City, Ind.) connected to Magnehelic differential pressure gauges (Dwyer Instrument, Inc.). All gaps and cracks in the chamber were sealed. The interior chamber walls were drywall painted with lead-free paint to prevent electrostatic effects. The lead-based paint removal (active abatement) was performed on the object mounted on the back wall of the chamber. The particles released during paint removal were measured at one or two of three locations, depending on the test objective: the location M_{SOURCE} (in the work area) was chosen to measure the particles aerosolized from the lead-based paint surfaces immediately after their release from the source; the locations M_{CENTER} (in the center of the chamber) and $M_{FAR\ WALL}$ (1 ft from the wall opposite to the work area) were chosen to be sufficiently far from the source to monitor dust settling in the chamber on termination of active abatement. In all three locations the airborne particles were sampled as close to the floor as was allowed by the vertical dimensions of the devices used for aerosol measurements: 4 inches for the Grimm monitor and 7 inches for the Andersen impactor.

Aerosol Source

Wooden doors of a standard height, ranging from 1.9 to 2.2 m, covered with lead-based paint were obtained for this study from five lead abatement sites in the inner city of Cincinnati. Both sides of each door were characterized for lead paint content by X-ray fluorescence (XRF) using a NITON-700 instrument (NITON Inc., Bedford, Mass.). Doors with XRF readings higher than 1 mg/cm^2, the U.S. federal government lead-based paint level, [1] were chosen for the study. Overall, 17 doors with XRF readings

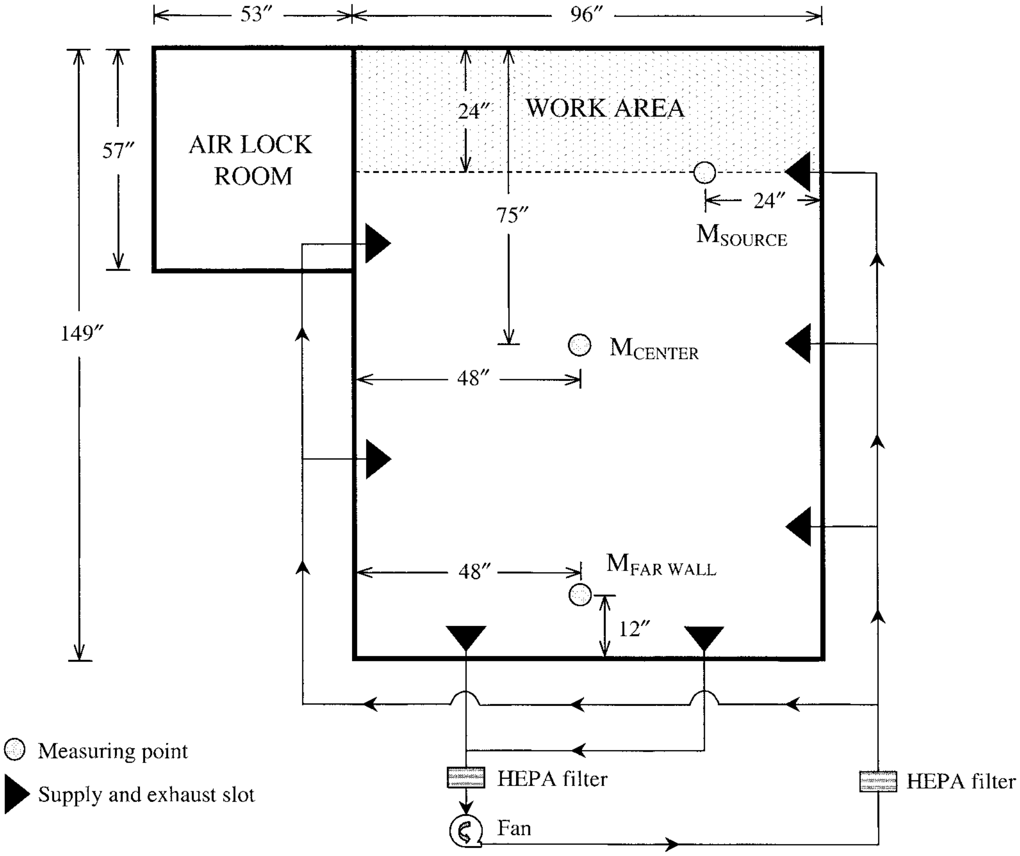

FIGURE 1. Test chamber (top view). Distances are given in inches.

ranging from 1.4 to 40.5 mg/cm^2 were used for active abatement in the test chamber. The XRF instrument was operated in accordance with its HUD/Environmental Protection Agency performance characteristic sheet.(20) Its software was calibrated by the manufacturer up to 70 mg/cm^2. It was noted, however, that the measurement reporting range extended higher than the single highest paint-lead loading of the samples in the archive used to prepare the performance characteristics sheet,(21) 30.11 mg/cm^2, as analyzed by a modified NIOSH Method 7082.(22) XRF readings obtained with each door were averaged and a standard deviation that represented spatial nonuniformity was calculated for each door.

Aerosolization Methods

Dry scraping and machine sanding were used as lead abatement methods in most of the tests because they provide a considerable amount of airborne leaded dust (higher than other particle removal methods).(19) In the preliminary study, two tests also were run using wet scraping. However, as the dust aerosolization rate for the wet method was lower by a factor of about 3, preference was given to the dry paint removal methods to generate aerosols sufficiently concentrated for intensive data analysis.

It is acknowledged that HUD recommends against dry scraping for lead-based paint abatement(13) and prohibits its use in certain federally owned and federally assisted housing(11) except for limited surface areas and near electrical outlets. However, preliminary experiments showed that lead-based paint removal from these relatively small areas can produce rather high airborne lead concentration levels. HUD recommends that dry machine sanding be performed using HEPA filter-equipped sanders connected to a local exhaust ventilation system placed under partial vacuum and requires such ventilation for work covered under its regulations. In the present tests, the local air exhaust ventilation system was disabled, thus simulating failure of proper use of the HEPA sander (such as may result from a clogged vacuum hose or overloaded filter).

Two scrapers, one with a 2½-inch and another with a 3-inch scraping blade, were used for scraping (Red Devil Inc., Union, N.J.). When applying wet scraping, a sponge was employed to wet the door surface. Two sanders (Model 7447, Black and Decker Inc., Towson, Md.) with sanding belts (3″ × 21″, medium 80, 3M Inc., St. Paul, Minn.) were used for sanding.

Experimental Procedure

Before each test, one door was randomly chosen from the stock of preselected doors, moved into the chamber, unwrapped, and mounted vertically onto the chamber's back wall. The air in the chamber was then cleaned for 30 min with the ventilation and air-purifying system operated at 10 air exchanges per hour. A specific active abatement method (scraping or sanding) was then used to remove leaded paint from the door. The height of the door determined the maximal height for abatement work. The scraper blades and the sanding paper of the machine sanders were replaced with new ones before every new test. The abatement was task-oriented: on each door being abated the paint was removed from a surface area of about 15 ft^2 (1.4 m^2) by two workers working intensively together. The active abatement time was in the range from 10 to 20 min; variations reflected the initial surface conditions of the door being abated. This procedure allowed creation of a sufficiently high concentration of airborne leaded dust in each experiment. The workers left the chamber after the active abatement task was completed.

The airborne particle concentrations and size distributions in the chamber were monitored with an optical particle-size spectrometer (model 1.108, Grimm Technologies Inc., Atlanta, Ga.) operated at a flow rate of about 0.0424 ft^3/min (1200 cm^3/min). The airborne particles were measured in real time. The cumulative number of particles was recorded every minute in 15 particle size channels, ranging from particle diameter, d_p, of 0.3 to over 20 μm. The last channel (>20 μm) was excluded from the analysis because preliminary experiments showed that it did not count a statistically significant number of particles immediately after active abatement. About 15 min after active abatement had ended, no particles were detected in this channel because all of these large particles had presumably settled by then. The first channel of the particle counter (0.3–0.4 μm) also was excluded as it represents the particle sizes near the instrument's threshold of detection. Thus, only data from 13 channels in the particle size range of 0.4 to 20 μm were analyzed.

In the preliminary experiments, two Grimm optical particle-size spectrometers were operated in parallel at M_{CENTER} and $M_{FAR\ WALL}$ during and after active abatement to determine whether the data were affected by the measurement location. No significant difference was found in their readings. Thus, only one instrument, located at M_{CENTER}, was used in the subsequent tests.

In the first set of experiments, the time evolution of the airborne particle concentration and size distribution in the chamber was monitored for about 15 hours following active abatement. For each of the two abatement methods, the tests were conducted at three air exchange rates: 0 (no air exchange), 2, and 10 air exchanges per hour.

In the second set of experiments, active abatement was followed by 1 hour of dust settling (first waiting period) after which a cleaning procedure was applied. The latter was a shortened version of the HUD-recommended cleanup procedure.(13) This approach simulated a worst case scenario in which the airborne lead concentration after cleaning had the highest possible level, thus projecting the longest second waiting period. The dry cleaning was conducted by one worker for 30 min. When scraping was used as the abatement method, the large paint chips on the floor were dry swept without the HUD-recommended water misting, and the swept material was then wrapped in plastic bags. The remaining dust and small debris were removed by a HEPA vacuum cleaner (model 767, WAP International Inc., Anaheim, Calif.). The dust produced during sanding did not contain particles of very large size that required sweeping. Therefore, only HEPA-vacuuming was performed after sanding. It was performed on all surfaces: floor, ceiling, and walls. The floor was HEPA-vacuum cleaned twice: in the beginning and at the end of the cleaning. Thus, contamination of the floor could occur only if leaded particles settled on the floor later. In this set of experiments the monitoring of the airborne particle concentrations covered the first waiting period (1 hour after active abatement), the cleaning procedure (30 min), and then about 14 hours after the cleaning was completed. The monitoring time was chosen to be considerably longer than 1 hour, the present standard for the second waiting period,(13) for use in assessing the potential need for a longer period.

After each experiment, all the surfaces in the test chamber were cleaned following the HEPA/wet-wash/HEPA cleaning procedure.(13) The air lock room was cleaned using the same procedure. Finally, the air in the chamber was purified by operating the ventilation and air-purifying system for 30 min at 10 air exchanges per hour.

A separate set of experiments was performed to characterize the leaded particles. The particles aerosolized during lead-paint removal were collected by a seven-stage Andersen Cascade Impactor (Andersen Instruments Inc., Smyrna, Ga.) with cut sizes of 0.43, 0.65, 1.1, 2.1, 3.3, 4.7, 7.4, and about 10.4 μm. The impactor was placed at M_{SOURCE} and was operated at a flow rate of 1 ft^3/min (28,300 cm^3/min). The airborne particles were collected on 81-mm glass fiber filters (Andersen Instruments Inc.) on each of the seven impactor stages. Based on preliminary measurements, the overall collection time was chosen to be at least 24 hours to allow collection of an amount of dust sufficient for fractional lead analyses. The leaded dust collected by each stage was analyzed by flame atomic absorption spectrometry (FAAS) (NIOSH Method 7082). A Perkin-Elmer 5000 spectrometer (Perkin-Elmer Inc., Norwalk, Conn.) was used and found to be sufficiently accurate for most analyses. Samples with lead loading lower than the FAAS limit of detection (LOD = 5 μg) were further analyzed by a more sensitive method, a graphite furnace atomic absorption spectrometry (GFAAS) (NIOSH Method 7105). For analyses by GFAAS, a Perkin-Elmer 5100 spectrometer was utilized (LOD = 0.05 μg). Each experiment was performed in triplicate.

During the experiments the workers (investigators) used personal protective equipment, including safety goggles, gloves, disposable protective suits with hoods and boot covers (DuPont Inc., Wilmington, Del.), and half-mask air-purifying respirators with HEPA filter cartridges (North Inc., Cranston, R.I.). The workers' training included standard industrial hygiene and safety procedures and was approved by the Institutional Review Board.

RESULTS AND DISCUSSION

Airborne Particle Concentration

The total particle counts in the monitored size range of $d_p = 0.4$ to 20 μm were measured by two identical Grimm optical particle counters located at M_{CENTER} and $M_{FAR\ WALL}$. Since it was anticipated that the airborne particle concentration might change from the work area toward the opposite wall, the measurement points were chosen along the chamber median line in that direction. Figure 2 shows the total airborne particle concentrations measured at these two locations every hour during a 15-hour period following active abatement. The data sets correlate well: $\beta = 0.990$, $r = 0.999$, $p < 0.001$, suggesting that the particles were distributed evenly in the chamber. This finding allowed the investigators to conduct further tests with only one optical particle counter, which was located in the center of the chamber.

Figure 3 shows how time duration after active abatement affects the particle size distribution within the monitored particle size range (the area limited by the dashed lines). The curves represent the particle size distributions recorded at four time points during the 15-hour period after scraping (Fig. 3a) and sanding (Fig. 3b): $t = 0$ (end of active abatement), 1, 5, and 15 hours. No cleanup was conducted during this set of experiments. Figures 3a and 3b each represent an individual experiment. Repeated measurements showed similar results. It is seen that the particle size

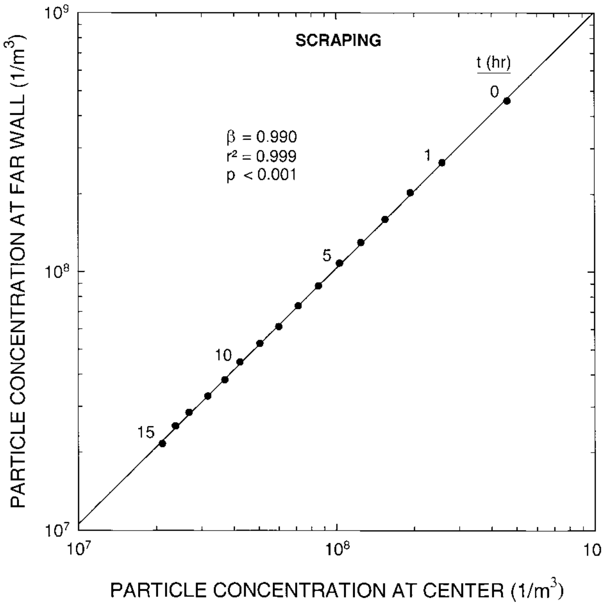

FIGURE 2. **Correlation between the total particle concentrations ($0.4 < d_p < 20$ µm) measured at the center of the chamber (point M_{CENTER}) and near the wall opposite to the abatement area (point $M_{FAR\ WALL}$). The experimental points represent the concentrations of particles generated by dry scraping, measured every hour from t = 0 to 15 hours.**

distribution changed substantially, primarily due to the gravitational settling of large particles. For example, more than 95% of 10 µm particles settled during the first hour in both cases. The particle size distributions produced by scraping and sanding show similar trends, except that the percentage of submicron sized particles aerosolized during sanding was higher.

Figure 4 shows the data from the same experiments presented as nondimensional fractional particle concentrations versus the time passed after the end of active abatement. The nondimensional fractional particle concentration is defined as a ratio of the particle concentration in a given size range determined at a given time to the initial concentration in the same size range determined at the end of active abatement (at the recorded time t = 0). The ratio is expressed in percentage points. The direct reading particle measurement method enabled the investigators to obtain fractional particle concentrations with sufficiently high particle size and time discriminations. Five relatively narrow particle size fractions, d_p = 0.4–0.5 µm; 0.8–1.0 µm; 2–3 µm; 4–5 µm; and 7.5–10 µm were selected to be shown in Figure 4. This nondimensional way of data presentation allows comparison of the particle concentration decay obtained for different size fractions. The gravitational settling time for a particle of a given size was calculated for each particle size fraction as the ratio of chamber height to the particle's settling velocity. For these calculations the tranquil settling model was used,(17,18) which is valid in a perfectly still air environment and is similar to the approach used in the HUD guidelines(13) for estimating the waiting period needed for leaded dust to settle. The range of τ_{TR}, the time that would be needed for all particles of a given size range to settle in perfectly still air, is indicated in Figure 4 for each curve.

In these tests the airborne particle concentration was found to decay exponentially with time. Indeed, Figure 4 shows essentially straight lines on a semilog plot. The lines representing submicron particles are slightly concave, perhaps reflecting the initial turbulence effect caused by workers' activity during paint removal. The exponential decay of the particle concentration is typical for indoor air environments with constantly mixed air. It has been quantitatively described as a stirred settling model(17,18) and has been observed for tobacco smoke particles in indoor air.(23) As in the latter study,(23) there was no intentional air mixing in these experiments. Very small air mixing may have occurred in the chamber due to the operation of the optical particle size spectrometer at a flow rate of 1200 cm³/min. It is estimated that this results in an average air velocity of up to 3 cm/hour. Air currents of this and even higher magnitude may be caused by small temperature gradients or extremely small leaks(23) that are unavoidable at abatement sites. The

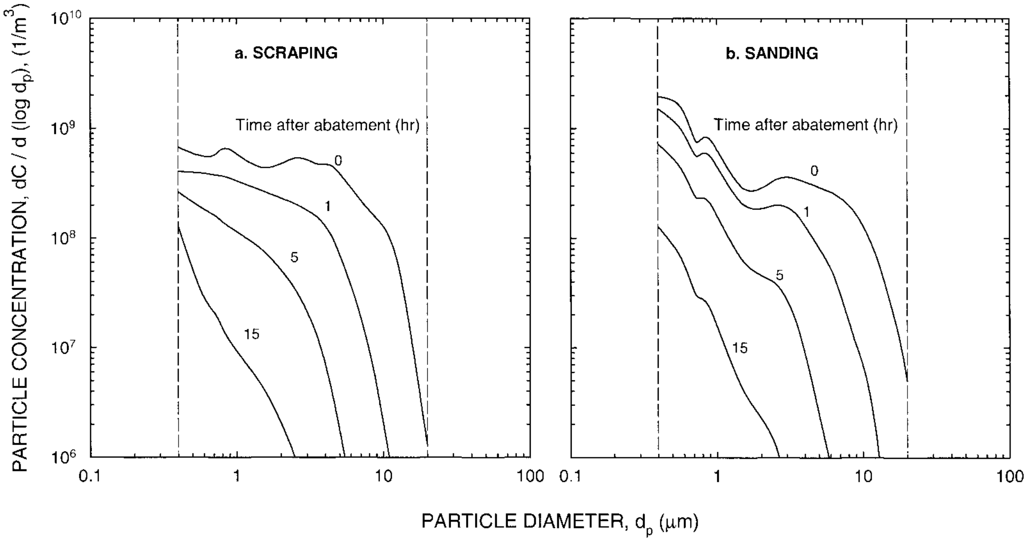

FIGURE 3. **Particle size distributions at t = 0, 1, 5, and 15 hours after (a) dry scraping and (b) dry machine sanding. Air exchange rate = 0. The vertical dashed lines represent the monitored particle size range.**

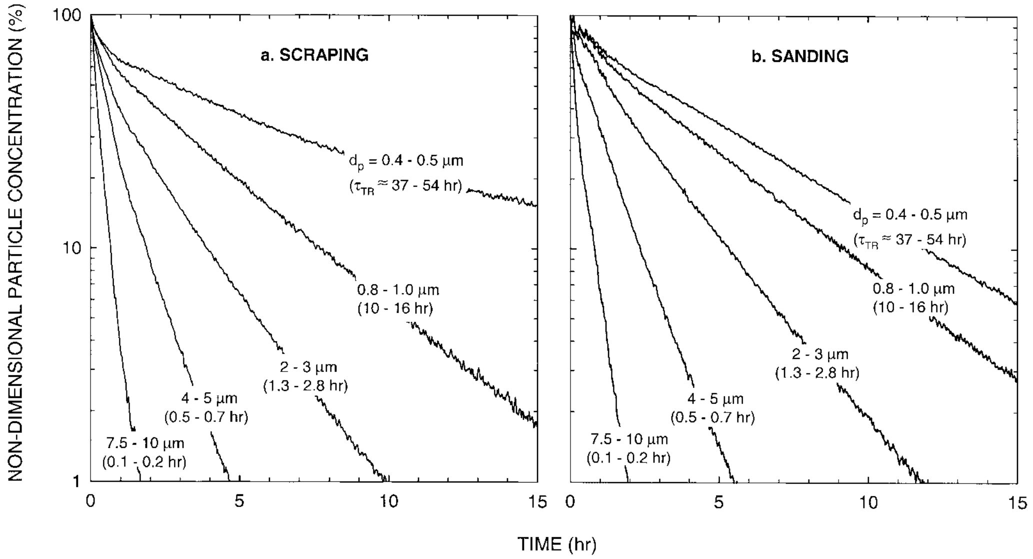

FIGURE 4. Nondimensional fractional particle concentration after (a) dry scraping and (b) dry machine sanding. Air exchange rate = 0. Settling time, τ_{TR}, calculated from the tranquil model, is equal to the time needed to settle out all particles of a given size range in a still air environment.

effect of air currents may be even more pronounced if the area being abated is kept under slightly negative pressure (the use of such "negative" air machines is a common field practice). Figure 4 shows that the particles remained airborne for a significantly longer time than predicted by the tranquil settling model. For example, for the size range d_p = 4–5 μm the tranquil model predicts a settling time of $\tau_{TR} \sim 0.5$–0.7 hour. However, the experiments show that more than 20 and 30% of particles in this size range generated by scraping and sanding, respectively, were still airborne after 1 hour of settling.

The exponential airborne particle concentration decay is described by the following equation:

$$C = C_o \exp(-kt) \quad \textbf{(1)}$$

where C is the particle number concentration at time t; C_o is the initial concentration at t = 0; and k is the exponential decay coefficient. The decay coefficients calculated from the experiments are shown in Table I. The monitoring time was 15 hours for submicron-sized particle fractions (d_p = 0.4–0.5 μm and 0.8–1.0 μm), 10 hours for d_p = 2–3 μm, 5 hours for d_p = 4–5 μm, and 2 hours for d_p = 7.5–10 μm. This monitoring time was reduced for larger particles due to their rapid settling. Each value presents an average of three replicates conducted with different doors. Thus, the standard deviation represents not only measurement errors but also the differences in the type of lead-paint on the door surfaces and in the performance of the abatement activity.

TABLE I. Exponential Decay Coefficient for Different Particle Size Fractions

Particle Size Fraction (μm)	Monitoring Time Interval (hr)	Experimental Decay Coefficient, k (1/hour)			
		Scraping		Sanding	
		Average	Standard Deviation	Average	Standard Deviation
0.4–0.5	15	0.089	0.027	0.180	0.006
0.8–1.0	15	0.255	0.017	0.239	0.008
2.0–3.0	10	0.433	0.043	0.414	0.029
4.0–5.0	5	0.938	0.121	0.911	0.092
7.5–10.0	2	2.65	0.46	2.57	0.37

The exponential decay coefficient was found to increase with increasing particle size. The coefficients determined for particles of the same size aerosolized by two different paint removal methods (scraping and sanding) had about the same values, except for the smallest size fraction of 0.4–0.5 μm. This may be attributed to the difference in physical properties of the submicron-sized particles aerosolized by these methods (e.g., the particle shape). Overall, the general trends of the particle settling were found to be similar for both active abatement methods.

Airborne Lead Mass Concentration

The data on the decay of the airborne particle concentration and on the evolution of the particle size distribution were used to determine the airborne mass concentration of particulates as a function of time for each test. The mass concentrations of airborne lead were calculated as a function of time using the data on the lead percentage (by mass) determined for different particle size ranges. The lead mass was measured for seven particle size ranges from 0.43 to ≥10.4 μm, and the lead mass fraction (%) in particulates was calculated as a ratio of the lead mass collected in a given size-selected subsample taken by the Andersen impactor to the dust mass collected in this subsample. The experimental results obtained with six wooden doors (three for scraping and three for sanding) are shown in Figure 5. The XRF readings ranged from 4.2±1.9 mg/cm^2 for Door A to 40.5±4.6 mg/cm^2 for Door F. The lead mass fraction in airborne particles of different sizes ranged from 2 to about 30% (20 to 300 mg/g) and was found to depend on the door tested rather than on the particle size. Thus, no significant particle size effect on the percentage of lead in airborne leaded dust was observed in this study.

The XRF reading on a specific door was related to the overall percentage of lead (by mass) in airborne particles released from this door due to paint removal. As a result of testing with 12 wooden doors using dry scraping and sanding, significant correlation was found between the XRF reading and airborne dust lead

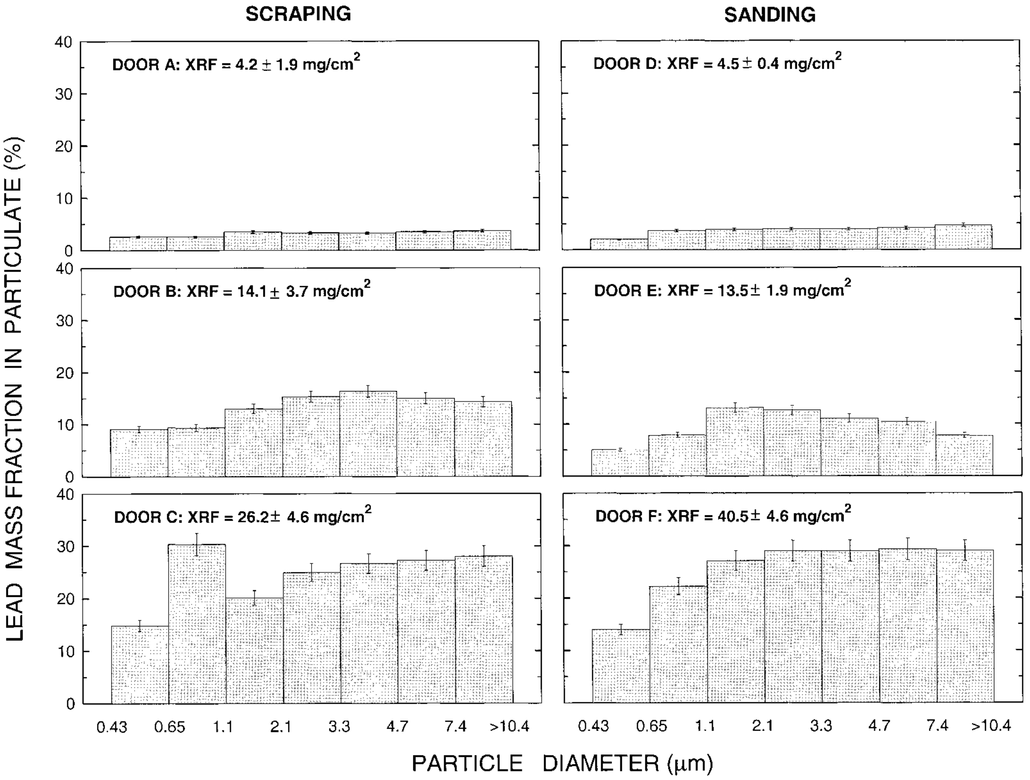

FIGURE 5. Lead mass fractions in particulate aerosolized during dry scraping (Doors A, B, C) and dry machine sanding (Doors D, E, F). Airborne leaded particles were collected by a seven-stage Andersen cascade impactor.

mass percentage: $r^2 = 0.64$, $p = 0.002$ (see Figure 6). This finding may need to be further proven through more accurate study, as the measurement data shown on Figure 6 cover the XRF reading range that is considerably broader than the range of samples used to prepare the performance characteristics sheet of the NITON-700.(20) In addition, this finding may be limited to certain type of leaded paint, door material, painting practice, and other conditions. Within these limitations, the data presented in Figure 6 suggest that lead contamination in air resulting from active abatement may be estimated for a particular set of conditions based on XRF readings on the lead-based painted surface.

Using the data on the overall lead percentage in particulate and the airborne dust concentration data, the mass concentration of airborne lead was calculated as a function of time, assuming a particle density of 2.5 g/cm³, similar to the assumption made in the HUD guidelines.(13) The maximum measured overall lead fraction in particulate (29% by mass) was used to calculate the highest possible concentration of airborne lead at the end of active abatement. In the current tests, this lead concentration was about 20,000 μg/m³. The lead mass concentration measured in the field during task-oriented abatement (dry scraping and non-HEPA sanding) ranged from 2300 to 11,800 μg/m³ with an average of 5800 μg/m³.(19) Thus, these tests reasonably simulated the worst case scenario of indoor air lead contamination resulting from active abatement.

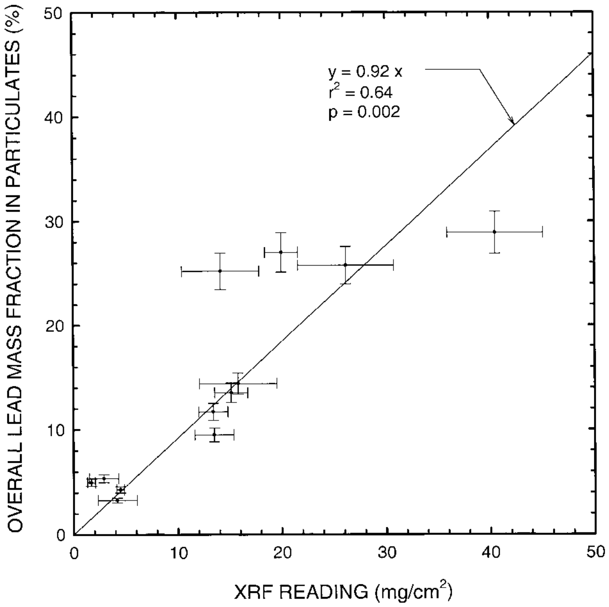

FIGURE 6. Correlation between the XRF reading on a door and the overall lead mass concentration in airborne particles generated during dry scraping and sanding.

Potential Floor Lead Loading

The calculations for an unventilated room (air exchange rate = 0) showed that about 90% of the airborne lead mass settled during the first hour after active abatement ended; about 95% settled

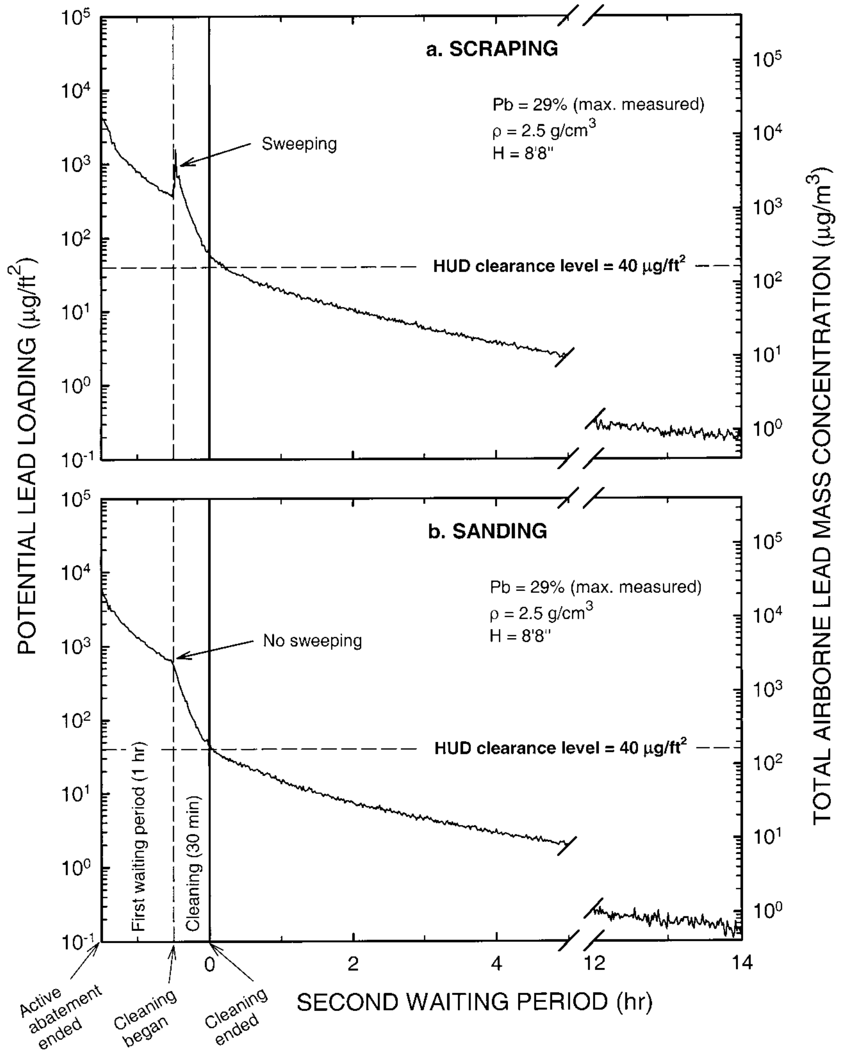

FIGURE 7. Estimated total airborne lead mass concentration after (a) dry scraping and (b) dry machine sanding in the test chamber. Air exchange rate = 0. The cleaning procedure, including HEPA vacuuming, was applied for 30 min.

within 1.6 hours. This result is essentially independent of the paint removal method (scraping or sanding).

In practice, some air exchange between the work site room and other rooms or the outside may occur even if an appropriate plastic containment system is installed. This air exchange may be caused by cracks and gaps in the walls in the abated building and through personnel access entryway configurations.

It was found that if the air exchange rate in the room was as significant as two exchanges per hour, the time needed to reduce the airborne lead mass by 90% is 32 min; and a 95% reduction is achieved by waiting 44 min. At 10 air exchanges per hour, the data showed that only 11 and 16 min are needed to clean indoor airborne lead by 90 and 95% of the lead mass, respectively. Assessments involving air exchange conditions were performed assuming that the lead concentration outside the work site room is negligible compared with that inside the room.

The HUD guidelines(13) recommend that the final cleaning process should start no sooner than 1 hour after the active abatement. According to data from the current study, at least 90% of airborne leaded dust will have settled before the cleanup.

In accordance with the HUD guidelines, cleaning was started 1 hour after the end of paint removal (the first waiting time). To continue considering the worst case scenario representing the highest possible lead contamination level and the least efficient air cleaning, the cleanup procedure recommended by HUD was reduced in these tests to only one cycle of HEPA vacuuming. No wet mopping was performed, and the settled dust was not water-misted before sweeping. The preliminary study showed that wet cleaning generally resulted in a more significant reduction of the airborne lead level than dry cleaning. Skipping wet cleanup procedures made the overall cleanup time shorter, thus intentionally providing an excessive level of the airborne lead concentration at the end of the cleanup procedure.

The results of our experiments are presented in Figure 7. The vertical logarithmic axis on the right side of Figure 7 represents (in micrograms per cubic meter) the mass concentration of leaded particles that remain airborne at a given time. The vertical logarithmic axis on the left side represents (in micrograms per square foot) the floor lead loading that will result from the settling of all the dust that is currently still airborne in this chamber (note that the ratio of ultimate lead loading to airborne lead concentration is proportional to the room height). The horizontal axis represents

TABLE II. Underestimates of Ultimate Floor Lead Loading as a Function of Second Waiting Period Duration

Second Waiting Period (hour)	Underestimate of Ultimate Floor Lead Loading[A] Scraping Loading (μg/ft^2)	Scraping Percentage (%)	Sanding Loading (μg/ft^2)	Sanding Percentage (%)
0.5	29.8	50.2	23.1	46.8
1.0	18.7	31.5	13.5	27.3
2.0	10.5	17.7	7.4	15.0

[A]Loading = L_t; percentage = $L_t/L_0 \times 100\%$.

the time scale: the first waiting period (1 hour of free dust settling after active abatement) and cleanup (next 30 min) and then the waiting period under question (zero corresponds to the beginning of the second waiting period). During the first 1 hour after active abatement has ended the airborne lead mass concentration decreased, as shown in Figure 7. During the subsequent 30 min of cleanup, the concentration continues to decrease, except for its short increase when starting dry sweeping of dry scraping debris (Figure 7a). During HEPA vacuuming of surfaces in the chamber, the vacuum cleaner also cleaned the air at the same time. Overall, the airborne lead concentration during the 30 min of vacuuming decreased drastically for both abatement methods. The same conclusions are true for potential lead loading on the floor surfaces. It is seen that the potential loading from the settling of airborne particles is below the HUD floor clearance standard(11) of 40 μg/ft^2 in the beginning of the second waiting period (first 15–20 min).

Only by waiting an infinite time will all of the airborne lead settle out. In fact, for smaller submicron particles, other effects, such as diffusion and electrostatics, may dominate over the gravitational settling. Thus, clearance testing after finite waiting periods underestimates the ultimate floor dust lead loading. However, while the small particles remain airborne, the airborne lead mass becomes negligible at a certain time: for example, in 14 hours after active abatement the lead mass concentration level becomes well below 1 μg/m^3; this corresponds to a potential lead loading of <0.2 μg/ft^2 (see Figure 7). The potential lead loading determined at the end of the second waiting period (L_t) is the measure of how the clearance test done at the time t underestimates the ultimate floor dust loading. The percentage underestimate is defined as the ratio (L_t/L_0) of the potential lead loading for clearance at end of a second waiting period of time t, to the potential lead loading at the beginning of the second waiting period, where $t = 0$. Table II presents the underestimates and the percentages determined for $t = 0.5$, 1, and 2 hours, for two abatement methods. For example, second waiting periods of 1 and 2 hours following cleaning result in floor lead loading underestimates of 18.7 and 10.5 μg/ft^2, respectively, for scraping, and 13.5 and 7.4 μg/ft^2, respectively, for sanding. These underestimates are comparable with the limit of precision of the clearance test (that may exceed 10 μg/ft$^{2(24)}$) and thus can be considered as of minor significance. This conclusion cannot be made for $t = 0.5$ hour. In percentage points, the underestimates do not exceed about 30% if the second waiting period is set up at 1 hour. As noted above, these underestimates are conservative, that is, higher than expected for actual work in the field when HEPA vacuuming and/or wet methods are used.

All the findings described above depend on the duration of the first waiting period, currently set at 1 hour. These findings do not suggest a need for extending the first waiting period beyond 1 hour. Using the data presented in Figure 7, the underestimates were calculated for reduced first waiting periods. It is projected that reducing the waiting period from 1 to 0.5 hours would roughly double the potential lead loading contributed by airborne lead at the corresponding second waiting period durations. The doubled floor lead loading in such a case may become close to 40 μg/ft^2; which is not desirable. Therefore, these data do not suggest revising the first waiting period.

Overall, this laboratory study shows that there is no need to revise the waiting periods recommended in the HUD guidelines.(13) When written in 1995, the guidelines' recommendation was based on a floor clearance standard of 100 μg/ft^2; even with HUD's lowering of the clearance standard(11) to 40 μg/ft^2, the 1-hour waiting periods remain valid.

CONCLUSIONS

Leaded dust was aerosolized from lead-painted door surfaces using dry scraping or dry non-HEPA machine sanding that generated the highest reasonably feasible airborne lead concentration levels. Particle settling was tested in a room-sized test chamber by measurement of residual particles in the air.

The conventional assessment of a waiting period between the final cleanup and clearance is based on a tranquil settling model, which assumes that the work room air is perfectly calm, a disputable assumption. The authors investigated the evolution of the airborne particle concentration and size distribution following lead abatement work in a controllable environment using direct airborne particle monitoring. It was found that the airborne particle concentrations decreased exponentially with time in all measured particle size ranges, even if indoor air was not intentionally mixed and no air exchange was applied. This result is consistent with the theoretical model of constantly mixed air (the stirred model), which predicts a longer settling period than the model of tranquil settling. Very low level air mixing that may be caused by temperature gradients and initial air turbulence in the room was found to affect the nature of particle settling. Approximately 90% of airborne lead (by particulate mass) settled within 1 hour following active abatement, before the cleaning procedure began. The final cleanup (even when reduced to 30 min of HEPA vacuuming) followed by another 1-hour waiting period resulted in further decreases of the airborne lead. Even for the lead-based paint removal techniques used in this research, for which normal dust control measures were intentionally defeated so as to reach a conservative (i.e., health-protective) conclusion, the clearance test may underestimate the actual lead loading by less than 20 μg/ft^2, or 30%, if the second waiting period is 1 hour. For more realistic conditions, the underestimates are expected to be much lower than the new 40 μg/ft^2 HUD clearance standards for floor dust lead. These experimental results were obtained for the first waiting period (between the end of active abatement and the beginning of cleaning) also set at 1 hour, as recommended by HUD guidelines. Thus, the data of this study demonstrate that there is no need to increase either the first or the second waiting period.

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