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FINAL REPORT

for the

COMPREHENSIVE ABATEMENT PERFORMANCE STUDY

VOLUME I: SUMMARY REPORT

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CONTRIBUTING ORGANIZATIONS

This study was funded and managed by the U.S. Environmental Protection Agency. The study was conducted collaboratively by two organizations under contract to the Environmental Protection Agency, Battelle Memorial Institute and Midwest Research Institute. Each organization's responsibilities are listed below.

Battelle Memorial Institute (Battelle)

Battelle was responsible for the design of the study, for producing the design documentation and the Quality Assurance Project Plan, for developing training for the field teams, for recruiting cooperators for the study, for providing team leaders for the field teams, for auditing the field teams, for data management of combined study data, for auditing the study data, for conducting the statistical analysis of the data, and for writing the final report.

Midwest Research Institute (MRI)

Midwest Research Institute was responsible for participating in the planning for the study, for writing certain chapters and appendices in the Quality Assurance Project Plan, for designing and producing a vacuum device for collecting field samples, for developing training for the field teams, for providing the technicians who collected the field samples, for auditing the field teams, for conducting the laboratory analysis of the field samples, for managing the data associated with the field samples, for auditing the laboratory results, and for contributing sections of the final report.

U.S. Environmental Protection Agency (EPA)

The Environmental Protection Agency was responsible for managing the study, for reviewing the design and the Quality Assurance Project Plan, for assessing the performance of the recruiters and the field teams, for reviewing audit reports, for reviewing the final report, and for arranging the peer review of the design and the final report. The EPA Work Assignment Managers were Ben Lim and John Schwemberger. The EPA Project Officers were Janet Remmers, Jill Hacker, and Phil Robinson.

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EXECUTIVE SUMMARY

In response to requirements mandated by the Lead-Based Paint Poisoning Prevention Act, in 1989 the U.S. Department of Housing and Urban Development (HUD) initiated the Lead-Based Paint Abatement Demonstration Study in seven urban areas across the U.S. The objectives of this study were to assess the cost, worker hazards, and short-term efficacy of various lead-based paint abatement methods. Among other conclusions, the FHA portion of this study estimated that abatement costs for a single-family dwelling could range from $2000 to $12,000. One question which was not answered by the HUD Abatement Demonstration was that of the long-term efficacy of the abatement methods. Therefore, in 1990 the U.S. Environmental Protection Agency (EPA), in cooperation with HUD, initiated the Comprehensive Abatement Performance (CAP) Study to address this question.

The CAP Study was a follow-up to HUD Abatement Demonstration activities performed in Denver, Colorado. There were four primary objectives of the CAP Study: (1) assess the long-term efficacy of two primary abatement methods, (2) characterize lead levels in household dust and exterior soil in unabated homes and homes abated by different abatement methods, (3) investigate the relationship between lead in household dust and lead from other sources, in particular, exterior soil and air ducts, and (4) compare dust lead loading results from cyclone vacuum sampling and wipe sampling protocols. To address these objectives, the CAP Study collected approximately 30 dust and soil samples at each of 52 HUD Demonstration houses in Denver, approximately two years after the abatements had been completed. The houses were all occupied at the time of the CAP Study field sampling, though they had not been continuously occupied between the completion of the abatements and the field sampling. The samples were analyzed for their lead content, and these lead measurements were then used in detailed statistical analyses addressing the four study questions.

The CAP Study included two approaches for assessing abatement efficacy, one direct approach and one indirect approach. In the direct approach CAP Study lead measurements, made at HUD Demonstration houses two years after abatement, were compared with pre-abatement lead measurements made at those same houses. Since pre-abatement dust lead measurements were limited, the CAP Study also included an indirect approach to assessing abatement efficacy. In this approach, lead levels were measured in dust and soil samples collected both at abated HUD Demonstration houses, and at the same time at unabated HUD Demonstration houses found to be relatively free of lead-based paint. The performance of the abatement methods was then assessed by comparing the lead levels at abated houses with those at unabated houses. Sampling at unabated houses provided a measure of the amount of lead introduced to the housing environment from low levels of lead in paint and sources other than lead-based paint. If the environmental lead levels at abated houses were found to be similar to those at unabated houses, this was taken as an indication that abatement either lowered pre-abatement lead levels, or at least did not significantly raise lead levels at abated houses. However, if lead levels at abated houses were higher than at unabated houses, this was taken as an indication that abatement failed to completely eliminate the lead hazard because lead was introduced to these environments either immediately through inadequate dust control during abatement, or more gradually over time. Clearly, an important limitation of the direct assessment of abatement efficacy is that the pre-abatement lead levels at abated houses were not available (except for foundation soil and limited numbers for floors and window stool[1] dust), and therefore, one can only conjecture about whether the observed post-abatement lead levels represent an improvement or worsening of the housing environment.

The results of the CAP Study from the direct approach of comparing post-abatement and pre-abatement lead levels were that for the two sample types for which a comparison was possible (foundation soil and window stools), there was no evidence that post-abatement lead levels are significantly higher than pre-abatement levels. Both pre-abatement and CAP results for window stool dust samples averaged between 175 and 200 µg/ft^2. In soil at the foundation of the house, levels were near 240 µg/g. These results are based on dust lead measurements made on window stools at 10 CAP Study abated houses, as well as soil lead measurements made at 24 CAP Study abated houses. A few floor dust samples obtained from three houses were also available for comparison, but were deemed insufficient for making substantive conclusions. These results are tempered by the fact that because of the small number of houses for which data were available, as well as the large variability in observed lead levels, relatively large differences between post-abatement and pre-abatement lead levels could not be judged to be statistically significant. For example, the confidence interval for the average ratio of post-abatement to pre-abatement levels on window stools was 0.37 to 3.46. In addition, further complicating the comparison of post-abatement and pre-abatement dust and soil lead measurements was the fact that different sampling and analysis protocols were used in the CAP Study and HUD Demonstration. Perhaps most

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[1] The window stool was defined as the horizontal board inside the window which extends into the house interior — often called the window sill. In contrast, the window channel was defined as the surface below the window sash and inside the screen and/or storm window.

significantly, the CAP Study utilized vacuum dust sampling while the HUD Demonstration utilized wipe dust sampling.

The indirect assessment of abatement efficacy found that abatement appears to have been effective, in this case in the sense that there is no evidence that post-abatement lead levels at abated houses were significantly different than lead levels at neighboring unabated houses found to be relatively free of lead-based paint. There were two exceptions to this statement; however, both of these exceptions were anticipated and are logically explained. First, lead concentrations in air ducts were significantly higher in abated houses than in unabated houses; air ducts were not abated in the HUD Demonstration. In addition, lead concentrations in the soil outside abated houses were significantly higher at the foundation and at the boundary than corresponding lead concentrations outside unabated houses. However, soil was also not abated during the HUD Demonstration; and these higher lead levels might in part be due to differences in the age of these houses, since on average the abated houses in this study were 17 years older than unabated houses. As with the caveat stated above, these results must also be tempered by the fact that not finding a significant difference in lead levels at abated and unabated houses for all other building components and sampling locations does not prove that no such differences exist. The CAP Study was designed to detect approximately two-fold differences between lead levels at abated and unabated houses under specified variance assumptions. For example, although the estimate of 1.76 for the ratio of lead loadings on floors in abated to unabated houses was not significantly different from one, the 95 percent confidence interval for this ratio was from about 0.87 to 3.5.

The CAP Study also assessed abatement by comparing encapsulation and enclosure methods versus removal methods. No significant differences among lead levels could be attributed to these two types of abatement methods, except for air ducts which, as stated above, were not abated. Air duct dust lead levels were higher in houses abated primarily by encapsulation and enclosure methods than in houses abated primarily by removal methods. It is important to note, however, that houses abated primarily by encapsulation and enclosure methods on average had greater amounts of abatement performed than houses abated primarily by removal methods. The CAP Study also performed a visual inspection of abated surfaces and recorded their condition as being intact, partially intact, or minimally intact. Less than 60% of the surfaces abated by encapsulation and chemical stripping methods were found to be intact, while more than 70% of the surfaces abated by all other methods were found intact.

With regard to the second study objective, lead levels were found to vary greatly for different media and sampling locations. Minimum individual lead concentrations for most sample types were typically on the order of 10 μg/g except in air ducts and window channels where levels were at least 50 μg/g. Maximum individual lead concentrations were lowest for boundary and entryway soil samples (1073 and 1068 μg/g, respectively) and highest for window stool and window channel dust samples (48,272 and 45,229 μg/g, respectively). Minimum individual lead loadings for all sample types were typically only 1 to 4 μg/ft^2. Maximum individual lead loadings were lowest for floor dust samples (334 μg/ft^2 by wipe and 11,641 μg/ft^2 by vacuum) and highest for window channel dust samples (244,581 μg/ft^2). Dust lead loadings were also evaluated in comparison with the HUD interim dust standards (HUD 1990b). Geometric mean lead loadings for both floors and window stools at both abated and unabated houses were found to be well below their respective HUD standards of 200 and 500 μg/ft^2. On floors, geometric mean lead loadings were also well below the EPA guidance standard of 100 μg/ft^2 (EPA, 1994). In addition, for both of these sample types, more than 75 percent of the samples collected in the CAP Study had lead loadings below their respective HUD standards, in both abated and unabated houses. However, geometric mean window channel lead loadings at both abated and unabated houses were found to be well above the HUD interim standard of 800 µg/ft^2, and well over half of individual observations were above this standard, at both abated and unabated houses.

Three primary results were found for the third CAP Study objective. First, significant correlations in lead concentrations at the house level were found for four pairs of sample types: window channels and window stools (correlation coefficient of 0.40), entryway soil and boundary soil (0.56), boundary soil and window stools (0.38), and entryway soil and interior entryway dust (0.29). Second, at the house level, significant correlations in dust lead loadings were found for two pairs of sample types: window channels and window stools (0.56), and air ducts and exterior entryways (0.41). Third, significant correlation was observed between dust lead concentrations at interior and exterior entryways (0.37). However, at the room level, no significant correlations in dust lead loadings were found. House level correlations were based on house averages; room level correlations were based in most cases on single measurements. The fact that more house level correlations were significant suggests that differences in lead levels are more related to broad differences among houses than to location-specific characteristics within houses.

Results for the fourth study objective found that when combined across substrates, the average difference between lead loadings measured by the cyclone vacuum method and by the wipe method was insignificant. Differences were overshadowed both by large side-by-side variability in the two methods, and a strong substrate effect. This latter effect was apparently related to the smoothness of the substrate. On linoleum, the two methods were approximately equivalent, whereas on tile, lead loadings measured by the cyclone were lower than those measured by wipe, and on wood, lead loadings measured by the cyclone were higher. These results should be considered when setting environmental standards and choosing sampling methods for testing regulatory compliance.

The CAP Study results provide potentially important information about the role of relatively high-cost abatement procedures for eliminating, or controlling, residential lead-based paint. The CAP Study found no significant differences between post-abatement and pre-abatement lead levels for exterior soil and the limited number of window stool dust lead measurements available. It also found no significant differences between post-abatement lead levels at abated houses and lead levels at unabated houses, with the exception of air duct dust and exterior soil which were not abated in the HUD Demonstration. In addition, for both floors and window stools the geometric mean lead loadings at abated houses were well below the "Lead-Based Paint: Interim Guidelines for Hazard Identification and Abatement in Public and Indian Housing" (HUD, 1990b) standards of 200 and 500 $\mu g/ft^2$. The lead loading geometric mean for floors at abated houses was also well below the EPA standard of 100 $\mu g/ft^2$ for floors (EPA, 1994). These results all suggest that the abatement activities were effective, in the sense that they do not appear to have increased lead levels at abated houses above interim standards. However, the CAP Study also found that the geometric mean dust lead loading for window channels at abated houses was well above the HUD interim standard of 800 $\mu g/ft^2$, although the same result was found for unabated houses relatively free of lead-based paint.

Comparisons between the wipe method and the vacuum method used to collect dust in the CAP Study indicate that results from wipe samples would likely be below the clearance standards for floors and window stools. For window channels, differences between wipe and vacuum methods, especially on wood, preclude concluding definitively that results from wipe samples would exceed the clearance standard for window channels.

Study Conclusion

The conclusion of this study is that lead-based paint abatements are effective. This conclusion is based on the study finding that there is no evidence that post-abatement lead levels at abated houses were significantly different from lead levels at unabated houses relatively free of lead-based paint, save for two exceptions. The two exceptions, differences in lead levels between the abated and unabated houses in air ducts and exterior soil, are explained by the fact that air ducts and soil were not abated. There are caveats to the study that should be kept in mind when interpreting and assessing the results and conclusion. The principal caveats are these: no biological monitoring was done in the study, and the study was designed to detect differences approximately a factor of two or larger between the abated houses and the unabated houses.

1.0 INTRODUCTION AND BACKGROUND

In response to requirements mandated by the Lead-Based Paint Poisoning Prevention Act (as amended by Section 566 of the Housing and Community Development Act of 1987), the Residential Lead-Based Paint Hazard Reduction Act of 1992, and other legislation, the U.S. Environmental Protection Agency (EPA), U.S. Department of Housing and Urban Development (HUD), U.S. Department of Health and Human Services, and other federal agencies are conducting a broad-based program of research, demonstration, and policy actions aimed at reducing the incidence of childhood lead poisoning in the U.S. An important part of the federal program is to identify and abate lead-based paint hazards in privately-owned and public housing. Toward this end, HUD initiated two important studies in 1989, the HUD National Survey of the incidence of lead-based paint in housing, and the HUD Lead-Based Paint Abatement Demonstration.

The HUD National Survey sampled both public and private housing in order to estimate the number of housing units with lead-based paint, the total housing surface area covered with lead-based paint, the condition of the paint, and the incidence of lead in household dust and surrounding soil (HUD, 1990a). The National Survey found that approximately 57 million homes, or 74 percent of all occupied housing units built before 1980, have some lead-based paint. Older homes are more likely to contain lead-based paint; 90 percent of housing units built before 1940 have lead-based paint. Within the 57 million homes there are on average 580 square feet of interior surfaces and 900 square feet of exterior surfaces covered with lead-based paint.

The HUD Abatement Demonstration was a research program in ten cities which assessed the costs and short-term efficacy of alternative methods of lead-based paint abatement. A variety of abatement methods were tested in approximately 120 multi-family public housing units in three cities -- Omaha, Cambridge, and Albany -- and similar methods were tested in 172 single-family housing units in the FHA inventory in seven metropolitan areas -- Baltimore, Birmingham, Denver, Indianapolis, Seattle, Tacoma, and Washington (HUD, 1991). The FHA demonstration evaluated two classes of abatement methods, encapsulation and enclosure methods, versus removal methods. The study found that the cost of encapsulation and enclosure abatements ranged from about $2000 to $8000 per housing unit, while the cost of removal abatements ranged from about $2000 to $12,000 per housing unit (HUD, 1990a).

Although the HUD Abatement Demonstration did assess the short-term efficacy of certain lead-based paint abatement strategies, it was not intended to evaluate the longer-term performance of these approaches. Therefore, in 1990 the EPA Office of Pollution Prevention and Toxics (formerly the Office of Toxic Substances) initiated the Comprehensive Abatement Performance (CAP) Study to further evaluate the abatement strategies used in the HUD Abatement Demonstration.

This report presents a summary of the results of the CAP Study. There are two reports: Volume I (this report) presents the overall study results and conclusions, while Volume II (EPA, 1996) presents more detailed results from the statistical analyses performed. Within Volume I the study approach, results, and discussion of results are presented in Sections 2, 3, and 4, respectively. Among the results presented in Volume II are descriptive statistics, explanation of the statistical models, evaluation of the abatement methods, correlations among lead levels in sampled media and locations, comparison of vacuum and wipe sampling methods, comparison of CAP Study and HUD Abatement Demonstration results, results from statistical outlier analyses, and analysis of field and laboratory quality control data.

2.0 STUDY APPROACH

Whereas the HUD Demonstration was intended to focus on the short-term cost-effectiveness of abatement methods, the CAP Study provided important information about the longer-term effectiveness of these same methods. Although clearance testing of lead levels in dust was done immediately after abatement in the HUD Demonstration, the longer-term performance of the abatement methods after these houses were reoccupied was not assessed. The CAP Study was therefore necessary to preclude spending large sums of money abating lead-based paint using methods that may prove in the long term to be ineffective at maintaining low lead levels in household dust.

High levels of lead in household dust pose serious health risks to occupants regardless of the source. Therefore the CAP Study also collected important information as to how lead from other media and locations may be deposited into household dust. It is possible that lead can be redeposited in homes after the house is reoccupied where the lead-based paint hazard has been removed or contained. Either prior to abatement or during the abatement process itself, leaded dust may have been deposited in the ventilation system or other parts of the house which, when reoccupied by new residents, could spread throughout the house. Also, activity patterns of the occupants may re-introduce lead from exterior soils.

2.1 STUDY OBJECTIVES

To help address the above concerns, the specific objectives of the CAP Study were as follows:

(1) Assess the long-term efficacy of two primary abatement methods;

(2) Characterize lead levels in household dust and exterior soil in unabated homes and homes abated by different abatement methods;

(3) Investigate the relationship between lead in household dust and lead from other sources, in particular, exterior soil and air ducts, and

(4) Compare dust lead loading results from cyclone vacuum sampling and wipe sampling protocols.

These objectives were intended to address at least three important concerns presented in the HUD Comprehensive and Workable Plan (HUD, 1990a): the durability of various abatement methods over time, the importance of adequate dust control during the abatement process, and the possible redeposition of lead from a variety of locations, such as exterior soil and air ducts. The fourth objective addresses a critical issue related to the measurement and characterization of dust lead levels within a house.

The HUD Demonstration intended to eliminate the lead-based paint hazard from housing environments either by containing the lead-based paint with encapsulation or enclosure methods, or by eliminating the lead-based paint with removal methods. Encapsulation and enclosure methods attempt to chemically bond or mechanically affix durable materials over painted surfaces, while removal methods attempt to either scrape or chemically strip lead-based paint from painted surfaces, or to completely remove and replace painted components (e.g., windows, doors, baseboards).

There are at least two performance concerns with these abatement methods. First, conducting the abatement methods themselves might generate large amounts of leaded dust that could be deposited throughout the housing environment. And second, the performance of the abatement measures might degrade over several months or years following abatement, allowing the lead hazard to be reintroduced to the housing environment. Encapsulation and enclosure methods do not attempt to remove lead-based paint from housing surfaces and therefore may have a greater potential to degrade. Both encapsulation and enclosure methods, as well as removal methods have the potential to spread leaded dust throughout the housing environment during abatement.

For the CAP Study, the ideal direct approach to assessing the long-term efficacy of the abatements performed in the HUD Demonstration would have been to collect pre-abatement dust and soil lead measures, and compare them with measures collected after abatement at the same locations. If the post-abatement measurements were not higher than pre-abatement lead levels, this could be taken as an indication that abatement had a positive effect on the housing environment. While the CAP Study did perform this direct assessment of abatement efficacy, only foundation soil samples and a limited number of dust samples were taken during the HUD Demonstration prior to abatement. Thus, only limited *direct* information could be obtained about the effects of abatement.

Realizing these limitations, the approach for addressing the first objective of the CAP Study also included an indirect assessment of abatement efficacy. In this second approach post-abatement dust and soil samples were collected and chemically analyzed for lead approximately two years after abatement both at abated houses, and at the same time at unabated houses known to be relatively free of lead-based paint. The performance of the abatement methods was then assessed by comparing the lead levels at abated houses with those at unabated houses. Sampling at unabated houses provided a measure of the amount of lead introduced to the housing environment from low levels of lead in paint and sources other than lead-based paint abatement. If the environmental lead levels at abated houses were found to be similar to those at unabated houses, this was taken as an indication that abatement either lowered pre-abatement lead levels, or at least did not significantly raise lead levels. However, if lead levels at abated houses were significantly higher than those at unabated houses, this was taken as an indication that abatement failed to completely eliminate the lead hazard because lead was introduced to these environments either immediately through inadequate dust control during abatement, or more gradually through redeposition over time.

Comparing post-abatement levels of lead in abated houses to levels in unabated houses does not necessarily reflect the degree to which abatement lowered levels of dust and soil lead compared to pre-abatement levels. However, it does provide a basis for discerning whether abatement reduces dust and soil lead levels to levels present in houses with no apparent need for abatement (based on portable X-ray fluorescence readings of lead levels in paint). The levels of lead in dust and soil were primarily assessed by the concentration of lead present in samples, measured as the weight of lead (in micrograms, μg) in a sample divided by the total weight of the sample (in grams, g). Higher lead concentrations at abated houses were generally taken as an indication that paint had contributed additional lead to the environment over that which had been deposited from other non-paint sources, such as prior fallout from automotive emissions. For dust, the lead levels were also assessed by the lead loading present, which is measured as the weight of lead (μg) collected in a sample divided by the total surface area sampled (in square feet, ft^2). The lead loading, which takes into account both the lead concentration present as well as the dustiness of the environment, provides a measure that can be combined with room dimensions to assess the total amount of lead to which residents are exposed.

2.2 STUDY DESIGN

Of the 172 single-family dwellings abated during the HUD Abatement Demonstration, three of these houses had pilot abatements performed, while the other 169 were completely abated. Soil was not abated at any of these houses. The distribution by city of these 169 houses is presented in Table 2-1. The specific houses for abatement were selected by first identifying older

Table 2-1. Number of Houses Abated in the HUD Demonstration

City	Interior Abatement Category*		Exterior Abatement Only**		Total
	Encap/ Enclos	Removal	Encap/ Enclos	Removal	
Baltimore	11	9	--	--	20
Birmingham	8	12	2	1	23
Denver	33	18	5	1	57
Indianapolis	17	10	3	4	34
Seattle/Tacoma	12	10	1	3	26
Washington	6	3	--	--	9
Total	87	62	11	9	169

* Each house was classified according to the abatement category accounting for the largest square footage of interior abatement.

** For houses having only exterior abatement performed, each house was classified according to the abatement category accounting for the largest square footage of exterior abatement.

housing likely to contain lead-based paint and then testing painted surfaces for lead using portable X-ray fluorescence (XRF). Houses abated in the HUD Abatement Demonstration were those found to have a significant number of structural components covered by paint with a high concentration of lead. When surveying houses for lead-based paint, HUD considered all painted surfaces both on the interior and exterior of the house.

The HUD Demonstration originally included six different abatement methods: encapsulation, enclosure, and four removal methods (i.e., chemical stripping, abrasive stripping, heat-gun stripping, and complete removal or replacement of painted components). Because of the diversity of housing components containing lead-based paint, it was generally true that no single abatement method could be used uniformly throughout a given house. One important consideration in the CAP Study was the appropriate way in which to summarize and classify the abatement activities conducted at each house. Detailed information was collected by HUD which listed each type of interior and exterior structural component abated in the Demonstration, along with the linear or square footage abated and the abatement method used. For the CAP Study, each house was primarily classified according to the abatement category (i.e., encapsulation/enclosure versus removal methods) accounting for the largest square footage of interior abatement. However, at many HUD Demonstration houses, a great deal of exterior abatement was also performed. Therefore, the data interpretation also considered which specific methods were used on both the interior and exterior of the house. Two other important considerations for the data interpretation are the sometimes widely different square footages abated at different houses and the different mix of methods used.

Selection of Abated Housing Units

Initial plans for the CAP Study included selection of housing units from all seven urban areas in the FHA portion of the HUD Demonstration. However, after conducting a pilot sampling and analysis program (EPA, 1995a), and subsequently developing a cost estimate for the CAP Study, it was decided that the CAP Study would only be conducted in Denver, where 57 of the 169 abated houses were located (Table 2-1). Because the number of abated houses in Denver was limited, all reoccupied houses were initially included for recruitment in the CAP Study. A preliminary statistical power analysis was conducted to examine the magnitude of the differences between dust lead levels in abated and unabated houses that could be detected with 80 percent power. The analysis utilized the available information about both the abated and unabated houses in Denver, as well as the results from the CAP Pilot Study. For the purposes of the analysis, it was assumed that two abated houses would be sampled for every one unabated house sampled. Power analysis results indicated that approximately 40 abated houses (and therefore 20 unabated houses) would be sufficient to detect two-fold differences between the dust lead levels in abated and unabated houses. (This analysis is described in detail in Appendix F of Volume II.) Given the initial set of 57 abated houses in Denver, 70% of these houses had to be successfully recruited into the study.

Selection of Unabated Housing Units

Only foundation soil samples and a limited number of dust samples were collected at the abated houses prior to abatement. This hindered the use of each abated house as its own control to provide a direct assessment of abatement performance. Therefore, in order to use the levels of lead measured in dust and soil samples at abated houses as a measure of the performance of abatement at those houses, lead levels associated with other environmental sources had to be characterized. Therefore, in addition to abated houses, dust and soil samples were collected from unabated houses that were previously tested by XRF in the HUD Demonstration and found to be relatively free of lead-based paint. The objective in measuring lead levels at unabated houses was to determine whether lead levels observed at abated houses were in fact greater than those found at houses having very few components covered with lead-based paint and therefore presumably affected primarily by non-paint sources of lead.

Some consideration was given to the idea of including a second type of unabated house, where significant amounts of lead-based paint were known to be present, and no abatement activities had yet been performed. Presumably, environmental lead levels measured in interior dust and exterior soil at these houses would have been significantly higher than those measured at abated houses and at houses that were known to be relatively free of lead-based paint. Houses with unabated lead-based paint could have supplied at least two additional interesting comparisons to the CAP Study:

- If it were demonstrated that no significant difference exists between environmental lead levels at houses with unabated lead-based paint and houses that contain relatively little lead-based paint, then this result might suggest that non-paint sources of lead dominate the housing environment.
- If environmental lead levels at abated houses were found to be significantly lower than those with unabated lead-based paint hazards, then this would indirectly suggest that abatement is successful in lowering lead levels at houses with lead-based paint.

Although these and other comparisons would have been quite informative, houses with unabated lead-based paint were not included in the CAP Study. The primary reason for excluding these houses was that they should be subsequently abated to protect residents' safety; however, EPA could not identify a suitable mechanism to conduct these abatements.

In the FHA portion of the HUD Demonstration, a total of 132 houses were tested by XRF for lead-based paint, but were not abated (Table 2-2). When performing the XRF tests, three replicate XRF readings were made at each sampling location and decisions at each location were based on the average of those three readings. When interpreting the results, an average reading greater than or equal to 1.0 mg/cm^2 was considered to be a positive indication that lead-based paint was covering the tested component. While only a single round of XRF testing was performed at unabated houses, in some cases a second round of XRF and/or AAS testing was performed at abated houses to confirm inconclusive XRF results.

Unabated houses for the CAP Study were recruited from the set of unabated houses in Denver that were tested by XRF in the HUD Demonstration. For the purpose of identifying unabated houses, the detailed XRF results were used under the assumption that they provided an accurate and current assessment of these houses. Using a criterion that equally weighted (1) the percentage of housing components testing positive by XRF for lead-based paint, and (2) the average XRF testing result, the 40 unabated houses in Denver were prioritized. Seventeen unabated houses were sampled for the CAP Study, including 16 houses from among the 31 with the lowest XRF results, and a 17th house which was 36th on the prioritized list. The 36th house on the prioritized list was recruited because it was the duplex to the 27th house which had already been recruited.

Table 2-2. Number of Unabated Houses Tested by XRF in the HUD Demonstration

City	Number of LBP Building Components*				Total
	0	1-2	3-9	10 or More	
Baltimore	1	6	3	10	20
Birmingham	4	5	--	5	14
Denver	13	10	14	3	40
Indianapolis	5	9	5	--	19
Seattle/Tacoma	10	3	2	5	20
Washington	4	2	4	9	19
Total	37	35	28	32	132

* Number of structural components for which XRF testing identified the presence of lead-based paint.

Recruitment of Housing Units

The FHA regional property disposition office in Denver was contacted with a request to complete a record of property disposition form for each abated and unabated home in the region. From this form the following data were obtained: name, address and telephone number of the purchaser; date of settlement; investor versus owner/occupant status of purchaser; date property was listed for sale; an indication of whether the house was cleared after abatement; and ages of children of owner/occupants.

Appointments were scheduled with residents using a combination of mailed information packets, telephone calls, and on-site visits by a recruitment team. A total of 83 houses (32 unabated, 51 abated) were approached during the recruitment phase of the CAP Study. Appointments were confirmed and two field teams collected samples during March and April of 1992 from 52 of these houses (17 unabated, 35 abated). Eight houses (5 unabated, 3 abated) refused to participate in the study. Remaining houses were either vacant or unreachable. An audit of the field sampling activities was performed during the second week of sampling. No significant problems were identified during this audit.

Selection of Rooms in Housing Units

Generally, two rooms were randomly selected from each housing unit for sampling. In unabated houses, the two rooms were selected from those rooms where XRF measurements had been taken in the room, and the average XRF reading was less than or equal to 0.2 mg/cm^2. In abated houses, where possible two rooms were selected with at least 50 square feet of abatement. However, this was not possible in 18 of the abated houses. In these houses, one unabated room was then selected where the average XRF reading was less than 0.2 mg/cm^2. Unabated rooms were sampled to determine whether abatement in other rooms of these houses may have caused increased lead levels in the unabated rooms. Additionally, in 13 houses with higher abatement square footages and two abated rooms already being sampled, an unabated room was also sampled. This was done to avoid a potential bias in the study results toward contrasts in houses requiring small amounts of abatement.

Design Limitations

There were certain specific limitations in the design of the CAP Study which are important to mention. The primary design limitation forms the basis for sampling unabated houses. As discussed above, to assess abatement efficacy one would ideally like to compare pre-abatement levels in each house with levels observed after abatement. This direct type of comparison was performed to the extent possible, however only foundation soil and a limited number of dust measures taken prior to abatement were directly comparable to the measures taken in the CAP Study. Therefore, an indirect measure of the effect of abatement was obtained by comparing post-abatement levels with levels in houses previously identified as relatively free of lead-based paint.

Another important design limitation was that the CAP Study houses abated primarily by encapsulation/enclosure methods had, on average, more abatement performed than those abated primarily by removal methods. Therefore, it is possible that any higher lead levels found in encapsulation/enclosure homes may be attributable to greater initial lead levels and greater amounts of lead-based paint present.

In addition, other minor distinctions exist among the groups of houses which should be understood in interpreting the results. The discussion of significant factors provided in Volume II of this report details dependencies of the factors related to abatement group. For example, on average, abated houses were 17 years older than unabated houses. This fact was controlled for in estimating the effect of house age.

2.3 SAMPLING DESIGN

During the CAP Study a variety of environmental samples were collected along with questionnaire and field inspection information to help assess the performance of abatement methods used in the HUD Demonstration. The environmental samples that were collected are summarized in Table 2-3. All samples were chemically analyzed to measure the amount of lead present. The results for vacuum dust samples were presented on both a concentration basis (i.e., micrograms of lead per gram of dust, µg/g) and a loading basis (i.e., micrograms of lead per unit area sampled, µg/ft^2). Only lead loading results were presented for wipe dust samples and only lead concentration results for soil core samples. All houses were sampled during a five-week period in late winter/early spring of 1992. Although seasonal variations have been documented in previous studies (EPA, 1995b), this short sampling interval reduced the need to control for such variations in comparisons associated with the study objectives.

The environmental sampling planned for the study included both regular samples (vacuum dust and soil cores) and field quality control samples (wipe versus vacuum dust, blanks, and side-by-side samples) intended to assess sampling variability and potential sample contamination. Field quality control samples were collected using the same procedures as regular samples. The role of each type of sample listed in Table 2-3 for meeting these objectives was as follows:

- Vacuum dust from floor perimeter and window stools -- Provided primary measure of performance for interior abatement (the window stool was defined as the horizontal board inside the window--often called the window sill);

- Vacuum dust from window channels -- Provided measure of performance for interior abatement, possible measure of performance for exterior abatement, and possible transport of exterior soil from outside to inside the house (the window channel was defined as the surface below the window sash and inside the screen and/or storm window);

- Vacuum dust from air ducts -- Primarily to provide measure of lead level in dust that has not been disturbed by cleaning and may be more indicative of previous levels of lead in the household dust at a particular home; provided measure of source contribution to interior dust lead levels;

- Vacuum dust from interior and exterior entryway floor -- Provided measure of possible transport of exterior soil from outside to inside the house;

- Soil cores -- Combined with pre-abatement measures, provided primary measure of performance of exterior abatement. Also provided measure of possible transport of exterior soil lead into the house.

Table 2-3. Summary of Environmental Sampling Planned for the CAP Study

Sample Type	Number of Samples Planned		
	For 17 Unabated houses	For 22 Abated Houses[(a)]	For 13 Abated Houses[(b)]
<u>Regular Samples</u>			
1. Vacuum dust			
a. Perimeter floor	2	2	3
b. Window channel	2	2	3
c. Window stool	2	2	3
d. Air ducts	2	2	3
e. Int. entryway floor	2	2	2
f. Ext. entryway concrete	2	2	2
2. Soil cores			
a. Near foundation	2	2	2
b. Property boundary	2	2	2
c. Entryway	2	2	2
<u>Quality Control Samples</u>			
3. Wipe vs. vacuum			
a. Floor wipe dust	0	2	2
b. Floor vacuum dust	0	2	2
4. Blanks			
a. Vacuum dust field blank	1	1	1
b. Vacuum dust trip blank	1	1	1
c. Soil core field blank	1	1	1
d. Wipe dust field blank	0	1	1
5. Side-by-side samples			
a. Vacuum dust floor	1	1	1
b. Soil cores	1	1	1
Total Samples	23	28	32

(a) 22 houses where sampling was conducted in two rooms.
(b) 13 houses where sampling was conducted in three rooms.

- Wipe versus vacuum dust from floors -- Provided consistency check against earlier results from HUD Demonstration and other studies by examining dust levels sampled using vacuum and wipe procedures from adjacent surfaces (recall that the HUD Demonstration Study collected wipe dust samples);

- Vacuum, wipe, and core blank samples -- Provided assessment of potential sample contamination and uncertainty in sample weighing; and
- Vacuum dust and soil core side-by-side samples -- Provided assessment of short-scale sampling variability.

Interior and Exterior Dust

Rooms were selected for sampling primarily to collect floor, window stool, and window channel dust samples. Some of the most important points related to dust sampling are as follows:

- Sampling was in general performed in two different rooms of each unabated house -- this provided a measure of the variability in background lead levels within a house.
- With one exception, sampling was performed in either 1 or 2 abated rooms for each abated house -- sampling 2 abated rooms provided a measure of the variability in abatement performance within a house[1].
- Sampling was performed in 1 unabated room in most abated houses[2] -- the CAP Study pilot sampling and analysis program demonstrated that unabated rooms in abated houses may contain significant amounts of leaded dust (EPA, 1995a). This leaded dust may be due to undetected and unabated lead-based paint in unabated rooms, or to deposition from abatements performed in other rooms of the house.
- If the rooms selected for sampling did not contain an entry, or if there were no air ducts present, or if side-by-side vacuum/wipe comparison samples could not be collected there (e.g., rooms were carpeted), additional rooms were selected from which these samples could be collected.

No abated rooms were sampled in one abated house — this house had only exterior abatement performed. One abated room was sampled in 18 abated houses. Two abated rooms were sampled in 16 abated houses.

No unabated rooms were sampled in three abated houses. One unabated room was sampled in 29 houses. Two unabated rooms were sampled in three houses.

- Abated rooms in abated houses were randomly selected from rooms with at least 50 ft^2 of abatement performed. In houses where the required number of rooms satisfying this condition was not available, rooms with the largest square footage abated were selected.

- In each of the rooms targeted for sampling, sampling was performed on floors, window channels, and window stools. For abated houses this provided a means to assess differences in the way an abatement method performed with respect to different structural components, and for unabated houses this provided a further measure of the within-house variability of background lead levels.

- In each abated house, an uncarpeted room was selected in which to compare the vacuum and wipe dust sampling protocols. To perform this comparison, two vacuum samples and two wipe samples (each sample from a 1 ft^2 area) were collected side by side in a random configuration from the floor perimeter. Where possible, these samples were collected from one of the originally selected rooms, but in some cases, it was necessary to select an additional room. (See previous footnotes * and **.)

- Sampling was performed in one supply air duct in each selected room; in cases where more than one supply air duct was available in a room, the air duct for sampling was randomly selected from those available. If no airducts were available in a room, then (where possible) an air duct was selected from a nearby room.

- Sampling was performed immediately inside and outside the front and rear entryways of each house -- for both abated and unabated houses, these samples provided a means of assessing possible transport of lead from exterior to interior locations.

Exterior Soil

As noted earlier, the HUD Demonstration evaluated the abatement of both interior and exterior painted surfaces, and in fact, for many houses exterior abatement was the most significant activity performed. Furthermore, the same abatement method might be expected to perform quite differently on interior and exterior surfaces. Therefore, the CAP Study evaluated both interior and exterior abatement.

Exterior foundation soil sampling provided the primary means for assessing the effects of exterior lead-based paint and abatement. In this assessment, lead concentrations measured in soil samples taken close to the foundation were compared with those measured in samples taken at the property boundary which were as far as possible from the foundation, and therefore, primarily affected by only background sources of lead, rather than lead-based paint. During the HUD Demonstration, no soil abatement was performed. Therefore, if elevated lead levels were found in the foundation soil, they could be due either to the earlier presence of lead-based paint, or to the exterior abatement activities. It is also possible that airborne lead deposition may be greater in the vicinity of walls than in open areas.

Some of the most important points to note for the soil sampling are as follows:

- Soil samples were collected both at the foundation of each house and at the property boundary -- for abated houses this provided a measure of both soil potentially affected by lead-based paint and/or abatement (i.e., at the foundation) versus soil affected mostly by background sources (i.e., at the property boundary); for unabated houses this provided a measure of the spatial variations in background soil lead levels.

- Samples were collected from two randomly selected sides of the house -- for abated houses this provided a measure of the variability in lead-based paint and/or abatement performance effects, while for unabated houses this provided another measure of the spatial variations in background soil lead levels.

- Samples were collected immediately outside the front and rear entryways -- for both abated and unabated houses this provided a means for assessing possible transport of exterior lead into the house.

2.4 SAMPLE SELECTION, COLLECTION AND ANALYSIS PROCEDURES

For dust collection, a cyclone vacuum was the primary sampling device used. The area vacuumed was nominally 1-ft^2 for floor samples, and nominally the entire accessible surface for window stools, channels, and air ducts. Two one-square foot wipe samples of surface dust were also collected from uncarpeted floors in abated houses.

Soil samples were collected with a soil recovery probe consisting of a 1-inch internal diameter plastic butyrate liner and a 12-inch stainless steel core sampler with cross-bar handle and hammer attachments. Each sample was a composite consisting of three soil cores, each 0.5 inches in depth as measured from the top of the soil surface. A new plastic liner was used for each sample, and the probe was cleaned with wet disposable wipes between each sample. To reduce cross-contamination, only the plastic liner was used where soil conditions allowed.

Sample preparation procedures for dust and soil samples were carried out using versions of EPA SW846 Method 3050, which included use of nitric acid and hydrogen peroxide for sample digestion. Sample digestates for all sample types were analyzed for lead levels using Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) at the 220 nanometer emission line.

3.0 STUDY RESULTS

This section provides a summary and analysis of the CAP Study results. The statistical methods, models, and results are more completely described in Volume II of this report (EPA, 1996). The discussion of results is organized according to the study objective to which they pertain.

3.1 ASSESSMENT OF LONG-TERM ABATEMENT EFFICACY

The CAP Study included two approaches for assessing abatement efficacy, one direct approach and one indirect approach. In the direct approach CAP Study lead measurements, made at HUD Demonstration houses two years after abatement, were compared with pre-abatement lead measurements made by HUD at those same houses. The indirect approach involved comparing lead levels measured in dust and soil samples collected both at abated HUD Demonstration houses, and at the same time at unabated HUD Demonstration houses found to be relatively free of lead-based paint.

Comparison of Pre-Abatement and Post-Abatement Lead Levels

The results of the CAP Study from the direct approach of comparing post-abatement and pre-abatement lead levels follow.

> ***Post- vs. Pre-Abatement.*** For the two sample types for which a comparison was possible, that is window stools and exterior soil, there was no evidence that post-abatement lead levels were significantly higher than pre-abatement levels. Pre-abatement lead loadings and lead loadings measured during the CAP Study averaged between 175 and 200 µg/ft^2. Pre-abatement foundation soil lead concentrations and lead concentrations measured during the CAP Study averaged near 240 µg/g.

This result is based on 21 dust lead measurements made on window stools at 10 CAP Study abated houses, as well as 45 soil lead measurements made at 24 CAP Study abated houses.

These results are tempered by the fact that because of the number of houses for which data were available, as well as the large variability in observed lead levels, relatively large differences between post-abatement and pre-abatement lead levels could not be judged to be statistically significant. For example, the confidence interval about an average ratio of post-abatement to pre-abatement levels for window stools was 0.37 to 3.46. This means that even if post-abatement levels were 3 times higher than pre-abatement levels, they would not be judged to be significantly higher. In addition, further complicating the comparison of post-abatement and pre-abatement dust and soil lead measurements was the fact that different sampling and analysis protocols were used in the CAP Study and HUD Demonstration. Perhaps most significantly, the CAP Study primarily utilized vacuum dust sampling while the HUD Demonstration exclusively utilized wipe dust sampling.

Modeling Results

Table 3-1 provides a summary of the sample types and abbreviations used to represent each sample type in subsequent tables and figures. The results of the CAP Study from the indirect approach of comparing post-abatement lead levels at abated houses with lead levels at unabated houses relatively free of lead-based paint were determined by fitting a series of statistical models to data collected for all sample types, that is, dust and soil sampled at several different locations. Table 3-2 displays estimates of the effects of the primary abatement factors on lead loadings and lead concentrations. The third column of Table 3-2 provides the number of samples included in the model for each sample type. The fourth column contains the estimated geometric mean in houses which were not abated. The log standard error of these estimates appears in parentheses below each estimate. The estimated geometric mean is to be interpreted as the average lead level in typical unabated houses.

Table 3-1. Symbols Used to Denote Sample Types in Tables and Figures

Sample Type	Symbol	Description
Dust	ARD	Vacuum dust samples collected from an air duct within the unit
	WCH	Vacuum dust samples collected from a window channel within the unit
	WST	Vacuum dust samples collected from a window stool within the unit
	FLW	Wipe dust samples collected from a floor within the unit
	FLR	Vacuum dust samples collected from a floor within the unit
	EWI	Vacuum dust samples collected from inside an entryway to the unit
	EWO	Vacuum dust samples collected from outside an entryway to the unit
Soil	EWY	Soil core samples collected adjacent to an entryway to the unit
	FDN	Soil core samples collected at the foundation of the unit
	BDY	Soil core samples collected at the boundary of the property

That is, it represents the estimated average when the significant covariates included in the model are fixed at the nominal levels (e.g., typical unabated house was owner occupied, built in 1943, etc.). Nominal levels and effects of these factors are discussed in Volume II of this report.

The fifth column in Table 3-2 displays the estimated ratio of levels in abated rooms of typical abated houses to levels in typical unabated houses. The abated houses were divided into two categories, according to their predominant method of abatement: encapsulation/enclosure (E/E) or removal. The sixth column contains the estimated impact of abatement method, which should be interpreted as the ratio of levels in abated rooms of typical E/E houses to levels in abated rooms of typical removal houses (a precise definition of "typical" is provided in Volume II). The seventh column in this table gives an estimate of the ratio of

Table 3-2. Estimates[a] of Effects of Primary Abatement Factors on Lead Loading and Lead Concentration; Controlling for Significant Covariates

(1) Response	(2) Sample Type	(3) No. Samples/ Denominator Degrees of Freedom	(4) Geometric Mean[b]	(5) Ratio of Abated to Unabated[c]	(6) Ratio of E/E to Removal[d]	(7) Ratio of Unabated Rooms to Abated Rooms[e]
Lead Loading (μg/ft²)	Air Duct (Vacuum) [ARD]	86 (35)	76 (0.52)	4.70 (0.61) .016	3.99 (0.68) .049	0.73 (0.39) .432
	Window Channel (Vacuum) [WCH]	86 (33)	1604 (0.60)	0.86 (0.68) .831	0.54 (0.80) .448	0.39 (0.53) .091
	Window Stool (Vacuum) [WST]	113 (60)	38.1 (0.39)	1.84 (0.50) .231	2.51 (0.57) .111	0.67 (0.43) .366
	Floor (Wipe)[f] [FLW]	65 (32)			0.93 (0.34) 0.833	
	Floor (Vacuum) [FLR]	233 (105)	16.2 (0.29)	1.76 (0.35) .105	2.02 (0.36) .053	0.56 (0.33) .087
	Entryway (Interior Vacuum) [EWI]	90 (34)	191 (0.31)	1.05 (0.38) .902	1.15 (0.44) .754	1.63 (0.41) .244
	Entryway (Exterior Vacuum) [EWO]	97 (46)	220 (0.37)	2.24 (0.44) .071	1.09 (0.50) .869	
Lead Concentration (μg/g)	Air Duct (Vacuum) [ARD]	86 (35)	332 (0.19)	1.59 (0.23) .049	2.01 (0.24) .006	0.79 (0.23) .301
	Window Channel (Vacuum) [WCH]	83 (29)	851 (0.44)	0.98 (0.51) .970	1.46 (0.59) .529	0.61 (0.40) .217
	Window Stool (Vacuum) [WST]	113 (60)	416 (0.30)	1.70 (0.39) .176	1.77 (0.44) .199	0.69 (0.31) .251
	Floor (Vacuum) [FLR]	233 (105)	137 (0.18)	1.03 (0.22) .888	1.30 (0.23) .258	0.87 (0.22) .534
	Entryway (Interior Vacuum) [EWI]	90 (34)	183 (0.22)	0.85 (0.27) .561	0.95 (0.31) .876	1.28 (0.26) .341
	Entryway (Exterior Vacuum) [EWO]	97 (46)	184 (0.22)	1.19 (0.26) .509	1.01 (0.29) .976	
	Entryway (Soil) [EWY]	109 (12)	126 (0.18)	1.48 (0.21) .087	1.26 (0.24) .365	
	Foundation (Soil) [FDN]	88 (14)	86 (.14)	1.82 (0.20) .009	0.81 (0.28) .452	
	Boundary (Soil) [BDY]	120 (20)	86 (0.13)	1.63 (0.15) .004	1.27 (0.18) .205	

[a] Top value in columns 5-7 is multiplicative estimate, middle value is logarithmic standard error of estimate, and bottom value is observed significance level.
[b] Geometric mean in unabated houses after controlling for effects of significant factors.
[c] Ratio of levels in abated rooms of abated houses to those in unabated houses.
[d] Ratio of levels in E/E houses to those in removal houses.
[e] Ratio of levels in unabated rooms of abated houses to those in abated rooms of the same houses.

[f] Floor wipe samples were only collected in abated houses; the geometric mean in abated houses was 11.3 $\mu g/ft^2$ after controlling for significant factors.

levels in unabated rooms of abated houses to levels in abated rooms of abated houses. The log standard error and significance level appear beneath each of these estimates. The latter represents the observed significance of a test that the ratio equals 1.

The models used to estimate these primary effects included various secondary abatement factors and additional non-abatement factors. Secondary abatement factors included total square feet abated by each method, the abatement contractor, phase of abatement, and XRF measures taken during the HUD Demonstration. The non-abatement factors included those related to sampling substrate and protocol deviations, as well as resident-related factors such as cleanliness, ownership, occupation, and activities. The specific factors included in each model and their effects are described in detail in Volume II.

In the subsequent discussion of the results, an effect is described as being "statistically significant" if the associated p-value is less than 5 percent. The reader is referred to Appendix C of Volume II of this report for specific p-values. These p-values can be interpreted as the probability that the observed result may have occurred simply by chance. Therefore, small p-values represent situations where the results are unlikely to be simply chance events.

The estimated ratios in Table 3-2 (i.e., columns 5-7) are displayed graphically in Figures 3-1 and 3-2 for lead loading and lead concentration, respectively. Reference lines are provided on these plots at a level of one (1) which indicates that the lead levels in both types of houses or rooms were equal. An asterisk indicates that the effect was significant at the 5 percent level. A bar which rises above the reference line for the 'Abatement' factor indicates that for this sample type levels were higher in abated houses than in unabated houses. A bar which rises above the reference line for the 'Method (E/R)' factor indicates that the levels in E/E houses were higher than those in removal houses. If the 'Unabated room' effect is greater than one, then levels in unabated rooms of abated houses

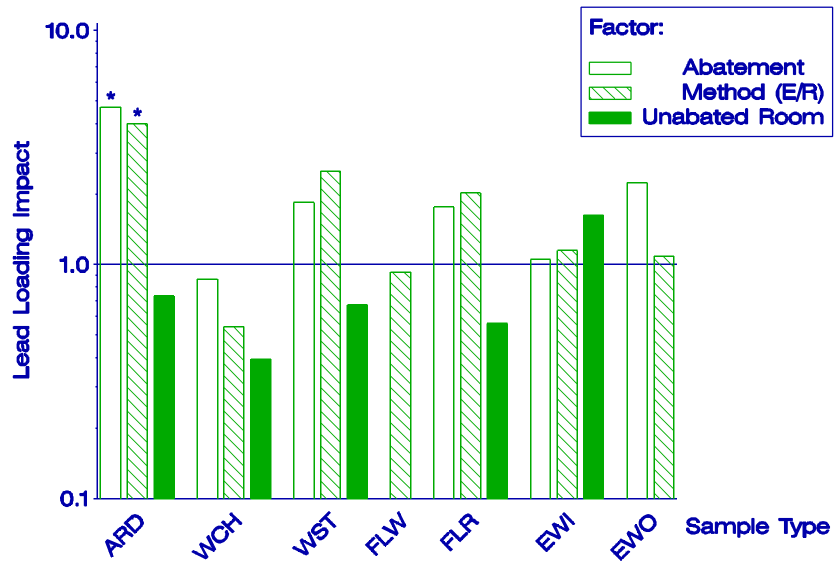

Figure 3-1. Estimated multiplicative effects of abatement from mixed model ANOVA: Lead Loading.

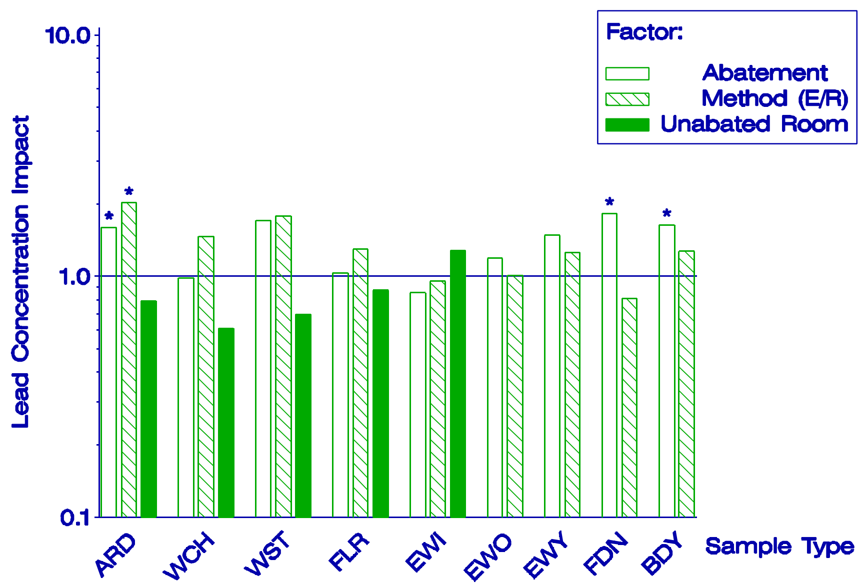

Figure 3-2. Estimated multiplicative effects of abatement from mixed model ANOVA: Lead Concentration

* Bars with a '*' indicate that the factor was statistically significant at the 5 percent level.

were higher than in abated rooms. The results presented in this table and these figures are discussed in the subsequent sections.

Comparison of Levels in Abated and Unabated Houses

The first objective of the CAP Study was to assess the long-term efficacy of abatements performed in the HUD Demonstration Study. The following conclusions can be made from the CAP Study results.

> ***Abated vs. Unabated Houses.*** Only in air ducts and soil were geometric mean lead levels significantly higher in abated houses than in unabated houses. In soil, lead concentrations were significantly higher than corresponding levels outside unabated homes at the foundation and at the property boundary. Neither soil nor air ducts was abated in the HUD Demonstration.

As illustrated in the fifth column of Table 3-2, lead concentrations were about 1.6 times higher in the air ducts of abated houses than in unabated houses. Lead loadings were on average 4.7 times greater in the abated homes, reflecting that ducts in the abated houses were also dustier than in unabated houses. On average, lead concentrations in soil were 82 percent greater at the foundation and 63 percent greater at the boundary of abated houses. The difference between the percentage estimates was statistically significant, reflecting a greater contrast between levels at abated and unabated houses in foundation soil than in boundary soil. This suggests that the contrasts between abated and unabated houses is, at least in part, due to lead-based paint. However, it is important to note that air ducts and soil were not abated in the HUD Demonstration. Also, abated houses in this study were 17 years older than unabated houses.

Comparison of Levels in Unabated and Abated Rooms of Abated Homes

To determine whether levels in abated houses varied systematically between abated and unabated rooms, dust samples were collected from floors, window stools, and window channels in both types of rooms, and the following results were found.

> ***Abated vs. Unabated Rooms.*** Lead levels were not significantly different between unabated rooms of abated houses and abated rooms of those same houses.

The seventh column in Table 3-2 lists the estimated multiplicative factor by which geometric mean lead levels in unabated rooms were lower (or higher) than geometric mean lead levels in abated rooms. No differences were statistically significant, although on floors and window channels lead loadings were somewhat lower in unabated rooms (with p values between 0.05 and 0.10).

<u>Comparison of Abatement Methods</u>

In addition to general assessments of abatement efficacy, measures were taken to assess different methods of abatement.

> ***E/E vs. Removal.*** Only in air ducts were mean lead levels significantly higher in houses abated by encapsulation/ enclosure methods than in houses abated by removal methods.

Lead loadings and lead concentrations were significantly higher in the air ducts of E/E houses than in removal houses. Two facts are important to note here. First, houses at which E/E methods were used generally had more lead-based paint present than houses at which removal methods were used. Second, air ducts, which were the only sample type for which significant differences were found with respect to E/E versus removal were not abated in the HUD Demonstration.

Floor lead loadings were on average twice as large in E/E houses as they were in removal houses. This was very nearly statistically significant (p=0.053), suggesting a difference worth recognizing. Noting that the difference in lead concentrations between abated and unabated houses was not signifcant, it is evident that the difference in lead loading is due primarily to increased dust loading in the abated houses.

In addition to sampling and analysis, at the time of sampling each abated substrate in a room or exterior area selected for sampling was visually inspected. Its condition was recorded as either completely (70 percent or more) intact, partially (50 to 70 percent) intact, or minimally (less than 50 percent) intact. Table 3-3 displays a summary of this data by method of abatement. Specific abatement methods are distinguished within the general E/E and removal categories.

Table 3-3. Condition of Abated Substrates, by Method of Abatement

Category	Method	Completely Intact	Partially Intact	Minimally Intact
E/E	Enclosure	40 (80%)	10 (20%)	0
	Encapsulation	109 (58%)	68 (36%)	10 (6%)
Removal	Chemical Stripping	30 (56%)	18 (33%)	6 (11%)
	Heat Gun	40 (70%)	17 (30%)	0
	Removal & Replacement	38 (95%)	2 (5%)	0

Visual Inspection Results. At least 70 percent of the substrates abated by enclosure, heat gun, and removal and replacement were completely intact at the time of sampling. Less than 60% of those substrates abated by chemical stripping and encapsulation methods were completely intact.

The components which were removed and completely replaced were in the best condition; 95 percent of these were completely intact. When interpreting these results, it should be noted that the abated houses were unoccupied at the time of abatement, and were not continuously occupied between the completion of abatement and the time of CAP Study sampling. Lack of temperature control and lack of regular cleaning may have more strongly affected the encapsulation or chemical stripping methods than the other abatement methods. Unoccupied houses may not have been heated in the winter, causing temperature swings which could lead to cracking or peeling.

With regard to interpreting all of the modeling results in this section, the reader should be aware of the large number of statistical tests involved in an analysis of this sort. Two or three primary abatement effects were estimated for each sample type listed in Table 3-2. This represents a total of 41 tests at the 5 percent significance level. If all these tests were independent, even if there were no true effects, one would expect about two effects to be identified as significant (41(0.05)=2.05). In fact, the tests are not independent. Concentration measurements are very much related to loading measurements. The exact impact of this dependence is impossible to quantify, however this relationship effectively reduces the actual number of tests being performed. In total, six of the 41 tests produced significant results.

3.2 CHARACTERIZATION OF LEAD LEVELS

The second objective of the CAP Study was to characterize lead levels in household dust and exterior soil for abated and unabated houses. The following three subsections present these levels, and compare them with interim clearance standards, as well as with results observed in other studies.

Descriptive Statistics

Table 3-4 presents a summary of descriptive statistics associated with the CAP Study. In addition to the geometric mean and the arithmetic mean, the minimum and maximum values are listed with the log standard deviation. The sample sizes in this table are sometimes greater than those presented in Table 3-2. This is because the results presented in the earlier tables controlled for various significant covariates. In cases where the significant covariates were unknown, samples were excluded from fitting the models. The results in Table 3-4 should be given less weight in interpreting the data, because they do not control for factors found to be significant. However, they are useful for comparing the CAP Study with other

Table 3-4. Descriptive Statistics for Lead Loading (µg/ft^2), Lead Concentration (µg/g), and Dust Loading (mg/ft^2) by Sample Type

Medium	Measurement	Statistic	Air Duct (Vacuum)	Window Channel (Vacuum)	Window Stool (Vacuum)	Floor (Wipe)	Floor (Vacuum)	Entryway Interior (Vacuum)	Entryway Exterior (Vacuum)
Dust	Lead Loading (µg/ft^2)	Number of Samples	109	98	113	67	238	100	97
		Geometric Mean	120.36	2515.59	74.43	11.24	27.15	208.00	384.17
		Arithmetic Mean	1530.60	13637.20	584.62	22.68	244.22	774.18	1234.56
		LN Standard Deviation	2.29	2.24	2.12	1.05	2.03	1.99	1.74
		Minimum	1.85	19.12	0.86	2.72	0.34	1.23	3.97
		Maximum	40863.60	244581.21	16710.45	333.56	11641.25	7349.00	14021.00
	Lead Concentration (µg/g)	Number of Samples	109	98	113		238	100	97
		Geometric Mean	427.19	1438.61	622.94		150.31	186.25	237.48
		Arithmetic Mean	664.07	4920.84	2168.84		395.92	344.97	542.39
		LN Standard Deviation	0.91	1.69	1.55		1.14	1.01	1.06
		Minimum	58.48	72.90	10.15		1.71	9.24	8.84
		Maximum	5644.54	45229.26	48271.93		13567.76	5332.00	16335.45
	Dust Loading (mg/ft^2)	Number of Samples	109	98	113		238	100	97
		Geometric Mean	281.75	1748.63	119.48		180.60	1116.70	1617.67
		Arithmetic Mean	3554.57	4386.95	244.15		572.17	2891.59	3143.55
		LN Standard Deviation	2.00	1.46	1.18		1.65	1.66	1.30
		Minimum	5.01	4.80	4.63		0.43	8.50	40.60
		Maximum	128646.00	46328.75	2824.00		14426.00	20857.40	22170.30
			Entryway	**Foundation**	**Boundary**				

studies where covariates were not controlled in the reporting of results.

Lead levels were found to vary greatly for different media and sampling locations. Minimum individual lead concentrations for most sample types were usually on the order of 10 μg/g except in air ducts and window channels where levels were at least 50 μg/g. Maximum individual lead concentrations were lowest for boundary and entryway soil samples (1073 and 1068 μg/g, respectively) and highest for window stool and window channel dust samples (48,272 and 45,229 μg/g, respectively). Minimum individual lead loadings for sample types were in general only 1 to 4 μg/ft^2 with window channels being the only exception. Maximum individual lead loadings were lowest for floor dust samples (334 μg/ft^2 by wipe and 11,641 μg/ft^2 by vacuum) and highest for window channel dust samples (244,581 μg/ft^2).

Modeling Results

The lead loadings and lead concentrations from the CAP Study models were summarized in Table 3-2, as well as in the following points:

> ***Lead Loadings.*** Geometric mean dust lead loadings in unabated houses varied from a low of 16 μg/ft^2 for floor vacuum dust samples to a high of 1604 μg/ft^2 for window channel samples.
>
> ***Lead Concentrations.*** Geometric mean lead concentrations varied in unabated houses from lows of 86 μg/g for boundary and foundation soil samples and 137 μg/g for floor vacuum dust samples to a high of 851 μg/g for window channel dust samples.

Results from modeling geometric mean lead loadings by housing category are provided in Table 3-5 for floor, window stool, and window channel samples based on an estimation procedure outlined in Volume II (EPA, 1996). This procedure uses the ratio estimates presented in columns 4, 5, and 6 of Table 3-2, along with exponents reflecting typical proportions abated by each method.

Table 3-5. Modeled Geometric Mean Lead Loadings by House Type for Floor, Window Stool, and Window Channels ($\mu g/ft^2$)

Sample Type	Unabated	Abated	Removal	E/E
Floor	16.2	28.5	17.3	35.0
Window Stool	38.1	70.1	36.5	91.7
Window Channel	1604	1379	2134	1152

Comparisons with HUD and EPA Standards

In addition to comparing relative lead levels among unabated, E/E, and removal houses, these levels in each housing category can be compared against "Lead-Based Paint: Interim Guidelines for Hazard Identification and Abatement in Public and Indian Housing" abatement clearance standards (HUD, 1990b). These standards for floor, window stool, and window channel dust samples are 200, 500, and 800 $\mu g/ft^2$. The EPA has proposed a reduced standard of 100 $\mu g/ft^2$ for floors, maintaining the 500 ug/ft^2 and 800 $\mu g/ft^2$ standards for window stools and window channels, respectively (EPA, 1994). Geometric mean floor vacuum lead loadings for unabated houses, abated houses, E/E houses, and removal houses were all well below the EPA standard of 100 $\mu g/ft^2$. Similarly, geometric mean window stool lead loadings for these four classes of houses were well below the HUD/EPA standard of 500 $\mu g/ft^2$. In addition, for both of these sample types, more than 75 percent of the samples collected in the CAP Study had lead loadings below their respective standards, in both abated and unabated houses. However, geometric mean window channel lead loadings at both abated and unabated houses were found to be well above the HUD/EPA interim standard of 800 µg/ft^2, and well over half of individual observations were above this standard, at both abated and unabated houses. It is interesting to note that modeled window channel lead loadings in typical abated houses were actually lower than those for the unabated houses; and that lead loadings were lower in houses abated by encapsulation/ enclosure methods than in houses abated by removal methods. However, the variability in both of these measures prevented either of these differences from being declared statistically significant.

<u>Comparisons with Other Studies</u>

Lead levels observed in the CAP Study were usually equivalent to, or below, levels observed in several other studies, with one notable exception being the HUD National Survey. Table 3-6 presents lead loadings in floor, window stool, and window channel samples for the CAP Study and four other studies. Along with the geometric mean lead loadings, these tables also present the 25th and 75th percentile lead loadings when they were available. The following main conclusion can be made from this table:

> ***Comparison with Other Studies.*** CAP Study lead loadings were at or below those in the other studies, with three exceptions. First, the CAP Study geometric mean window channel lead loadings (approximately 2500 µg/ft^2) were significantly higher than those recorded for the HUD Demonstration Study (approximately 500 µg/ft^2). Second, for floor, window stool, and window channel samples, the CAP Study geometric mean lead levels were typically at least an order of magnitude higher than for National Survey samples. Third, CAP Study geometric mean lead loadings for window channels were approximately twice as high as post-abatement levels in the second Kennedy-Krieger Study.

The greater observed window channel lead loadings might be due to the fact that the CAP Study sampled only in Denver, while the HUD Demonstration Study sampled in Denver and six other metropolitan areas. The difference might also be due to increased sample recovery achieved in the CAP Study using cyclone vacuum sampling as opposed to the HUD Demonstration Study wipe sampling. Also,

Table 3-6. Descriptive Statistics for Lead Levels Observed in Various Field Studies

Sample Type	Study		House Type	Sample Size	25%	Geom. Mean	75%
Floor lead loading (μg/ft^2)	CAPS		Unabated Abated	51 187	5.71 6.73	21.38 28.97	64.99 104.34
	HUD Demonstration[1]			1026	23.55	66.01	185.06
	National Survey		High XRF[2] Low XRF[3]	686 90	0.42 0.16	1.47 0.47	5.13 1.41
	Kennedy-Kreiger[4]	Pre-Abatement Post-Abatement Post (6 months)	Traditional Abatement Modified Abatement Traditional Abatement Modified Abatement Traditional Abatement Modified Abatement	280 82 271 50 234 57	na na na na na na	250.84 288.00 1440.00 650.32 315.87 315.87	na na na na na na
	Kennedy-Kreiger[5]	Pre-Abatement Post-Abatement Post (6 months)		70 70 63	na na na	520.26 130.06 55.74	na na na
Window stool lead loading (μg/ft^2)	CAPS		Unabated Abated	35 78	9.85 15.43	46.90 91.57	224.68 467.23
	HUD Demonstration[1]			783	26.70	89.06	297.09
	National Survey		High XRF[2] Low XRF[3]	329 38	0.82 0.24	4.32 1.26	22.77 6.68
	Kennedy-Kreiger[4]	Pre-Abatement Post-Abatement Post (6 months)	Traditional Abatement Modified Abatement Traditional Abatement Modified Abatement Traditional Abatement Modified Abatement	280 82 271 50 234 57	na na na na na na	1337.80 1802.32 3595.35 603.87 1542.19 1635.09	na na na na na na
	Kennedy-Kreiger[5]	Pre-Abatement Post-Abatement Post (6 months)		70 70 63	na na na	4607.99 325.16 408.77	na na na
Window channel lead loading (μg/ft^2)	CAPS		Unabated Abated	27 71	738.00 510.51	2330.21 2589.90	12427.41 18883.56
	HUD Demonstration[1]			756	138.10	506.21	1855.57
	National Survey		High XRF[2] Low XRF[3]	142 7	12.08 2.97	72.64 28.94	436.72 282.33
	Kennedy-Kreiger[4]	Pre-Abatement Post-Abatement Post (6 months)	Traditional Abatement Modified Abatement Traditional Abatement Modified Abatement Traditional Abatement Modified Abatement	280 82 271 50 234 57	na na na na na na	15496.2 2 18274.0 314353. 52 8082.56 12467.5 9 24879.4 3	na na na na na na
	Kennedy-Kreiger[5]	Pre-Abatement Post-Abatement Post (6 months)		70 70 63	na na na	29422.3 9 938.32 1003.35	na na na

(1) All metropolitan areas in the FHA portion.
(2) Predicted maximum interior or exterior XRF reading at these residences was at least 1.0 mg/cm^2.
(3) Predicted maximum XRF reading at these residences was below 1.0 mg/cm^2.
(4) Farfel and Chisolm (1990).
(5) Farfel and Chisolm (1991).

it may be that lead re-accumulated from sources, such as soil and air ducts, in the period between abatement and sampling, or that CAP Study houses were dustier due to differences in cleaning practices.

The second case in which CAP Study lead loadings were relatively high was in comparison with HUD National Survey results. For floor, window stool, and window channel samples, the CAP Study lead levels were typically at least an order of magnitude higher than for National Survey samples. Some of these differences are accounted for by low sample recoveries obtained in the HUD National Survey. Vacuum versus wipe field testing by EPA (EPA, 1995a) indicated that the vacuum sampling protocol used in the HUD National Survey recovered only about 20% of the lead dust that would be recovered by a wipe sample. Wipe sample results tended to be less than or equivalent to those from the CAPS vacuum sampler. Hence there is likely to be at least a five fold difference between CAPS vacuum dust results and National Survey vacuum dust results, which would account for some of the differences in lead loadings between the CAP Study and the National Survey.

3.3 CORRELATION OF LEAD LEVELS IN DIFFERENT MEDIA AND LOCATIONS

The third objective of the CAP Study was to investigate the relationship between lead levels in different media (i.e., dust and soil) and different sampling locations (e.g., floors, window channels, foundation soil). These relationships were quantified by between-house and within-house correlation coefficients. Between-house correlations reflect house-to-house relationships among different sample types, such as between air ducts and window channels. Within-house correlations are similar measures, except they are based on room-to-room differences within a house, after controlling for house average lead levels. For some pairs of sample types (e.g., entryway interior and floor vacuum), there were insufficient data available to estimate the within-house correlations after fitting the statistical model. Correlation coefficients were calculated for both lead loadings and lead concentrations. However, only a relatively small number of correlation coefficients were found to be significant. The significant relationships found are presented in Table 3-7 and summarized in the following points:

Table 3-7. Significant Between-House and Within-House Correlations

Response	Correlated Sample Types	Correlation	DF[1]	Significance
Between-House Lead Loading	Air duct and exterior entryway dust	0.41	36	.01
	Window channel and window stool	0.56	41	<.01
	Floor (wipe) and exterior entryway dust	0.44	27	.02
Between-House Lead Concentration	Window channel and window stool	0.40	41	.01
	Window stool and boundary soil	0.38	44	.01
	Interior entryway and entryway soil	0.29	44	.05
	Entryway soil and boundary soil	0.56	44	<.01
Within-House Lead Loading	No significant correlations	-	-	-
Within-House Lead Concentration	Interior entryway and exterior entryway dust	0.37	31	0.03

Between-House Correlations for Lead Loadings. At the house level, significant correlations in dust lead loadings were found for three pairs of sample types. These were between window channels and window stools (correlation coefficient of 0.56), between air ducts and exterior entryways (0.41),

This column lists the degrees of freedom available to estimate correlation after controlling for significant model factors.

and between floor (wipe) samples and exterior entryways (0.44).

Between-House Correlations for Lead Concentrations. Significant correlations in lead concentrations at the house level were found for four pairs of sample types. These were between lead concentrations in window channel and window stool dust (0.40), between entryway soil and boundary soil (0.56), between boundary soil and window stool dust (0.38) and between entryway soil and interior entryway dust (0.29).

Within-House Correlations. At the room level, no significant correlations in dust lead loadings were found. However, significant correlation was observed between interior and exterior entryway dust lead concentrations (0.37).

The reader should note that there were a total of 50 correlation tests performed. With a 5 percent significance level, one could expect about two to three significant relationships simply by chance. A total of eight significant correlations were identified.

3.4 COMPARISON OF CYCLONE AND WIPE DUST SAMPLING

A final objective of the CAP Study, which was not originally stated at the study design stage but which evolved during the course of the study, was to compare the performance of two dust sampling protocols: cyclone vacuum sampling and wipe sampling. The results of this comparison are presented in Table 3-8, and can be summarized as follows:

Vacuum vs. Wipe Ignoring Substrate. Lead loadings from side-by-side wipe and (cyclone) vacuum dust samples were not significantly different when pooled across the various substrates sampled in the CAP Study.

Vacuum vs. Wipe by Substrate. The performance of these two sampling protocols was found to be different for different substrates. On tile and linoleum surfaces cyclone vacuum lead loadings were not found to be significantly different from wipe lead loadings. Cyclone lead loadings were higher than wipe lead loadings on wood surfaces (3.9 times higher).

The 95% confidence interval for the ratio of vacuum to wipe recovery on wood was 1.13 to 13.59.

Table 3-8. Vacuum/Wipe Multiplicative Bias Estimates

Substrate	Sets of Observations	Estimated Vacuum/Wipe Multiplicative Bias	Lower Confidence Bound	Upper Confidence Bound
Tile	5	0.69	0.12	3.90
Linoleum	18	1.02	0.42	2.44
Wood	9	3.92	1.13	13.59
Combined	33	1.38	0.75	2.54

3.5 RESULTS OF THE QUALITY CONTROL AND DATA VERIFICATION PROCEDURES

Results of the quality control (QC) procedures confirmed that the sampling and analytical protocols employed in the CAP Study produced data of sufficient quality. Analysis of the blank samples suggested little if any procedural contamination. The majority of blanks were measured with a lead content below the instrumental level of detection. Despite some procedural problems in their creation and analysis, the results for the recovery samples indicated very good method performance. Spiked duplicate samples created in the laboratory exhibited very good agreement. Finally, there was no significant evidence of a time-based trend in any of the QC samples.

Additional data verification procedures included a laboratory review of potential outliers statistically identified in the data, an audit of the data management system, and a laboratory quality assurance audit. The results of these procedures further verified the accuracy of the data upon which the analyses were based. Moreover, a statistical analysis audit confirmed that the reported statistical analyses were correctly performed.

The inherent variability between field samples, however, was evident in the results of the side-by-side field samples. Despite being collected side-by-side, a number of the pairs were measured to have very different lead contents. Greater inherent variation was seen in dust samples than in soil samples. The median ratio of the larger to the smaller of two side-by-side vacuum dust lead loadings in the CAP Study was about 2.33. The median ratio for lead concentrations was 2.07. These results suggest that studies to assess abatement performance and potential lead hazards must be carefully designed to control for these complicating sampling variations. For example, random selection of sampling locations was incorporated into the CAP Study design to eliminate biases in sample selection.

4.0 DISCUSSION

The CAP Study demonstrated that an accurate assessment of potential lead hazards can be seriously complicated by the high degree of variability commonly found in environmental lead measures. Lead determinations can depend heavily on the sampling and analysis procedures used, and they can vary greatly among similar housing environments and among different sampling locations within a single housing environment.

Pre- Vs. Post-Abatement Lead Levels

The CAP Study included two approaches for assessing abatement efficacy, one direct approach and one indirect approach. The results of the CAP Study from the direct approach of comparing post-abatement and pre-abatement lead levels were that for the two sample types for which a comparison was possible, abatement appears to have been effective, in the sense that there is no evidence that post-abatement lead levels were significantly higher than pre-abatement levels. This result is based on dust lead measurements made on window stools at 10 CAP Study abated houses, as well as soil lead measurements made at 24 CAP Study abated houses. Several floor dust samples were also available for comparison, but were deemed insufficient for making substantive conclusions.

These results indicate that while the abatements may not have reduced lead levels in dust and soil from their pre-abatement condition, the abatements were successfully performed without raising lead levels in these two media. This finding is significant since the pre-abatement lead levels in dust and soil were already relatively low in comparison with levels found by other field studies. However, these results are tempered by the fact that because of the small number of houses for which data were available, as well as the large variability in observed lead levels, relatively large differences between post-abatement and pre-abatement lead levels could not be judged to be statistically significant. For example, the confidence interval about an average ratio of post-abatement to pre-abatement levels on window stools was 0.37 to 3.46, indicating that three-fold differences would be judged insignificant. In addition, further complicating the comparison of post-abatement and pre-abatement dust and soil lead measurements was the fact that different sampling and analysis protocols were used in the CAP Study and HUD Demonstration. Perhaps most significantly, the CAP Study utilized vacuum dust sampling while the HUD Demonstration utilized wipe dust sampling.

Lead Levels in Abated vs. Unabated Houses

The indirect assessment of abatement efficacy also found that abatement appears to have been effective, in this case in the sense that there is no evidence that post-abatement lead levels at abated houses were significantly different from lead levels at neighboring unabated houses found to be relatively free of lead-based paint. There were two exceptions to this statement; however, both of these exceptions were anticipated and are logically explained. First, lead concentrations in air ducts were significantly higher in abated houses than in unabated houses; air ducts were not abated in the HUD Demonstration. In addition, lead concentrations in the soil outside abated houses were significantly higher at the foundation and at the boundary than corresponding lead concentrations outside unabated houses. This difference between soil lead concentrations at abated and unabated houses was significantly more pronounced near the foundation than it was at the boundary. This suggests that these contrasts are due at least in part to lead-based paint at the abated houses. However, soil also was not abated during the HUD

Demonstration; and these higher lead levels might in part be due to differences in the age of these houses, since on average the abated houses in this study were 17 years older than unabated houses. As with the caveat stated above, these results must also be tempered by the fact that not finding a significant difference in lead levels at abated and unabated houses for all other building components and sampling locations does not prove that no such differences exist. The CAP Study was designed to detect approximately two-fold differences between lead levels at abated and unabated houses under specified variance assumptions. For example, although the estimate of 1.76 for the ratio of lead loadings on floors in abated to unabated houses was not significantly different from one, the 95 percent confidence interval was from about 0.87 to 3.5.

Comparison of Abatement Methods

The CAP Study also assessed abatement by comparing encapsulation and enclosure methods versus removal methods. No significant differences among lead levels could be attributed to these two types of abatement methods, except for air ducts which, as stated above, were not abated. Air duct dust lead levels were higher in houses abated primarily by encapsulation and enclosure methods than in houses abated primarily by removal methods. The CAP Study also performed a visual inspection of abated surfaces and recorded their condition as being completely intact, partially intact, or minimally intact. Less than 60% of the surfaces abated by encapsulation and chemical stripping methods were found to be completely intact, while more than 70% of the surfaces abated by all other methods were found completely intact.

These results suggest that both encapsulation/enclosure and removal abatement methods can be performed in residential housing environments without depositing significant amounts of residual lead in dust and soil. Of course, proper dust control procedures must be employed while conducting any lead-based paint hazard abatement. However, while dust and soil lead levels were not found to be significantly different two years after abatement, there is some indication from the visual inspection information that residual problems may be seen in the future at locations abated with encapsulation and chemical stripping methods.

Characterization of Lead Levels

With regard to the second study objective, lead levels were found to vary greatly for different media and sampling locations. Dust lead loadings were also evaluated in comparison with the HUD and EPA interim dust clearance standards. Geometric mean floor lead loadings at both abated and unabated houses were below the EPA standard of 100 $\mu g/ft^2$. Geometric mean window stool lead loadings were found to be below the HUD/EPA interim standard of 500 $\mu g/ft^2$. In addition, for window stools in both abated and unabated houses, and for floors in unabated houses, more than 75 percent of the samples collected in the CAP Study had lead loadings below their respective standards, in both abated and unabated houses. The 75th percentile of floor lead loadings in abated houses was about 104 $\mu g/ft^2$. However, geometric mean window channel lead loadings at both abated and unabated houses were found to be well above the HUD interim standard of 800 $\mu g/ft^2$, and well over half of individual observations were above this standard, at both abated and unabated houses.

Most of the samples in the CAP Study were collected by a vacuum method of dust collection. Clearance samples are usually collected by a wipe method. In the CAP Study comparison of vacuum and wipe methods, wipes tended to produce either equivalent or lower lead levels than the vacuum used in the CAP

Study, with the most pronounced difference on wood substrates. The CAP Study vacuum samples resulted in geometric mean lead loadings that were less than the clearance standards for floors and window stools. From the relationship between wipe and vacuum samples demonstrated in the CAP Study, it is plausible to infer that wipe samples would also produce geometric mean lead loadings less than the clearance standards for floors and window stools. However, for window channels, the CAP vacuum samples were generally above the clearance standard. Because of the difference between vacuum and wipe samples, especially on wood, it is not clear that wipe samples on window channels would exceed the clearance standard.

Overall Assessment of Abatement

The CAP Study found no significant differences between post-abatement and pre-abatement lead levels for exterior soil and the limited number of window stool dust lead measurements available. It also found no significant differences between post-abatement lead levels at abated houses and lead levels at unabated houses, with the exception of air duct dust and soil which were not abated in the HUD Demonstration. In addition, for both floors and window stools the geometric mean lead loadings at abated houses were well below the HUD standards of 200 and 500 $\mu g/ft^2$. These results all suggest that the HUD abatement activities were effective, in the sense that they do not appear to have increased lead levels at abated houses above interim standards. However, the CAP Study also found that the geometric mean lead loading for window channels at abated houses was well above the HUD interim standard of 800 $\mu g/ft^2$, although the same result was found for unabated houses relatively free of lead-based paint.

Correlations Among Media and Sampling Locations

Three primary conclusions were found for the third CAP Study objective. First, significant correlations in lead concentrations at the house level were found for four pairs of sample types: window channels and window stools (correlation coefficient of 0.40), entryway soil and boundary soil (0.56), boundary soil and window stools (0.38), and entryway soil and interior entryway dust (0.29). Second, at the house level, significant correlations in dust lead loadings were found for three pairs of sample types: window channels and window stools (0.56), air ducts and exterior entryway dust (0.41), and floor (wipe) dust and exterior entryway dust (0.44). And third, at the room level, no significant correlations in dust lead loadings were found. However, significant correlation was observed between dust lead concentrations at interior and exterior entryways (0.37). House level correlations were based on house averages; room level correlations were based in most cases on single measurements.

The fact that significant correlations were found in the CAP Study suggests that lead may be redistributed over time throughout a residential housing environment. However, the fact that more house-level correlations were significant suggests that overall lead levels are more related to broad differences among houses than to location-specific characteristics within houses.

Cyclone Vacuum vs. Wipe Dust Sampling

Combined across substrates, the difference between dust lead loadings measured by the cyclone vacuum method and by the wipe method was not significant. Differences were overshadowed both by large side-by-side variability in the two methods, and a strong substrate effect. This latter effect was apparently related to the smoothness of the substrate. On tile and linoleum, the two methods were approximately equivalent, whereas on wood lead loadings measured by the cyclone were higher than those measured by wipe. Thus, the level of lead measured depends on the way in which it is collected. This study has led to several subsequent investigations of dust collection methods, including the Rochester Study of the relationship between different dust collection methods and children's blood lead levels, and an EPA laboratory study of different dust collection methods.

Future Research

Several research issues have been raised but not addressed by the CAP Study. The two main issues are discussed in this section.

There has been no direct assessment of the relationship between health risks and the environmental sampling being performed in the CAP Study. In the CAP Study, an implicit assumption was made that health risks are correlated with dust and soil lead levels at residences. No blood or other health-based observations were made at the houses sampled in the CAP Study, precluding the assessment of abatement efficacy with respect to the prevention of health risks.

The methods used for abatement in the CAP Study were generally expensive. Removal and enclosure methods can be particularly costly. Other less costly approaches to abatement such as regular wet mopping, dust cleaning, paint stabilization, and in-home education deserve consideration and study.

Other ongoing studies are investigating the efficacy of less costly means of abatement. These include a dust cleaning products study, the Repair and Maintenance Study in Baltimore, the Milwaukee Low-Cost Efficacy Study, and additional low-cost abatement studies in other cities co-funded by EPA and the Centers for Disease Control and Prevention.

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15. Supplementary Notes

Support staff involved in the conduct of this study and the production of this report included Tamara Collins, Nick Sasso, Casey Boudreau, Ben Pierce and Joan Cwi of Battelle, and Paul Constant, Jim McHugh, Jack Balsinger, Scott Cogbill, Mark Daniels, Dave Griffin, and Rose Habib of Midwest Research Institute.

16. Abstract (Limit 200 words)

In response to requirements mandated by the Lead-Based Paint Poisoning Prevention Act, in 1989 the U.S. Department of Housing and Urban Development (HUD) initiated the Lead-Based Paint Abatement Demonstration Study in seven urban areas across the U.S. The objectives of this study were to assess the cost, worker hazards, and short-term efficacy of various lead-based paint abatement methods. Among other conclusions, the FHA portion of this study estimated that abatement costs for a single-family dwelling could range from $2000 to $12,000. One question which was not answered by the HUD Abatement Demonstration was that of the long-term efficacy of the abatement methods. Therefore, in 1990 the U.S. Environmental Protection Agency (EPA), in cooperation with HUD, initiated the Comprehensive Abatement Performance (CAP) Study to address this question.

The CAP Study was a follow-up to HUD Abatement Demonstration activities performed in Denver, Colorado. There were four primary objectives of the CAP Study: (1) assess the long-term efficacy of two primary abatement methods, (2) characterize lead levels in household dust and exterior soil in unabated homes and homes abated by different abatement methods, (3) investigate the relationship between lead in household dust and lead from other sources, in particular, exterior soil and air ducts, and (4) compare dust lead loading results from cyclone vacuum sampling and wipe sampling protocols. To address these objectives, the CAP Study collected approximately 30 dust and soil samples at each of 52 HUD Demonstration houses in Denver, approximately two years after the abatements had been completed. The houses were all occupied at the time of the CAP study field sampling, though they had not been continuously occupied between the completion of the abatements and the field sampling. The samples were analyzed for their lead content, and these lead measurements were then used in detailed statistical analyses addressing the four study questions. This report documents the results of the CAP Study.

17. Document Analysis a. Descriptors

Lead-Based Paint Abatement, Lead in Dust, Lead in Soil, Long-Term Effectiveness of Abatement, Vacuum Collection of Dust, Wipe Collection of Dust

b. Identifiers/Open-Ended Terms

Lead, Lead-Based Paint, Lead-Based Paint Abatement, Abatement, Encapsulation, Enclosure, Removal of Lead-Based Paint, Clearance Standards, Pre- and Post -Comparisons, Comparisons to Unabated Houses

c. COSATI Field/Group

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