An Approach for Estimating Changes in Children's IQ from Lead Dust Generated during Renovation, Repair, and Painting in Residences and Child-Occupied Facilities

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DISCLAIMERS

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1.0 SCOPE OF THE DOCUMENT

The U.S. Environmental Protection Agency (EPA) has proposed new requirements to reduce exposure to lead hazards created by renovation, repair, and painting activities that disturb lead-based paint in housing and child-occupied facilities. The Federal Register Notice for the Lead Renovation, Repair, and Painting (LRRP) proposed rule for residences is available at http://edocket.access.gpo.gov/2006/06-71.htm and the Supplemental Proposed Rule on Child-Occupied Facilities is available at http://www.epa.gov/lead/pubs/renovation.htm. This action supports the Federal government's goal of eliminating childhood lead poisoning by 2010. The proposed rule establishes requirements for training renovators and dust sampling technicians; certifying renovators, dust sampling technicians, and renovation firms; accrediting providers of renovation and dust sampling technician training; and for renovation work practices. These requirements apply to "target housing," where any child under age 6 resides. "Target housing" is defined in section 401 of the Toxic Substances Control Act (TSCA) as any housing constructed before 1978, except housing for the elderly or persons with disabilities (unless any child under age 6 resides or is expected to reside in such housing) or any 0-bedroom dwelling. Initially the rule would apply to all renovations for compensation performed in target housing where a child with an increased blood lead level resides, and rental and owner-occupied target housing built before 1960, unless the person performing the renovation obtains a statement signed by the owner-occupant that the renovation will occur in the owner's residence and that no child under age 6 resides there. EPA has proposed to phase in the applicability of this proposal to all rental target housing and owner-occupied target housing built in the years 1960 through 1977 where a child under age 6 resides.

The Supplemental Proposed Rule on Child-Occupied Facilities is intended to add child-occupied facilities to the universe of buildings covered by the initial proposal. A child-occupied facility will be defined as a building, or a portion of a building, constructed prior to 1978, visited regularly by the same child, under six years of age, on at least two different days within any week (Sunday through Saturday period), provided that each day's visit lasts at least three hours and the combined weekly visits last at least six hours, and the combined annual visits last at least sixty hours. Child-occupied facilities may be located in public or commercial buildings or in target housing. In public or commercial buildings, the child-occupied facility will only encompass those only those areas that are routinely used by children under age six, such as restrooms and cafeterias, and the adjacent exterior walls. Areas that children under age six only pass through, such as hallways, stairways, and garages, will not be included.

The EPA is currently developing the final LRRP rule. This LRRP rulemaking is based on the TSCA Title IV statutory requirement that EPA revise the lead abatement regulations to apply to renovation and remodeling activities that create lead-based paint hazards. The statutory term "lead-based paint hazards" includes, but is not limited to any condition that causes exposure to lead from lead-contaminated dust and lead-contaminated soil. EPA has promulgated quantitative lead-based paint hazard standards. Thus, a primary consideration in developing the regulations is the extent to which the lead-based paint hazards resulting from renovation and remodeling activities are eliminated. This is different from other TSCA rulemakings in which a "no unreasonable risk" determination must be made. However, as with other rulemakings, which are determined to be "significant regulatory action[s]" under Executive Order 12866 - *Regulatory*

Planning and Review, EPA is required to conduct an economic analysis of the costs and benefits associated with the rulemakings.

To support the benefits assessment in the economic analysis, EPA's Office of Pollution Prevention and Toxics (OPPT) has developed the draft document entitled "An Approach for Estimating Changes in Children's IQ from Lead Dust Generated during Renovation, Repair and Painting in Residences and Child-Occupied Facilities". The quantified benefits analysis will be based primarily on changes in neurocognitive function in children (as measured by IQ) due to lead exposure from specific renovation, repair and painting (RRP) activities. OPPT is using data from a variety of sources, including the American Housing Survey (US Census Bureau, 1997, 2003) and the Property Owners and Managers Survey (US Census Bureau, 1995), to determine the specific types and frequencies of RRP activities that occur in residences and child-occupied facilities. There are obviously many types and ranges of RRP activities that can occur in any given residence or child-occupied facility. Thus, one residence may have a kitchen remodeled, another may have one room repainted, and another may have multiple activities such as window replacements, painting, and a kitchen and bathroom remodeled. OPPT is currently examining the types and number of RRP activities or combination of activities that may occur in U.S. residences and child-occupied facilities, although the exact number has not yet been determined. The number is anticipated to be in the hundreds.

In support of the economic analysis, it is necessary to have a scientifically sound approach for estimating changes in children's IQ from lead exposure due to a variety of RRP activities in residences and child-occupied facilities. The purpose of this document is to outline the general approach that will be used. This method can then be used to "build" all the houses and child-occupied facilities required for the economic analysis.

This document describes an approach for estimating lead exposures and resulting changes in IQ for children under age 6 that could result from various RRP activities. The approach is designed to characterize lead exposures in residences and child-occupied facilities, with and without the various control options that are under consideration for the final rule. The general steps involved in estimating changes in neurocognitive function in children from lead exposure due to RRP activities are shown in the following flow chart.

Estimate dust lead generated from specific renovation activity(s)

↓

Convert dust lead loadings to dust lead concentrations

↓

Estimate blood lead

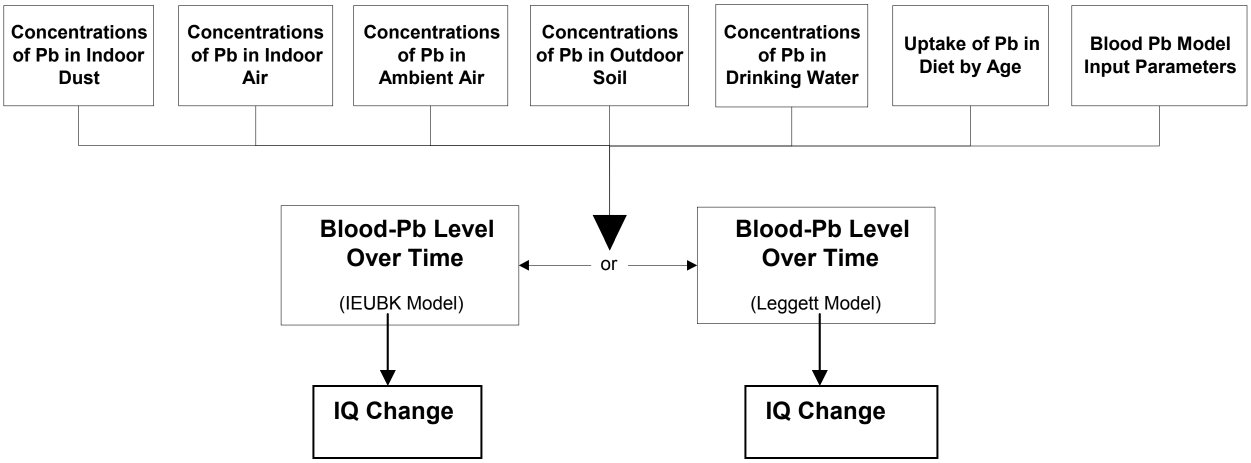
↓

Estimate IQ change

Two examples are provided to illustrate the approach presented in this document. The first is for a residence with a single RRP activity, window replacement. The second example is for a residence with multiple RRP activities. Data from the U.S. Census Bureau were examined to identify a likely combination of RRP activities for this example. The example for multiple RRP activities describes a residence with eight RRP activities, including a bathroom renovation, a kitchen renovation, 10 door or window replacements, interior painting, HVAC work, electrical wiring work, plumbing work, and installation of a security system.

In this document, estimates of dust lead loading are made for the two examples, the house with the single RRP activity (window replacement), and the house with eight RRP activities. Estimates are made for each example with and without the requirements of the LRRP proposed rule. The dust lead loadings are then converted to dust lead concentrations. For each of the two examples, a distribution of blood lead levels is estimated for children under age 6. Finally, the distribution of IQ change due to the resultant lead exposure is characterized for the two examples. The examples used in this document are only two examples of a variety of activity combinations. The two examples used in this document illustrate the approach that will be used in the economic analysis. An extensive analysis of the health effects associated with lead exposure is provided in EPA's recently released final Air Quality Criteria Document (AQCD) for lead (US EPA, 2006). The AQCD is used as the source for the information on lead and neurocognitive function in children that is presented in Section 2 of this document.

There are multiple aspects to the step of estimating lead in any specific renovation activity. Two biokinetic models were used to estimate blood lead levels in children. These include the IEUBK model (US EPA, 2005a), and the Leggett model (Leggett, 1993). The following schematic expands the previous flow chart to show these steps.



The examples provided in this document are for residences. The input data are selected to represent typical housing in the U.S. expected to have lead paint. The variability in these data is characterized to the extent possible and analyzed using sensitivity and Monte Carlo techniques. The age of the housing (i.e., vintage) is an important consideration when collecting these input data since the concentration of lead in paint will vary by the age of the housing and housing component. When data stratified on vintage are available, separate input values can be used to characterize exposure media concentrations for different vintages. The vintages considered in this document include houses built prior to 1940, houses built between 1940 and 1959, and houses built between 1960 and 1979. Although no specific examples of child-occupied facilities are provided in this document, the general approaches used to estimate exposure media concentrations will be similar to the approaches used for residences, with some slight modifications.

2. NEUROCOGNITIVE EFFECTS OF PB IN CHILDREN: PB AND IQ

EPA's Final Air Quality Criteria Document (AQCD) for Pb (US EPA, 2006a) provides an extensive review of the most recent data available on Pb. This document updates the 1986 AQCD for Pb (US EPA, 1986a), associated Addendum (US EPA, 1986b) and the 1990 Supplement (US EPA, 1990). In an effort not to duplicate efforts, pertinent sections in this document are taken directly from the Final 2006 AQCD for lead (Pb), hereafter referred to as the AQCD.

2.1 Blood Pb as a Biomarker

Section 4 of the AQCD presents a comprehensive discussion of the use of blood Pb as both a biomarker of Pb body burden and a biomarker of exposure (see US EPA 2006a, Sections 4.3.1.4, 4.3.1.5, and 4.3.1.6). In addition, a summary of these sections is presented in Section 8.3.2 of the AQCD (US EPA, 2006a). A summary of the pertinent points made in these sections follows.

Blood Pb concentration is often used in epidemiologic and toxicologic studies as an index of exposure and body burden. The prevalence of the use of blood Pb as an exposure metric is mainly due to the feasibility of incorporating its measurement into human studies relative to other potential dose indicators (e.g., Pb in kidney, plasma, urine, or bone) and due to the variety of health effects associated with Pb exposure that have been reported in the literature. The Pb is exchanged between blood and bone and blood and the soft tissues. The exchanges between the blood and bone vary with duration and intensity of exposure, age, and other variables. Resorption of bone in pregnant or nursing women or in postmenopausal women (through osteoporosis) results in a mobilization of Pb from bone to circulation. Therefore, the blood Pb concentration measured in an individual will be determined by the recent exposure history of the individual as well as by the long-term exposure history that gives rise to accumulated bone Pb stores.

In comparison to adults, bone mineral is turning over much more quickly in children as a result of growth. Therefore, changes in blood Pb concentration in children are thought to more closely parallel changes in total body burden. Several recent studies have shown that blood Pb levels reflect Pb exposures (Abadin and Wheeler, 1997; Lanphear et al., 1998; Succop et al., 1998). These studies have shown that Pb levels in air, dust, and soil are reflected by blood Pb levels in humans.

2.2 Neurocognitive Effects of Pb in Children

Emphasis in this document is placed on discussion of the neurocognitive effects of Pb exposure in children. As described in detail in Section 6.2 of the AQCD, neurocognitive effects in children are of particular concern due to the increasingly lower levels at which they have been reported and the potential for lifelong impact (US EPA, 2006a). The negative influence of Pb on neurobehavior has been reported with remarkable consistency across numerous studies of various study designs, populations studied, and developmental assessment protocols, even following adjustment for numerous confounding factors. Collectively, the prospective cohort and cross-sectional studies have reported that Pb exposure affects intellectual attainment of preschool and school age children at blood Pb levels less than 10 micrograms per deciliter (µg/dL) (most clearly in the 5 to 10 µg/dL range, but possibly lower). Several studies have reported quantitative relationships between measures of intelligence quotient (IQ) and current blood Pb levels for children aged 2 to 11 years old. Children are particularly at risk due to sources of exposure, mode of entry, rate of absorption and retention, and partitioning of Pb in soft and hard tissues. As described in Section 6.2.11 of the AQCD, the neurocognitive effects reported in children appear to persist into adolescence and young adulthood in the absence of marked reductions in environmental exposure to Pb (US EPA, 2006a). Excessive accumulation of Pb in childhood has latent and/or persistent adverse health effects on both the peripheral and central nervous systems of human adults assessed 19 to 29 years later (see US EPA, 2006a; Section 8.4.2.8). Also, studies in humans and animals suggest that chelation treatment can transiently decrease blood Pb levels—but it does not appear to reverse or ameliorate Pb-induced cognitive deficits or behavioral problems (see US EPA, 2006a, Sections 5.3.5, 6.2.11, and 8.5.2).

Given the strength of evidence for association with blood Pb levels below 10 ug/dL, the strength of the dose-response information at these exposure levels, and the persistence of cognitive effects in the absence of reduced exposure levels; neurocognitive impact, specifically decrement in IQ in young children, is the focus of the approach outlined in this document.

2.2.1. Epidemiologic Studies on Neurocognitive Effects of Pb in Children

As described in Section 6.2.3 of the AQCD, the most widely used measure of cognitive function in epidemiologic studies is the IQ score (US EPA, 2006a). An IQ score is a global measure reflecting the integration of numerous behavioral processes. The effects of Pb on human neurocognitive ability have been assessed in epidemiologic studies largely by use of age-appropriate, standardized IQ tests. A broad net approach using global assessments of cognition, such as IQ, has proven to be the most consistently sensitive across studies of various design and sample characteristics. Such measures combine subscales that are representative of a broad number of underlying cognitive functions; thus, they are likely to pick up exposure-related deficits across cohorts that differ in their functional expressions of toxicity. Global measures of IQ have also been used so widely because of their outstanding psychometric properties. Although the definition of "intelligence" is quite abstract, IQ remains a useful outcome measure as it is correlated with important measures of life success, such as academic achievement, earnings, and social status.

Epidemiologic studies linking Pb exposure to health effects are presented in detail in Chapter 6 of the AQCD, and Chapter 5 presents the toxicologic data (US EPA, 2006a). Synthesis of the most salient health-related findings and conclusions are presented in Chapter 8 of the AQCD (US EPA, 2006a). Based on the AQCD, it is evident that neurotoxic effects in children are of great public health concern (US EPA, 2006a). There are numerous epidemiologic studies, as well as extensive experimental animal evidence substantiating the plausibility of these epidemiologic findings, that demonstrate inverse relationships between children's blood Pb concentrations and IQ.

The studies identified in the AQCD that are most relevant to the approach outlined in this document are Canfield et al. (2003) and Lanphear et al. (2005) (US EPA, 2006a). These large, well-conducted studies provide both qualitative and quantitative evidence of neurocognitive deficits, measured by IQ, in children at blood Pb levels less than 10 µg/dL. Two other studies, Kordas et al. 2006 and Tellez-Rojo et al. 2006, also indicate detrimental effects on specific cognitive abilities (but not specifically IQ) in children with blood Pb levels below 10 μg/dL. Descriptions of the Canfield et al. (2003) and Lanphear et al. (2005) studies, taken from Sections 6.2.3.1.9 and 6.2.3.1.11 of the AQCD, are presented below (US EPA, 2006a).

The Rochester prospective study, initiated in 1994, examined the relationship between blood Pb levels and IQ at 3 and 5 years of age in 172, predominantly African-American, lower socioeconomic status (SES) children (Canfield et al., 2003). Participants were enrolled when children were 5 to 7 months of age in what was originally a study of Pb dust control methods (Lanphear et al. 1999). Blood Pb concentrations were assessed at 6-month intervals until 2 years and annually thereafter. No data were available on prenatal exposure. The measure of IQ was the abbreviated Stanford-Binet Intelligence Scale-4th Edition (SBIS-4). Potential confounders assessed included gender, birth weight, iron status, Home Observation for Measurement of the Environment (HOME) Inventory scores, maternal IQ, SES, and tobacco use during pregnancy.

Blood Pb concentrations in the Rochester cohort (Canfield et al., 2003) were quite low for an urban population as this study was conducted after public health measures to reduce blood Pb levels in children were already having a dramatic impact in the United States (U.S.) population. Blood Pb levels peaked at 2 years of age (mean 9.7 μg/dL). The mean lifetime average blood Pb concentration was 7.7 μg/dL at the age of 3 years and 7.4 μg/dL at the age of 5 years. At 5 years of age, 56% of the children had a peak blood Pb concentration below 10 μg/dL. Following adjustment for covariates, there were significant inverse associations with full scale IQ at both 3 and 5 years of age for all blood Pb variables, including lifetime average up to age of behavioral assessment.

The effect of Pb on IQ was estimated in all children using lifetime average, peak, concurrent, and average in infancy (6 to 24 months of age) blood Pb levels. The effects of Pb on IQ for the subgroup of children whose peak Pb concentration never exceeded 10 μg/dL also was estimated. Covariate-adjusted changes in IQ for each 1 μg/dL increase in blood Pb concentration for all children and children with peak blood Pb concentrations below 10 μg/dL were estimated. In all cases, the effect estimates were larger in the subsample of children with peak blood Pb concentrations below 10 μg/dL. For example, the overall estimate including all children indicated that an increase in the lifetime average blood Pb concentration of 1 μg/dL was associated with a decrease of 0.46 points [95% Confidence Interval (CI): 0.15, 0.76] in IQ. In comparison, a 1 μg/dL increase in lifetime average Pb concentration was associated with a decline of 1.37 points (95% CI: 0.17, 2.56) in children with peak blood Pb concentrations below 10 μg/dL. In an accompanying editorial of the Canfield et al. (2003) study, Rogan and Ware (2003) noted that the steepness in the concentration-response relationship below 10 μg/dL might have been influenced by 10 children with blood Pb concentrations at or below 5 μg/dL and IQs above 115. However, they added that it was unlikely that the associations reported by Canfield et al. were solely due to these values. Regression diagnostics performed by Canfield et al. identified only one potential outlier (a child who had a low IQ and low Pb concentration); however, this value was retained in all analyses as it did not pass the discordancy test. In the Rochester study, the relationship between children's IQ score and their blood Pb level was found to be nonlinear. A semiparametric analysis indicated a decline of IQ of 7.4 points for a lifetime average blood Pb concentration of up to 10 μg/dL, while for levels between 10 to 30 μg/dL a more gradual decrease of approximately 2.5 points IQ was estimated. The authors concluded that the most important aspect of their findings was that effects below 10 µg/dL that have been observed in previous cross-sectional studies (e.g., Chiodo et al., 2004; Fulton et al., 1987; and Lanphear et al., 2000) were confirmed in this rigorous prospective longitudinal investigation.

Lanphear et al. (2005) reported on a pooled analysis of seven prospective studies that were initiated prior to 1995. The analysis involved 1,333 children with complete data on confounding factors that were essential in the multivariable analyses. The participating sites included Boston, Massachusetts; Cincinnati, Ohio; Cleveland, Ohio; Rochester, New York; Mexico City; Port Pirie, Australia; and Kosovo, Yugoslavia. A prospective cohort study conducted in Sydney, Australia was not included because the authors were unable to contact the investigators (Cooney et al. 1989 and 1991). The sample size of 175 for children aged 7 years in the Sydney cohort and the wide confidence intervals of the effect estimates, as implied by the lack of significant associations, indicate that the non-availability of this study is unlikely to influence the results of the pooled analysis by Lanphear et al. (2005).

The primary outcome measure was full scale IQ measured at school age (mean age at IQ testing was 6.9 years). All children were assessed with an age-appropriate version of the Wechsler scales. Four measures of Pb exposure were examined: concurrent blood Pb (blood Pb level closest in time to the IQ test), maximum blood Pb level (peak blood Pb measured at any time prior to the IQ test), average lifetime blood Pb (mean blood Pb from 6 months to the concurrent blood Pb test), and early childhood blood Pb (defined as the mean blood Pb from 6 to 24 months). A pooled analysis of the relationship between cord blood Pb levels and IQ also was conducted in the subsample for which cord blood Pb tests were available.

Multivariate regression models were developed adjusting the effect of blood Pb for site as well as assessing ten common covariates likely to be confounders of the relationship between Pb and cognitive development, including HOME Inventory scores, birth weight, maternal education and IQ, and prenatal substance abuse. A thorough statistical analytic strategy was employed to determine the linearity or nonlinearity of the relationship between blood Pb levels and full-scale IQ. Regression diagnostics also were performed to ascertain whether Pb coefficients were affected by collinearity or influential observations. The fit of all four measures of postnatal blood Pb levels was compared using the magnitude of the model square of the correlation coefficient (R^2). The blood Pb measure with the largest R^2 (adjusted for the same covariates) was nominated a priori as the preferred blood Pb index relating Pb exposure to IQ in subsequent inspections of the relationships. The primary analysis was done using a fixed-effects model, although a mixed model treating sites as random effects was also examined.

The median lifetime average blood Pb concentration was 12.4 µg/dL (5th to 95th percentile, 4.1 to 34.8) with about 18% of the children having peak blood Pb levels below 10 µg/dL. The 5th to 95th percentile concurrent blood Pb levels ranged from 2.4 to 30 µg/dL. The mean IQ of all children was 93.2 [Standard Deviation (SD) 19.2] but this varied greatly between studies. All four measures of postnatal exposure were highly correlated. However, the concurrent blood Pb level exhibited the strongest relationship with IQ, as assessed by R^2. Nevertheless, the results of the regression analyses for all blood Pb measures were very similar. Multivariable analysis resulted in a six-term model including log of concurrent blood Pb, study site, maternal IQ, HOME Inventory scores, birth weight, and maternal education.

Various models, including the linear model, cubic spline function, the log-linear model, and the piece-wise linear model, were investigated in this analysis. The shape of the dose-response relationship was determined to be non-linear; the log-linear model was found to provide the strongest relationship for the data. Using the log-linear models, the authors estimated a decrement of 1.9 points (95% CI: 1.2, 2.6) in full scale IQ for a doubling of concurrent blood Pb. However, the IQ point decrements associated with an increase in blood Pb from below 1 to 10 µg/dL compared to 10 to 20 µg/dL were 6.2 points (95% CI: 3.8, 8.6) versus 1.9 points (95% CI: 1.2, 2.6). The individual effect estimates for the seven studies used in the pooled analysis also generally indicate steeper slopes in studies with lower blood Pb levels compared to those with higher blood Pb.

Ernhart (2006) expressed the concern that one study site was driving the results and that the HOME Inventory score was not always measured with the IQ test. Other limitations were also mentioned, such as the use of capillary finger stick for the early blood Pb tests rather than venous blood Pb samples. Lanphear et al. (2006) noted that though they agree that using an early measure of the HOME Inventory in the Rochester cohort was a potential limitation, excluding this cohort, from the pooled analysis changed the coefficient by less than 3%. Sensitivity analyses reported in Lanphear et al. (2005) indicated that no single study was responsible for the estimated relationship of Pb and deficits in IQ; thus, diminishing concerns about unique attributes or potential limitations for any specific sites.

In summary, the log-linear model in Lanphear et al. (2005) estimated a decline of 6.2 points in full scale IQ for an increase in concurrent blood Pb levels from less than 1 to 10 µg/dL. This effect estimate was comparable to the 7.4 point decrement in IQ for an increase in lifetime mean blood Pb levels up to 10 µg/dL observed in the Rochester study (Canfield et al., 2003), as well as other studies presented in the AQCD (US EPA, 2006a).

2.3 Influence of Timing of Exposure

Epidemiological studies investigating blood Pb and IQ effects have considered various blood Pb metrics, including but not limited to blood Pb levels concurrent to the time of the IQ measurement taken, average over the "lifetime" of the child at measurement, peak or maximum levels at a specific age range, and early childhood concentrations (usually the mean concentration for 6 to 24 months of age). All of these blood Pb metrics have been correlated with IQ measurements.

Available studies do not provide a definitive answer to the question of whether Pb-associated neurodevelopmental deficits are the result of exposure during a circumscribed critical period or of cumulative exposure. Although support can be cited for the conclusion that it is exposure within the first few postnatal years that is most important in determining long-term outcomes (Bellinger et al., 1992), other studies suggest that concurrent blood-Pb level is as predictive, or perhaps more predictive, of long-term outcomes than are early blood-Pb levels (Canfield et al., 2003; Dietrich et al,. 1993 a, b; Tong et al., 1996; Wasserman et al., 2000). Because of the complex kinetics of Pb, an accumulative toxicant, it is extremely difficult to draw strong conclusions from these observational studies about windows of heightened vulnerability in children. The high degree of intra-individual "tracking" of blood Pb levels over time, especially among children in environments providing substantial, chronic exposure opportunities (e.g., residence near a smelter or in older urban dwellings in poor repair), poses formidable obstacles to identifying the time interval during which exposure to Pb caused the health effects measured in a study. It could be that damage occurred during a circumscribed period when the critical substrate was undergoing rapid development, but that the high correlation between serial blood Pb levels impeded identification of the special significance of exposure at that time.

Under such circumstances, an index of cumulative blood Pb level or concurrent blood Pb level, which might be a good marker of overall body burden under conditions of relatively steady-state exposure, could be expected to bear the strongest association with the effect. Under these circumstances, however, it would not necessarily be correct to conclude that it was the later exposures, incurred around the time that the effect was detected, that were responsible for producing the effect. While some observations in children as old as adolescence indicate that exposure biomarkers measured concurrently are the strongest predictors of late outcomes, the interpretation of these observations with regard to critical windows of vulnerability remains uncertain. Additional research will be needed to distinguish effects that reflect the influence of later Pb exposures from effects that reflect the persistence of effects resulting from exposure during some prior critical window. Resolving this issue solely on the basis of data from observational studies will be difficult due to the high intercorrelation among blood Pb measures taken at different ages.

2.4 Summary of Data: Pb and IQ in Children

As stated in the AQCD, the effects of Pb on neurobehavior have been reported with remarkable consistency across numerous studies of various designs, populations studied, and developmental assessment protocols (US EPA, 2006a). The negative impact of Pb on IQ and other neurobehavioral outcomes persists in most recent studies following adjustment for numerous confounding factors including social class, quality of caregiving, and parental intelligence. Moreover, these effects appear to persist into adolescence and young adulthood in the absence of marked reductions in environmental exposure to Pb. In addition, although there are no direct animal tests parallel to human IQ tests, “in animals a wide variety of tests that assess attention, learning, and memory suggest that Pb exposure results in a global deficit in functioning, just as it is indicated by decrements in IQ scores in children” (US EPA, 2006a).

Neurotoxic effects in children are among those best substantiated as occurring at blood-Pb concentrations as low as 5 to 10 µg/dL (or possibly lower). Consistently, several recent epidemiologic studies have observed significant Pb-induced IQ decrements in children with peak blood Pb levels below 10 µg/dL (e.g., Canfield et al., 2003 and Lanphear et al., 2005) and, in some cases possibly below 5 µg/dL (Bellinger and Needleman, 2003 and Tellez-Rojo et al., 2006). An international pooled analysis of seven prospective studies with a total of 1,333 children estimated a decline of 6.2 IQ points for an increase in concurrent blood Pb levels from less than 1 to 10 µg/dL.

Due to the strength of evidence for association with blood Pb levels below 10 ug/dL, and the strength of the dose-response information at these exposure levels, neurocognitive impact, specifically decrement in IQ in young children, is the focus of this approach.

3. DEVELOPMENT OF BACKGROUND AND ACTIVITY-RELATED INPUTS

This chapter presents exposure data that can be used to describe various RRP activities included in the proposed rule. It provides the exposure data used to calculate background exposure values for various media and also presents the method used to estimate lead content in these media. It also describes the source of data for RRP activities and how these data can be used to "build" houses undergoing any desired single or multiple RRP activity. These methods can then be used to "build" all the houses required for the benefits analysis. The chapter provides the context necessary to understand how background and activity-related inputs are developed (Sections 3.1 and 3.2), describes the approach for characterizing background conditions (Section 3.3), and describes the approach for characterizing the activity-related inputs (Section 3.4). Throughout this chapter and subsequent chapters, two "real world" examples are provided to illustrate how this approach would be used to develop these background and activity-related inputs for a single activity and for multiple activities.

The data presented in Exhibit 3-1 for the two examples are drawn from the *Draft Final Report on Characterization of Dust Lead Levels after Renovation, Repair, and Painting Activities* (Battelle, 2007), hereafter referred to as the OPPT Dust Study. The approach described in this document uses data from the OPPT Dust Study to estimate the comparative lead exposure impact of each type of RRP activity. For each activity, the relevant exposure media are identified – indoor dust and indoor air for inside activities and outdoor soil for outside activities. For some of these activities, it is possible that there are contributions to Pb concentrations from both indoor and outdoor sources. In particular, it is known that a significant proportion of indoor lead dust is due to outdoor dust and soil. The approach is limited in this regard because the OPPT Dust Study data only include Pb loadings for either a limited selection of air, dust, and soil for each job. This is recognized as a limitation in using these data.

Exhibit 3-1. Crosswalk of Activity Names Used in the Examples and Job Descriptions from the OPPT Dust Study

THIS APPROACH	**OPPT DUST STUDY ACTIVITY**	
Activity Name	**Job Description**	**Experiment Number**
Single Activity Example-- Window Replacement		
Window replacement *(Window Replacement)*	Window replacement (x1)	Window replacement #1 (Experiment #s 41-44) Window replacement #2 (Experiment #s 9-12)
Multiple Activities Example-- Kitchen Renovation, Bathroom Renovation, 10 Door or Window Replacements, Interior Painting, HVAC, Wiring, Plumbing, & Security System		
Renovating kitchen *(Kitchen Renovation)* *(Bathroom Renovation)*	Kitchen gut (x 2)	Kitchen gut #1 (Experiment #s 49-51, 76) Kitchen gut #2 (Experiment #s 67-70)
Window replacements *(Window Replacements)* *(Door Replacements)*	Window replacement (x10)	Window replacement #1 (Experiment #s 41-44) Window replacement #2 (Experiment #s 9-12)
Interior flat component LBP removal, scraping *(Interior Painting)*	Dry scrape (x1)	Dry scrape #1 (Experiment #s 5-8) Dry scrape #2 (Experiment #s 26-29)
Cut-outs *(HVAC)* *(Wiring)* *(Plumbing)* *(Security System)*	Cut-outs (x4)	Cut-outs #1 (Experiment #s 22-25) Cut-outs #2 (Experiment #s 45, 46, 71, 72)

In this approach, exposures to the following media are considered:

- Air (ambient and indoor)
- Indoor dust
- Outdoor soil
- Diet
- Drinking water

Exposures to drinking water and diet are assumed to be unaffected by RRP activities and thus are characterized using reasonable, national-scale default values (as discussed in Sections 4.4 and 4.5, respectively). The characterization of exposures for air, indoor dust, and outdoor soil (which are considered potentially impacted by RRP activities) involves first developing an understanding of typical background conditions and estimating the magnitude and timing of Pb dust generated by RRP activities.

The approach is designed to characterize Pb exposures in two types of buildings: residences with children under six years of age and COFs. For the purposes of this approach, a COF is defined as a building, or a portion of a building, constructed prior to 1978, visited regularly by the same child, under age 6, on at least two different days within any week, provided that each day's visit lasts at least 3 hours and the combined weekly visit lasts at least 6 hours, and the combined annual visits last at least 60 hours. Examples of COFs are daycare centers, preschools, and kindergarten classrooms. As for residences, the variability in COF input data is characterized to the extent possible and analyzed using sensitivity and Monte Carlo analyses. No data sufficient to characterize the age (vintage) of daycare centers or schools in the U.S. have been identified and thus vintage is not considered in the approach for COFs.

The overall approaches used to estimate exposure media concentrations for each building type are identical; however, to the extent possible, separate input values are applied for each type. For residences, input data are selected from the OPPT Dust Study to represent typical housing in the U.S. expected to have leaded paint. The variability in these data is characterized using variability estimates from the OPPT Dust Study and analyzed using sensitivity and Monte Carlo analyses. The age of housing (i.e., vintage) is an important consideration when collecting these input data because lead concentrations vary with the age of housing and housing component. When data stratified on vintage are available, separate input values should be used to characterize exposure media concentrations for different vintages. The vintages considered in this approach include houses built prior to 1940, houses built between 1940 and 1959, and houses built between 1960 and 1979.

For the LRRP rule, several control options are being considered for indoor and outdoor RRP activities. They were examined in developing this approach.

The following four combinations of these control methods are included in this approach for indoor activities:

- No plastic, baseline cleaning (Control Option 0)
- No plastic, rule cleaning (Control Option 1)
- Rule plastic, baseline cleaning (Control Option 2)
- Rule plastic, rule cleaning (Control Option 3, proposed rule requirements)

The following two control combinations are included in this approach for outdoor activities:

- No plastic (Control Option A)
- With plastic (Control Option B, proposed rule requirements)

The control options are described in more detail in Section 3.4.2.

3.1 Exposure Periods and Phases for the RRP Activities

The first step in developing an approach for characterizing air, indoor dust, and outdoor soil concentrations is to develop an understanding of how Pb concentrations in these media are expected to change over time. Based on this understanding, the exposure duration can be divided into discrete components that can be characterized separately and then combined to define the concentrations over the course of the exposure. This section describes how these temporal components were developed for this approach.

The exposure duration is assumed to be six years, which covers the entire range of children's ages addressed by the RRP rule. This exposure duration is divided into three exposure periods: Pre-renovation, Renovation, and Post-renovation. The Pre-renovation exposure period represents the period of exposure before initiation of the RRP activity or activities and thus consists of background contributions only. The Renovation exposure period represents the period of exposure beginning with the initiation of the RRP activity or activities and concluding with the completion of the renovation and any contractor cleaning. The Post-renovation exposure period represents the period of exposure following the renovation and any contractor cleaning and ending when the child reaches six years of age. Each exposure period can be subdivided into phases, which can differ across indoor air, indoor dust, and outdoor soil (see Exhibit 3-2). Within some exposure periods, multiple phases may occur within a medium (indoor dust, indoor air, and outdoor soil), and some coincide with similar phases in the other media. The phases for each of the media are described in greater detail in the following sections.

Exhibit 3-2. Exposure Periods and Associated Phases
for Indoor Dust, Indoor Air, and Outdoor Soil

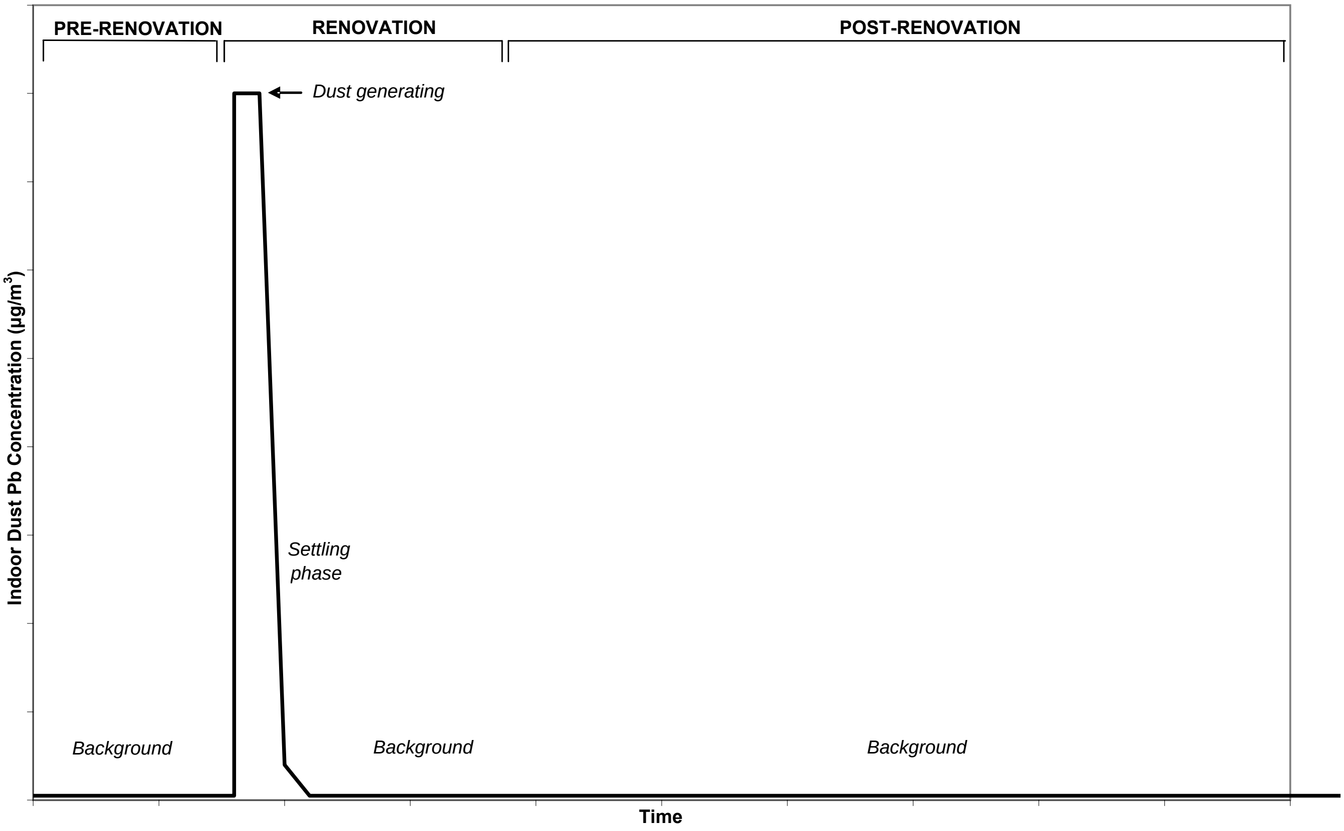
Exposure Period	Phase		
	Indoor Dust	**Indoor Air**	**Outdoor Soil**
Pre-renovation	Pre-renovation (Background)	Pre-renovation (Background)	Pre-renovation (Background)
Renovation	Renovation (Dust Generating)	Renovation (Dust Generating)	Renovation (Renovation)
	Renovation (After Baseline Cleaning)	Renovation (Settling)	
		Renovation (Background)	
Post-Renovation	Post-Renovation (Routine Cleaning)	Post-Renovation (Background)	Post-Renovation (Post-Renovation)
	Post-Renovation (Background)		

3.1.1 Indoor Air Exposures

In the approach for indoor air exposures, the Pre-renovation and Post-renovation exposure periods both consist of only Background phases. The Renovation exposure period consists of three phases: Dust Generating; Settling; and Background. In this approach, exposure concentrations are estimated for each phase separately.

During the Pre-renovation (Background) phase, exposures are represented by the estimated constant background indoor air concentration. During the Renovation (Dust Generating) phase, exposure concentrations are represented by the estimated Pb concentrations during the portion of the renovation where RRP activities are creating leaded dust (e.g., during demolition). During the Renovation (Settling) phase, exposure concentrations are represented by the estimated Pb concentrations during the period of time following completion of the Dust Generating activities during which the dust in air settles onto the floor. During the Renovation (Background) phase, exposure concentrations are represented by the estimated Pb concentrations during the period of time from the end of the Settling phase until the end of the Renovation period. During the Post-renovation (Background) phase, exposure concentrations are represented by background concentrations. Exhibit 3-3 provides a detailed graph of the indoor air exposure periods and phases used in the approach.

Exhibit 3-3. Indoor Air Exposure Periods and Associated Phases

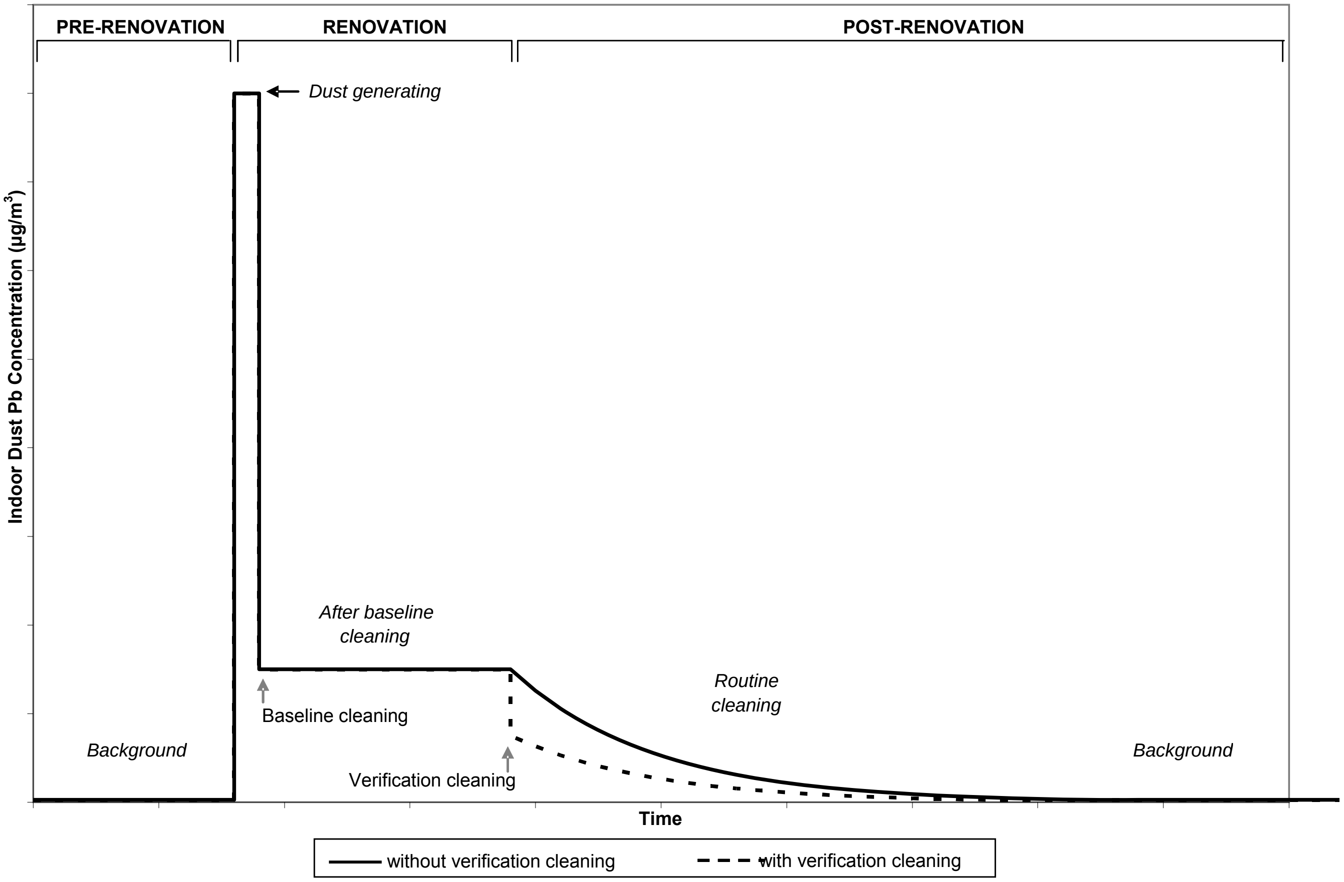


3.1.2 Indoor Dust Exposures

In the approach for indoor dust exposures, the Pre-renovation exposure period consists of only a Background phase. The Renovation exposure period is divided into two phases: Dust Generating and After Baseline Cleaning. The Post-renovation exposure period is divided into two phases: Routine Cleaning and Background phases. Just as for indoor air, exposure concentrations are estimated for each phase separately in this approach.

During the Pre-renovation (Background) phase, exposures are represented by the estimated constant background indoor dust concentrations. During the Renovation (Dust Generating) phase, exposure concentrations are represented by the estimated Pb concentrations during the portion of the renovation when RRP activities are creating leaded dust (e.g., during demolition). Exposure concentrations for the Renovation (After Baseline Cleaning) phase are characterized using Pb loading data collected after the baseline cleaning (i.e., the one-time cleaning conducted by the contractor immediately following completion of the RRP activity) and before any routine cleaning is performed. The Post-renovation (Routine Cleaning) phase begins at the end of the Renovation exposure period and continues until the Post-renovation (Routine Cleaning) dust concentrations have decreased due to routine cleaning performed by the building occupant to background dust concentrations. The initial Pb concentration for the Post-renovation (Routine Cleaning) phase is determined based on the Control Option being evaluated, with the Renovation (After Baseline Cleaning) concentration used if only baseline cleaning is performed and Post-verification cleaning concentration used if both baseline and verification cleanings are performed (see Section 3.4.2 for more explanation of the different cleaning Options). During the final phase, Post-renovation (Background), exposure concentrations are represented by the estimated background concentration. Exhibit 3-4 provides a graph of the indoor dust exposure periods and phases used in this approach.

Exhibit 3-4. Indoor Dust Exposure Periods and Associated Phases

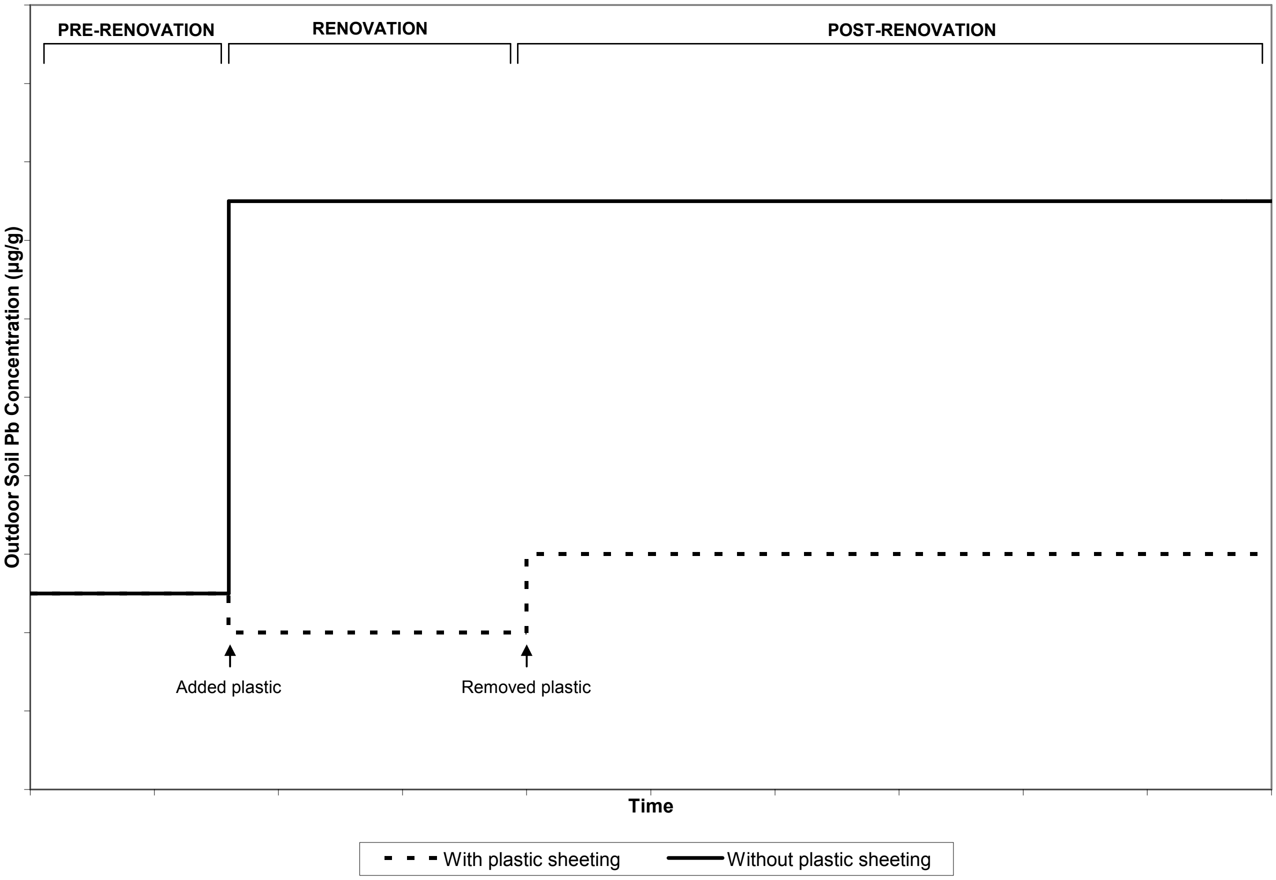


3.1.3 Outdoor Soil Exposures

In the approach for outdoor soil exposures, none of the exposure periods consists of more than one phase. For the Pre-renovation (Background) phase, exposures are represented by the estimated constant background outdoor soil concentrations. For the Renovation period, exposure concentrations are represented by the estimated Pb concentrations during the activity. Note that for Control Options where plastic sheeting is used, exposure from outdoor soil can decrease slightly during this period. This occurs because the Pb loadings associated with the RRP activities typically result in lower concentrations than background and the plastic sheeting prevents exposures to the underlying soil during this period. Although the Pb concentration in outdoor soil does not actually decrease, the Pb exposure that occurs during contact with outdoor soil can be lower during this period.

For the Post-renovation period, exposure concentrations are represented by the estimated Pb concentrations following the completion of the activity and any removal of Pb associated with the relevant Control Option (e.g., removal of plastic with Pb-containing debris). Note that for Control Options that do not include plastic sheeting (i.e., Base Control Option and Control Option 1), Renovation period concentrations will be the same as Post-renovation concentrations. Unlike for indoor dust and air, there are no assumed loss processes that result in a reduction of the Post-renovation soil concentrations (i.e., no cleaning) and thus soil concentrations are assumed to remain at Post-renovation phase levels for the remainder of the exposure period. Exhibit 3-5 provides a graph of the outdoor soil exposure periods and phases used in this approach.

Exhibit 3-5. Outdoor Soil Exposure Periods and Associated Phases



3.2 Overview of Approaches for Estimating Air, Indoor Dust, and Outdoor Soil Concentrations

This section presents summaries of the approaches for estimating air, indoor dust, and outdoor soil concentrations. These summaries provide an understanding for how the background and activity-related inputs developed as described in Sections 3.3 and 3.4 are used to estimate exposure media concentrations.

3.2.1 Air

Concentrations in both ambient (i.e., outdoor) and indoor air are required for characterizing Pb exposures. In this approach, it is assumed that RRP activities do not contribute to ambient air Pb concentrations and thus ambient air concentrations are characterized using only background contributions. Conversely, indoor air concentrations are estimated by considering the contributions of both background and RRP activity-related sources. Exhibit 3-6 provides an overview of how indoor air concentrations are characterized in this approach. Note that the steps in black are described in Sections 3.4 and 3.5; the steps in grey are described in Chapter 4. This flowchart provides the steps involved in characterizing indoor air concentrations for a multiple RRP activity scenario. For single activity scenarios, the step labeled “Average concentrations across all activities” would not be required. For multiple activity scenarios, the steps in the left column prior to “Average concentrations across all activities” would be repeated for all activities and these individual results would be combined in this step to characterize the overall impacts from all of the involved activities.

3.2.2 Indoor Dust

Indoor dust concentrations are estimated in this approach by considering the contributions of both background and RRP activity-related sources including from exterior activities. Exhibit 3-7 provides an overview of how indoor dust concentrations are characterized. Note that the steps in black are described in Sections 3.4 and 3.5; the steps in grey are described in Chapter 4. This flowchart provides the steps involved in characterizing indoor dust concentrations for a multiple RRP activity scenario. For single activity scenarios, the step labeled “Sum loadings across all activities and add background” would consist of summing the Pb loadings for background and the single activity. For multiple activity scenarios, the steps in the left column prior to “Sum loadings across all activities and add background” would be repeated for all activities and these individual results would be combined in this step to characterize the overall impacts from all of the involved activities.

3.2.3 Outdoor Soil

In the approach presented in this document, outdoor soil concentrations are estimated by considering the contributions of both background and RRP activity-related sources. Exhibit 3-8 provides an overview of how outdoor soil concentrations are characterized. Note that the steps in black are described in Sections 3.4 and 3.5; the steps in grey are described in Chapter 4. This flowchart provides the steps involved in characterizing outdoor soil concentrations for a multiple RRP activity scenario. For single activity scenarios, the step labeled “Sum concentrations across all activities and add background” would consist of summing the Pb concentrations for background and the single activity. For multiple activity scenarios, the steps in the left column prior to “Sum concentrations across all activities and add background” are repeated for all activities and these individual results are combined in this step to characterize the overall impacts from all of the involved activities.

Exhibit 3-6. Flow Chart of Steps Used in this Approach to Calculate Indoor Air Concentrations

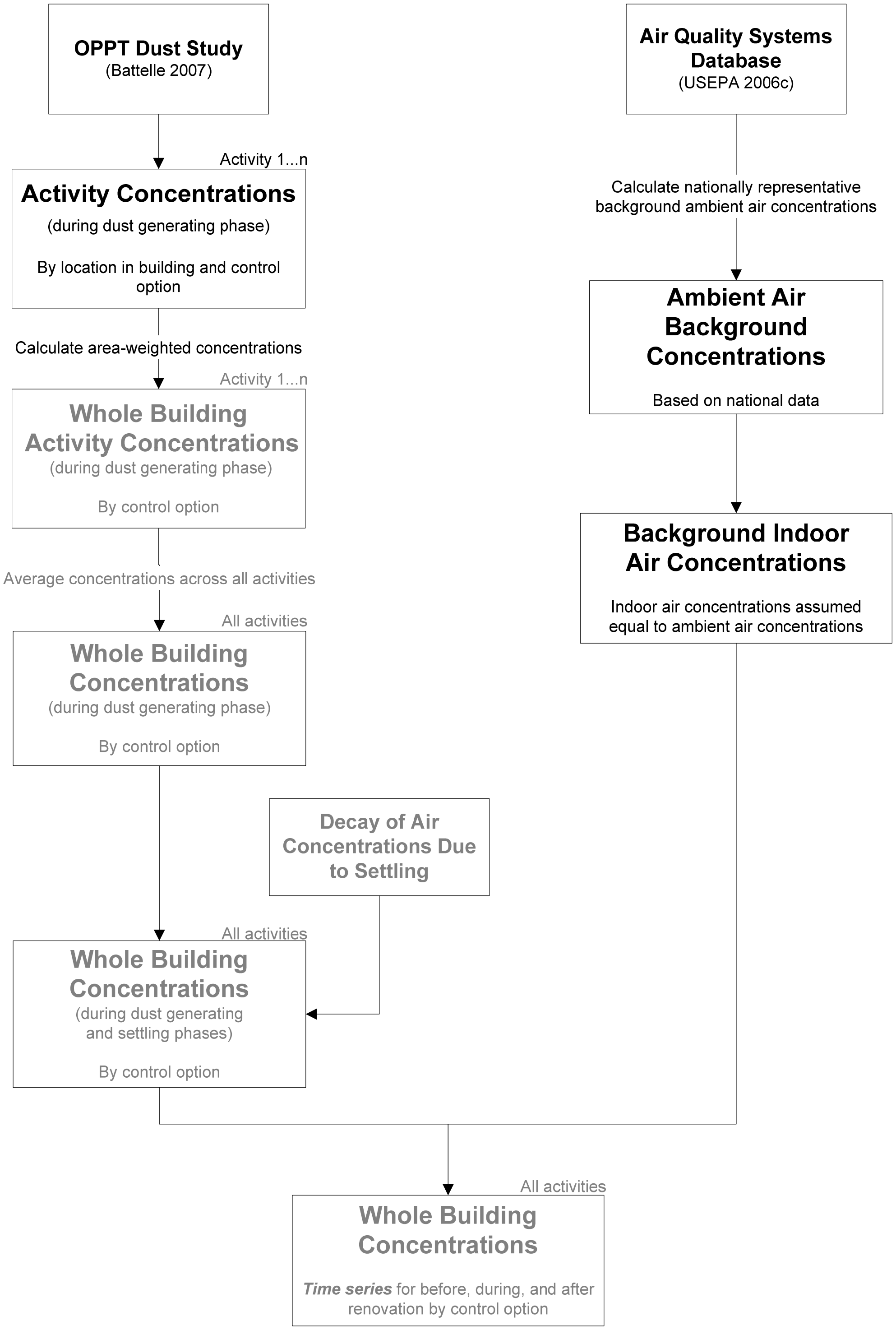


Exhibit 3-7. Flow Chart of Steps Used in this Approach to Calculate Indoor Dust Concentrations

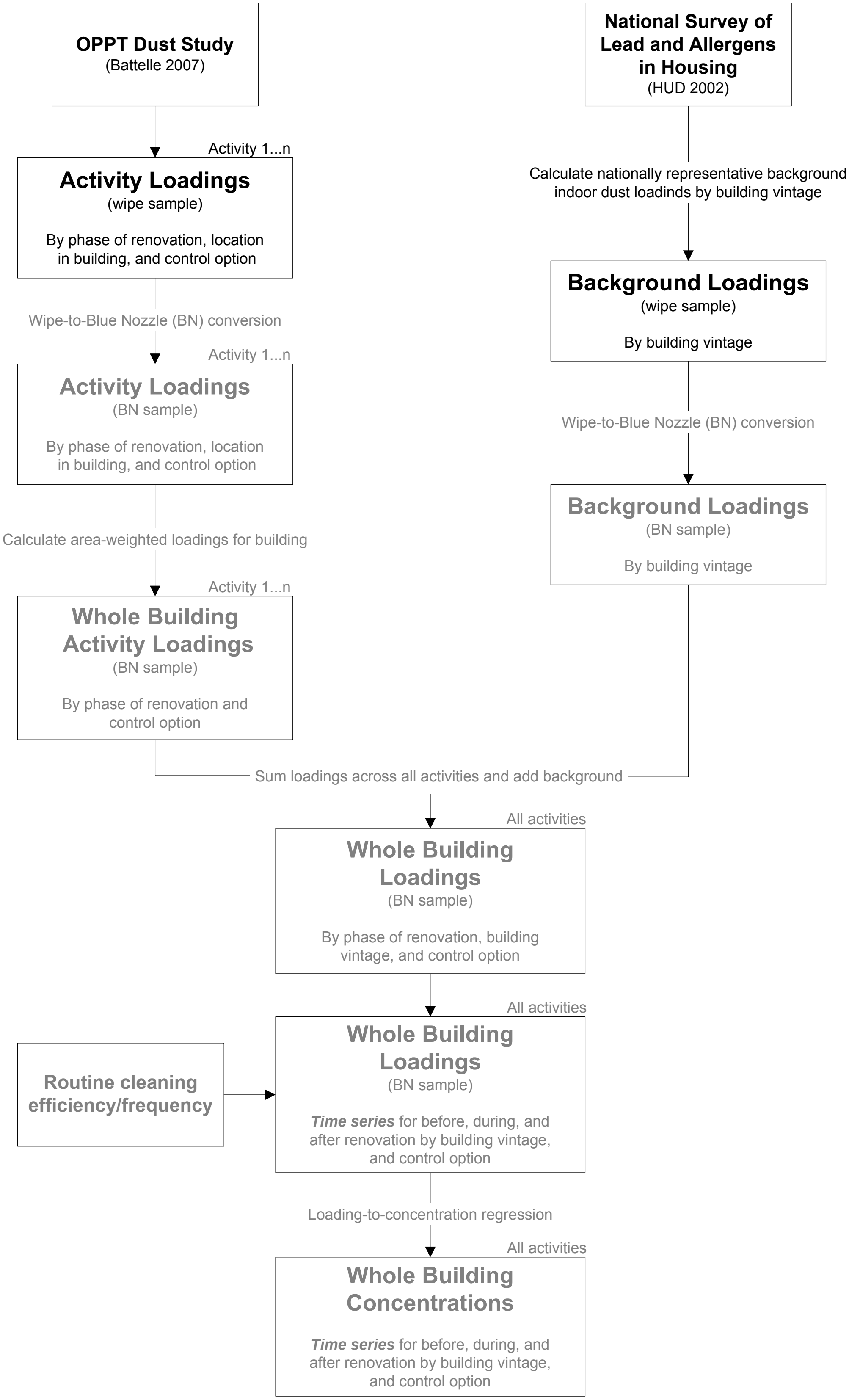
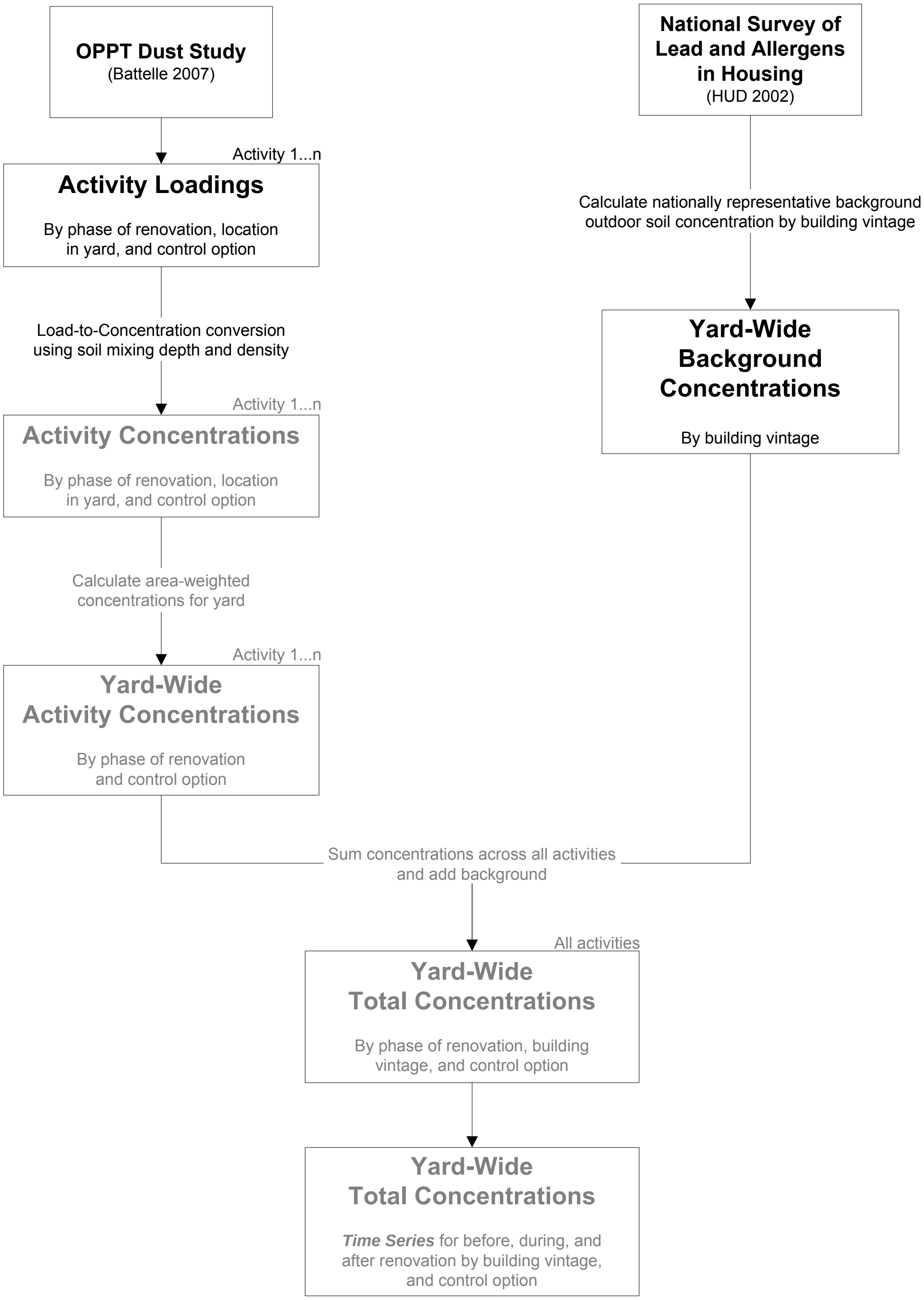


Exhibit 3-8. Flow Chart of Steps Used in this Approach to Calculate Outdoor Soil Concentrations



3.3 Background Pb Levels by Media Type

A child's exposure to Pb over the first six years of life consists of exposure to both Pb released as a result of RRP activities and background Pb concentrations. Therefore, background levels of Pb in indoor air, indoor dust, and outdoor soil represent an important component of total Pb exposure for children. It is necessary to characterize these background levels for accurate estimation of blood Pb levels and to allow for the determination of the portion of the blood Pb levels attributable to RRP activities under different Control options.

3.3.1 Air

3.3.1.1 Data Sources

The background Pb concentration data for ambient and indoor air used in this approach comes from a review of the 2005 annual average total suspended particulate (TSP) monitoring data for Pb contained in EPA's Air Quality Systems (AQS) database (USEPA 2006b).

3.3.1.2 Ambient Air

Background ambient air Pb concentrations used in this approach come from 2005 annual average total suspended particulate (TSP) monitoring data for Pb contained in EPA's Air Quality Systems (AQS) database (USEPA 2006b). The range of concentrations in this database is quite large, with a 5th percentile concentration of 0.002 microgram per cubic meter ($\mu g/m^3$) and a 95th percentile concentration of 0.37 $\mu g/m^3$. Based on these data, the median concentration (0.025 $\mu g/m^3$) was selected as the background exposure concentration. This value is likely biased high because Pb monitors are often located in areas with nearby Pb emission sources.

3.3.1.3 Indoor Air

No representative background indoor air concentration data were located for this approach. As a result, it was assumed that these concentrations would equal the background ambient air Pb concentration (0.025 $\mu g/m^3$) presented in Section 3.3.1.2. It is unclear whether this assumption would tend to positively or negatively bias blood Pb level results since no comparative indoor air concentration data were found. The assumption is a recognized limitation of this approach.

3.3.2 Indoor Dust

3.3.2.1 Data Sources

The National Survey of Lead and Allergens in Housing (NSLAH) (HUD 2002) provided the Pb loading data that are used to estimate background indoor dust Pb concentrations used in this approach. The NSLAH data set was selected from a number of potential studies, which are described in the Risk Analysis to Support Standards for Lead in Paint, Dust, and Soil (USEPA 1998), including the HUD National Survey of Lead-Based Paint in Housing (NSLBPH), HUD Grantees Evaluation of HUD Lead-Based Paint Hazard Control Grant Program ("HUD Grantees"), Lead-Based Paint Abatement and Repair & Maintenance (R&M) Study in Baltimore, and the Rochester Lead-in-Dust Study. The HUD (2002) data set was selected based on a study design that provides data that are representative of all housing groups throughout the U.S. and focused on homes with children (HUD 2002). It is also the largest and most recent survey completed that used wipe samples in accordance with ASTM E1728-95 (USEPA 1998).

3.3.2.2 Development of Values

The HUD (2002) Pb dust loading data used in this approach are limited to weighted values for those houses containing Pb based paint (LBP), and they were broken down into three building vintages (< 1940, 1940 to 1959, and 1960 to 1979). The values are weighted to reflect the sampling stages with the goal of summing to the U.S. housing stock that does not exclude children. Values below the limit of detection are handled in the same manner as described in HUD (2002), with values that were below 0.375 microgram per square feet ($\mu g/ft^2$) set equal to 0.375 $\mu g/ft^2$, which is equal to one quarter of the detection limit. Three values for background indoor dust levels were developed. The Mid value is used in deterministic simulations (described in Chapter 4) to characterize a "best estimate." The Low and High values were used to develop input distributions that are used in the probabilistic simulations. The low, mid, and high background indoor Pb dust loading values used in this approach, which are shown in Exhibit 3-9, are the 5th, 50th, and 95th percentile values of the data set.

Exhibit 3-9. Background Pb Loadings in Floor Dust Used in This Approach by Building Vintage

Building Vintage	**Pb Loadings ($\mu g/ft^2$)**		
	Low	**Mid**	**High**
<1940	0.1	0.6	5.7
1940 to 1959	0.1	0.3	4.1
1960 to 1979	0.1	0.2	1.7

3.3.3 Outdoor Soil

3.3.3.1 Data Sources

The HUD (2002) report served as the source of the background outdoor soil Pb concentration data used in this approach. A number of alternative data sets were considered, including the HUD National Survey of Lead-Based Paint in Housing (NSLBPH) (HUD 2002), HUD Grantees

Evaluation of HUD Lead-Based Paint Hazard Control Grant Program ("HUD Grantees"), Lead-Based Paint Abatement and Repair & Maintenance (R&M) Study in Baltimore, Rochester Lead-in-Dust, and a number of other studies discussed in Chapter 3 of U.S. EPA's 2000 supplemental report (USEPA 2000). The HUD (2000) data set was chosen because it is the most recent large survey of soil Pb concentrations that is designed to be representative of all housing groups throughout the U.S. and focus on homes with children (HUD 2002).

3.3.3.2 Development of Values

The HUD (2002) soil concentration data used in this approach are limited to values for houses containing LBP, with their sampling weights, and they are broken down into three building vintages (< 1940, 1940 to 1959, and 1960 to 1979). Values below zero were handled according to the manner described in HUD (2002), with values that were below 0 microgram per gram (µg/g) set equal to 5 µg/g. Three values for background outdoor soil levels were developed. The Mid value is used in deterministic simulations (described in Chapter 4) to characterize the "best estimate." The Low and High values were used to develop distributions for this input that are used in the probabilistic simulations. The low, mid, and high background outdoor Pb soil concentration loading values used in this approach, which are shown in Exhibit 3-10, are the 5th, 50th, and 95th percentile values of the data set.

Exhibit 3-10. Background Soil Pb Concentrations Used in This Approach by Building Vintage

Building Vintage	Soil Pb Concentrations (µg/g)		
	Low	Mid	High
<1940	40.6	426.8	3,225.8
1940 to 1959	31.2	119.6	1,680.4
1960 to 1979	7.5	90.5	1,332.1

3.4 Activity-Related Inputs by Media Type

In order to create a full picture of Pb exposure for a child, it is necessary to examine Pb levels generated during RRP activities along with the background Pb levels discussed in Section 3.3. A RRP event can consist of a single activity (e.g., replacing a window) or several activities (e.g., renovating a kitchen and replacing several windows). The goal of this section is to describe the methods used in this approach to build the activity-related inputs. The methods applied to develop these inputs for the single activity and multiple activities examples are provided in Sections 3.4.3 and 3.4.4, respectively. These sections describe the methods using two "real world" examples. Unlike Chapter 4, separate sections do not describe the approach and examples because the methods used to develop these inputs are much simpler than those described in Chapter 4 and they are more easily presented through the use of examples.

The two examples are indoor events that do not involve Pb in soil tracked in from the outdoors. The approach will be augmented to account for Pb in tracked-in soil when the approach is applied for an outdoor RRP event.

In this approach, it is assumed that indoor air, indoor dust, and outdoor soil are the three media types that contain increased levels of Pb as the result of RRP activities. It is a recognized limitation of this analysis that the Pb concentration of outdoor air is assumed to be unaffected by RRP activities. Although the tendency of this limitation would be to underestimate total exposures, the increased ventilation in the outdoor environment as compared to indoor ventilation would likely reduce the effect.

3.4.1 Data Sources

The OPPT Dust Study (Battelle 2007) provides the data used in this approach to determine the activity-related Pb levels. Two other data sources were also considered for the analysis: U.S. EPA's *Lead Exposure Associated with Renovation and Remodeling Activities: Environmental Field Sampling Study* (hereafter referred to as "EFSS") (USEPA 1997) and the National Association of Home Builders's *Lead-Safe Work Practices Survey Project Report* (hereafter referred to "NAHB LSWP") (NAHB 2006). The OPPT Dust Study was selected over these studies because it provides the combinations of activities and control options that were necessary to analyze the RRP rule. Additional detail on the reasons the other studies were not chosen is provided below.

3.4.1.1 EFSS

The EFSS study was not used for this approach primarily because its use requires a significant increase in the use of assumptions that have minimal supporting data when compared to use of the OPPT Dust Study. Use of the EFSS necessitates the "building" of activities by estimating the number of tasks (e.g., sawing, drilling, etc.) required to complete each activity. Data supporting the development of these assumed equivalencies are quite limited. Such assumptions also mask the ways in which activities performed sequentially (e.g., drilling in a piece of wood followed by sawing that wood) might produce different levels of dust compared to performing those tasks separately. For the OPPT Dust Study, the activities of interest were performed in their entirety.

In addition, the EFSS did not provide measurements of the effectiveness of the different Control Options that were being evaluated, which necessitated the use of highly uncertain assumptions regarding control efficiencies. The EFSS also did not provide loading estimates after cleanings were completed, which would have led to reliance on uncertain assumptions regarding cleaning efficiency. The data provided in the OPPT Dust Study were specific to the Control Options of interest for this approach and provided post-work and post-cleaning measurements of Pb dust that allowed analysis of the efficacy of contractor cleaning (Battelle 2007).

3.4.1.2 NAHB LSWP

The objective of the NAHB LSWP study was to measure the amount of Pb dust generated during "typical" RRP activities and assess whether routine RRP activities increased Pb dust levels in the work area and property. This study was not used to supplement the OPPT Dust Study due to four key limitations.

Properties included in the NAHB LSWP study contained significantly higher initial (Pre-renovation) Pb levels (by 1 to 2 orders of magnitude) than the background indoor dust levels (see

Section 3.3.2). In the NAHB LSWP study, unlike the OPPT Dust Study, the properties were not cleaned prior to the start of the activity, which resulted in pre-work dust levels being higher than post-work levels for 89 percent of the RRP activities evaluated. This makes it difficult to estimate what the exposures would have been if the properties did not have significant dust levels at the beginning of the study.

For both the NAHB LSWP and OPPT Dust Study, post-work dust levels were collected after RRP activities were completed. In the OPPT Dust Study, these samples were collected both after the work was completed (before any cleanup) and following the cleaning. In the NAHB LSWP study, post-work samples were only collected after the final cleanup was performed, so there is no measurement of potential dust loadings associated with particular activity types and no information on cleaning efficiencies. Such measurements and information are necessary in order to be able to apply the approach described in this document.

The NAHB LSWP did not use the same range of work practice Control Options as the OPPT Dust Study, which limited its utility in evaluating the exposure scenarios of interest. Three types of work practice Control Options were evaluated in the NAHB LSWP study: routine, modified LSWP, and EPA/HUD LSWP. The routine Control Option could be assumed to be similar to the Base Control Option (baseline cleaning, no plastic sheeting) in this approach and the EPA/HUD LSWP Controls could be assumed to be similar to the Control Option 3 (rule cleaning, plastic sheeting), but the modified LSWP Controls are not clearly similar to any of the Control Options assessed in this approach. The NAHB LSWP study also examined the EPA/HUD LSWP practices infrequently, with only 5 of the 60 events[1] evaluated using the EPA/HUD LSWP practices.

For NAHB LSWP, a total of eight interior activities were evaluated, but these RRP activities differed from the interior activities that were evaluated in the OPPT Dust Study and this approach (e.g., no door planing was evaluated). Other interior jobs were similar (e.g., window replacement, door replacement, kitchen work), but they were not necessarily performed in a similar manner. Finally, there were no exterior jobs evaluated in NAHB LSWP, so no exterior soil or air samples were available.

3.4.2 Information Regarding the OPPT Dust Study

The OPPT Dust Study (Battelle 2007) provides the activity-related Pb concentrations and loadings, and thus it is critical to understand how its structure relates to the structure of this approach. This section presents three principal relationships that help clarify how this approach uses data from the OPPT Dust Study.

The first relationship is between the control options discussed in this approach and the phases used in the OPPT Dust Study. The relationship is summarized for indoor and outdoor data in Exhibit 3-11. It is important to note that the OPPT Dust Study did not have separate experiments for the two outdoor Control Options (with and without plastic sheeting) in this approach. The OPPT Dust Study did, however, provide loading data for above and below the plastic sheeting,

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[1] An event is defined as an RRP activity conducted with one of the work practice Control Options in place.

and these data were used to estimate separate results for the two outdoor Control Options as described in Section 3.4.3.3.

In order to describe this relationship, it is necessary to understand the control options that are being considered for the RRP rule (and therefore examined in this approach) for indoor and outdoor activities.

For indoor activities, there are three methods for controlling lead released during RRP activities: baseline cleaning; rule cleaning; and plastic sheeting. Each of these methods is described briefly below.

- Baseline Cleaning - A series of steps used to remove dust that is representative of current standard cleaning practices used by RRP contractors (i.e., ones that are used now in the absence of a RRP rule). These steps include sweeping and vacuuming with a non-HEPA vacuum. (Battelle 2007)
- Rule Cleaning - The cleaning required by under the proposed RRP rule. It is comprised of HEPA vacuuming and wet-mopping with two-bucket method. (Battelle 2007)
- Plastic (interior) - Plastic coverings were set up in the workspace by the RRP contractor according to the proposed RRP rule. This included closing and sealing all doors into the workspace; covering all doors within the workspace that had to be used while the job was being performed with plastic sheeting in a manner that allowed workers to pass through, while confining dust and debris to the workspace; covering the entire floor surface with taped-down plastic sheeting in the workspace; and taping plastic to the outside of the window frame, if a window was being replaced as part of a job, so that no debris could fall to the ground outside the window. The floor of the primary decontamination area (just outside the workspace; either a hallway or tool room) was also securely covered with plastic. (Battelle 2007)

The following four combinations of these control methods are included in this approach for indoor activities:

- No plastic, baseline cleaning
- No plastic, rule cleaning
- Plastic, baseline cleaning
- Plastic, rule cleaning

For outdoor activities, the only control measure being considered in this approach is the use of plastic sheeting, which is briefly described below.

- Plastic (exterior): The exact size and location of the Rule Containment Plastic took into account any physical constraints such as property lines, fences, nearby houses, and the placement of the vertical containment structure. The plastic was set up by the RRP contractor in accordance with the proposed RRP rule. This included laying securely taped- or weighed-down plastic on top of the containment plastic extending out from the edge of the building a reasonable distance to collect falling debris. All doors and windows within 20 feet of and below the work area were closed. (Battelle 2007)

The following two control combinations are included in this approach for outdoor activities:

- No plastic sheeting
- With plastic sheeting

Exhibit 3-11. Control Options Used in this Approach and the Phases Used in the OPPT Dust Study

This Approach			**OPPT Dust Study**	
Control Option (CO) Name	**Description**	**Control Option (CO) ID**	**Exposure Phase ID**	**Description**
Indoor				
Base Control Option	No plastic sheeting, Baseline cleaning	0	Phase IV	No plastic and baseline cleaning
Control Option 1	No plastic sheeting, Rule cleaning	1	Phase III	No plastic and rule cleaning
Control Option 2	Plastic sheeting, Baseline cleaning	2	Phase II	Plastic coverings and baseline cleaning
Control Option 3	Plastic sheeting, Rule cleaning	3	Phase I	Plastic coverings and rule cleaning
Outdoor				
Control Option A	No plastic sheeting	A	N/A	See footnote [a]
Control Option B	Plastic sheeting	B	N/A	See footnote [a]

[a] Note that the OPPT Dust Study did not have two separate experiments for the two outdoor Control Options (A and B) per se. It did provide loading data above and below the plastic sheeting, which were used to estimate separate results for Control Options A and B as described in Section 3.4.3.3.

The second relationship is between the sampling location or area in the yard in the OPPT Dust Study (Battelle 2007) and the area of the building or yard that those sample locations are used to represent in this approach. For indoor sampling, samples that were taken in the Work Room in the OPPT Dust Study were used to represent the Workspace in this approach, while the Tool Room and Observation Room samples, respectively, were used to represent the Adjacent Room and the Rest of Building in this approach. For outdoor sampling, OPPT Dust Study samples that were taken on plastic or under plastic were used to represent the Dripline in this approach (different combinations of the On Plastic and Under Plastic samples were used to represent conditions under different Control Options as described in Section 3.4.3.3). A summary of this relationship is provided in Exhibit 3-12.

Exhibit 3-12. Sampling Locations in the OPPT Dust Study and Areas of Building or Yard They Represent in This Approach

Location in Building Used in This Approach	**Sampling Rooms in OPPT Dust Study**
Workspace	Work Room
Adjacent Room	Tool Room
Rest of Building	Observation Room
Areas of Yard in This Approach	**Sampling Areas in Yard in OPPT Dust Study**
Dripline	On Plastic *and* Under Plastic [a]
Nearby	Near Plastic

[a] Note that both the On Plastic and Under Plastic designations in the OPPT Dust Study indicate that the sample was taken within the area referred to in this approach as the Dripline.

The third relationship is between the sample types reported in the OPPT Dust Study and the exposure periods and phases in this approach for which they are used. The sample types describe the times at which the samples were taken over the course of a particular RRP activity. A summary of this relationship is provided in Exhibit 3-13. It is important to note that both the Post Cleaning and the Post Verification sample types are sometimes used in this approach for the indoor dust Post-renovation (Routine Cleaning) phase, depending on which Control Option is being considered.

Exhibit 3-13. Exposure Periods and Phases of This Approach and OPPT Dust Study Sample Types Used for Each

This Approach		**OPPT Dust Study**
Exposure Phase (PH) Name	**Phase (PH) ID**	**Sample Types** [a]
Indoor Dust		
Pre-renovation (Background)	1	N/A
Renovation (Dust Generating)	2	Post Work
Renovation (After Baseline Cleaning)	3	Post Cleaning
Post-renovation (Routine Cleaning)	4	Post Cleaning ***or*** Post Verification [b]
Post-renovation (Background)	5	N/A
Indoor Air		
Pre-renovation (Background)	i	N/A
Renovation (Dust Generating)	ii	Post Work
Renovation (Settling)	iii	N/A
Renovation (Background)	iv	N/A
Post-renovation (Background)	v	N/A
Outdoor Soil		
Pre-renovation (Background)	A	N/A
Renovation	B	Post Work
Post-renovation	C	Post Work

[a] The sample types describe the time at which the sample was taken over the course of a particular RRP activity.
[b] It is important to note that both the Post Cleaning and the Post Verification sample types are used in this approach for the indoor dust Post-renovation (Routine Cleaning) phase depending on which Control Option is being considered, as is described in Section 3.3.2).

Please note that the remainder of this approach will primarily use the language identified in Exhibit 3-11, Exhibit 3-12, and Exhibit 3-13 as the nomenclature of this approach. In the cases where the nomenclature of the OPPT Dust Study is used, a DS marker will appear in parentheses following the term (e.g., the indoor dust Post Work (DS) samples were used in this approach to determine the indoor dust loadings for the Renovation (Dust Generating) exposure period and phase). It may be useful to return to the three exhibits to trace the nomenclature of this approach to the appropriate OPPT Dust Study terminology.

3.4.3 Single Activity Example

The development of Pb air concentrations, indoor dust loadings, and outdoor soil loadings resulting from the replacement of a single window (based on OPPT Dust Study data) is presented in this section. This information is provided as an example of the methodology used in this approach to calculate concentrations and loadings for a single RRP activity.

3.4.3.1 Indoor Air

The OPPT Dust Study provides window replacement, Post Work (DS) Pb air concentration data for the Workspace, Adjacent Room, and Rest of Building under the conditions of the four Control Options. The first step to estimate activity-related indoor air concentrations is to group samples for each unique combination of location and Control Option. The geometric mean, minimum, and maximum concentrations from each group are used as the mid, min, and max concentrations, respectively, in this approach. These indoor air concentrations are displayed in Exhibit A-4 in Appendix A. The mid concentration serves as the input for the deterministic simulations to generate “best estimate” results (as described in Chapter 4), while the min and max provide the range for the probabilistic modeling. The geometric mean is selected as the mid value because it corrects for positively skewed data by assuming a log normal distribution of the data. In reviewing the concentrations, it is important to note that all data points that are below the limit of detection are set to one half the limit of detection.

Although the OPPT Dust Study does provide Post Cleaning (DS) and Post Verification (DS) samples, neither of these is used for indoor air in this approach. For a single activity such as a window replacement, the entire renovation activity is assumed to happen within a one week Renovation (Dust Generating) phase, during which the Post Work (DS) concentrations were assumed to prevail. During the following week, which corresponds to the Renovation (Settling) phase in this approach, the concentrations are assumed to remain at the Post Work (DS) level for the length of the sampling period (i.e., the time over which the sample was collected), which varied across the samples but was typically two hours. For the remainder of the Renovation (Settling) phase, the concentrations are decreased towards background using decay coefficients from Choe et al. (2000). Once background is reached, the concentration is assumed to remain at that level for the duration of the Renovation (Settling) and Renovation (Background) phases. A generalized example of how these concentrations change over the course of the exposure periods and phases is provided in Exhibit 3-3.

One shortcoming of the data in the OPPT Dust Study is that the duration of the sampling period was not consistent across samples. This is important, particularly during the Post Work (DS) period, because concentrations can change relatively quickly, which means that a shorter sampling period may not be representative of the results if the sampling period had been extended. The selected approach deals with this by using the actual sampling period and applying a decay function from the end of this period until the concentration reached background. An alternative approach would have been to convert each sample into an eight-hour average, which would normalize all of the samples to the same sampling time. This approach was not chosen because it would have assumed that the air concentration was zero for all times within the eight hours when the sampling was not performed, which would have likely biased the air concentrations low.

The post-cleanup and, if applicable, post-verification measurements of Pb dust loadings are expected to be lower than the Pb dust loadings measured post-work, because the post work measurement occurs prior to any clean-up and/or verification. This trend should apply to all dust samples – those collected in the Workspace, the area adjacent to the Workspace, and the Rest of Building. The dust study data for the single activity example of window replacements, however, support this assumption only in some cases.

The post-work measurements of Pb air concentrations are expected to be lower in areas adjacent to the Workspace and the Rest of Building when the plastic sheeting is used, because the plastic sheeting is employed to contain the air-borne dust and prevent it from moving outside of the Workspace. Thus, it is expected that the area adjacent to the Workspace and the Rest of Building will have higher Pb air concentrations in the Base Control Option and Control Option 1, which do not involve plastic sheeting. Similarly, the Workspace might be expected to have higher Pb air concentrations in Control Options 2 and 3, because the plastic sheeting used in those control options should limit the movement of dust to areas outside the Workspace. Because post cleaning and post verification samples are not considered here, the type of cleaning – baseline and rule – is not anticipated to affect the concentrations of interest (i.e., post work concentrations in this case). The dust study data for the single activity example of window replacements, however, support this assumption only in some cases. The Workspace air Pb concentrations for Control Options 2 and 3 are indeed higher than the Workspace air Pb concentrations measured for the Base Control Option and Control Option 1. Unexpectedly, Control Option 2 also reports the highest air Pb concentration for the area adjacent to the Workspace, at 8.42 $\mu g/m^3$, while the air Pb concentration for areas adjacent to the Workspace are lower for the Base Control Option and Control Option 1 (3.68 $\mu g/m^3$ and 4.62 $\mu g/m^3$, respectively). Under Control Option 3, the air Pb concentration for the area adjacent to the Workspace is the lowest, at 2.23 $\mu g/m^3$. These relationships illustrate the dependence of any conclusions for any RRP activity or combination on the dust study results used.

3.4.3.2 Indoor Dust

The OPPT Dust Study provides window replacement Post Work (DS), Post Cleaning (DS), and Post Verification (DS) floor and window sill Pb dust loadings for the Workspace, Adjacent Room, and Rest of Building under the conditions of the four Control Options. In some cases, bulk debris samples (i.e., samples containing excess debris that could not be collected with a dust wipe but were analyzed separately for their Pb content) were collected and analyzed, and were included with floor and sill wipe results. Because Pb contained in bulk debris is accessible for exposure, this approach incorporates bulk debris results into the analysis as described below.

The floor and window sill dust samples are grouped by each unique combination of sample type (i.e., Post Work (DS), Post Cleaning (DS), or Post Verification (DS)), location, Control Option, and bulk debris type (i.e., with or without bulk debris). The geometric means are calculated and the minimum and maximum detected loadings are identified for both floor and window sill dust groups. For floor and sill dust groups that differed only by bulk debris type (i.e., data groups with the same sample type, location, and Control Option that differ only in that one group included bulk debris while the other did not), a geometric mean is taken across the geometric means for the groups. In other words, each group has a geometric mean, so a geometric mean is taken of these geometric means (i.e., geometric means of geometric means (GMM) were calculated). The geometric means or GMMs (where applicable) for each group are selected as the mid values for indoor dust loading. These mid values, which are presented in Exhibit A-6 in Appendix A, are used in the deterministic simulations to generate “best estimate” results (as described in Chapter 4). The geometric means and GMMs are used as mid values because geometric means correct for positively skewed data by assuming a log normal distribution. In reviewing the loadings, it is important to note that all data points that are below the limit of detection are set to one half the limit of detection for GM and GMM calculation.

The maximum detected loadings for each floor dust group were modified to include 10 percent of the maximum window sill loading value for the corresponding group. The addition of the window sill loading data to the floor dust loading results is intended to account for the potential contribution of window sill dust to a child’s overall Pb exposure. In developing the methodology for this approach, it was noted that window sills are an important source of Pb exposure that may not be fully captured by the floor dust wipe (i.e., it is unclear that a window sill with high dust levels would necessarily contribute significantly to the surrounding floor dust levels). As a result, a moderate proportion of the window sill data was incorporated to approximate the maximum floor dust loading. These modified maximum loadings and the minimum loadings served as the high and low indoor dust loading values, respectively, and they were used in the development of the indoor dust loading input distributions for the probabilistic modeling (as described in Chapter 4). These values are presented in Exhibit A-6 in Appendix A.

The loadings assumed to be representative of each exposure period and phase are summarized in Exhibit 3-13. After a one-week Renovation (Dust Generating) phase in which the loading is assumed to be characterized by Post Work (DS) samples, it is assumed that the RRP contractor would stop actively generating dust (e.g., through demolition activities). The loading levels are assumed to drop after the Renovation (Dust Generating) phase to a level that is equivalent to either the Post Cleaning (DS) or Post Verification (DS) sample loading. The choice of Post Cleaning (DS) or Post Verification (DS) is based on what type of cleaning is performed. When verification cleaning is performed (i.e., Control Options 1 or 3), it is assumed that the Post Verification (DS) loading is representative because that is the value in the OPPT Dust Study after intensive rule cleaning has been performed. Conversely, when only baseline cleaning is performed (i.e., Base Control Option or Control Option 2), the Post Cleaning (DS) value is assumed to be representative. These Post Verification (DS) or Post Cleaning (DS) values are assumed to be the starting point for the Post Renovation (Routine Cleaning) phase, over which the loading values are decayed until they reach background. A generalized example of how concentrations, which are calculated from these loadings using a formula described in Section 4.2, change over the course of the exposure periods and phases is provided in Exhibit 3-4. It is important to note, however, that in the single activity example, it is assumed that the Renovation (After Baseline Cleaning) phase has a length of zero weeks (because the end of the dust-generating activities coincides with the end of the renovation).

In general, one would expect the dust loadings to decrease from the post work measurements to the post cleaning measurements and from the post cleaning measurements to the post verification measurements. This general trend, however, is not always present in the OPPT data. For example, in window replacements for the Base Control Option, dust loadings in areas adjacent to the Workspace increased between the post work (4.1 µg/ft^2) and post cleaning measurements (12.8 µg/ft^2). Similarly, the loading values for the Rest of Building increased between the post work and post cleaning measurements, from 1 µg/ft^2 to 1.5 µg/ft^2, respectively. This trend may be due to the fact that cleaning only occurred in the Workspace, and the cleaning may have generated air-borne dust which spread to other regions of the house or that somehow different areas were measured across phases. For Control Options 1 and 3, plastic was placed over the door in an effort to avoid such spreading from the Workspace to other portions of the house. In some instances, however, (e.g., for the rest of the building for Control Option 1), the loading again increased between the post work and post cleaning phases.

In addition, instances exist in the OPPT Dust Study where the post verification loadings are higher than the post cleaning loadings. For example, in Control Option 3 the dust loadings for the rest of the building decreased from the post work to post cleaning samples, but increased from 1.4 µg/ft^2 (post cleaning) to 1.6 µg/ft^2 (post verification). In general, these differences are small and may be attributable to measuring error. Although in general the Workspace loadings decreases after the post work and post cleaning phases, such a trend is not a general rule in the adjacent and rest-of-building areas.

3.4.3.3 Outdoor Soil

No example is provided in this approach for exposures from outdoor RRP activities. As a result, this section presents a generic discussion of the methodology that will be used to estimate activity-related outdoor soil concentrations.

The OPPT Dust Study provides outdoor dust wipe sample loadings for only one exposure period, and it does not provide data for separate experiments to permit evaluating the relative effectiveness of Control Options A and B. As a result, this approach estimates the loadings for the Renovation and Post-renovation exposure periods using different combinations of the Post Work (DS) samples measured on Top of Rule Plastic (DS), Under Rule Plastic (DS), and Outside Rule Plastic (DS), as is shown in Exhibit 3-14. For simplicity, this discussion is broken up by Control Option.

For Control Option A (i.e., no plastic), it is assumed that all dust that is deposited on a particular area of soil remains in that area and undergoes no loss processes (e.g., erosion). In the Dripline, it is assumed for the Renovation and Post-renovation exposure periods that the total available Pb dust available for exposure is equal to the Post Work dust loading on Top of Rule Plastic (DS) plus the dust loading Under Rule Plastic (DS). The reason for this assumption is that under Control Option A, no plastic would be used in the Dripline for a RRP activity. In the Nearby area, for which the OPPT Dust Study only provides data on top of the containment plastic, it is assumed for the Renovation and Post-renovation exposure periods that the total available Pb dust available for exposure is equal to the Post Work (DS) dust load on Top of Containment Plastic (DS). During an actual RRP project, this containment plastic would not be used (it is not a requirement under either Control Option A or B), so all the dust falling in the Nearby area would be available for exposure. A generalized example of how concentrations, which are calculated from these loadings using a formula described in Section 4.1, change over the course of the exposure periods and phases is provided in Exhibit 3-5.

For Control Option B (i.e., plastic), it is assumed that plastic is used to prevent the loading of some dust onto soil. In the Dripline, it is assumed that for the Renovation exposure period, the total available Pb dust available for exposure is equal to the Post Work (DS) dust loading on Top of Rule Plastic (DS). The reason for this assumption is that under Control Option B, the Dripline plastic would prevent lead contamination of the dust under the plastic, and prevent exposure to dust that is sitting on top of the plastic. For the Post Renovation (DS) exposure period, the loading is assumed to equal the Post Work (DS) dust loading Under Rule Plastic (DS). The rationale behind this assumption is that when the plastic is removed after the job is complete, the dust on top of the plastic is also removed, leaving only the dust under the plastic for exposure. In the Nearby area, for which the OPPT Dust Study only provides data on top of the containment plastic, it is assumed for the Renovation and Post-renovation (DS) exposure periods that the total available Pb dust available for exposure calculations is equal to the Post Work (DS) dust load on Top of Containment Plastic (DS). During an actual RRP project, this containment plastic would not be used (it is not a requirement under either Control Option A or B), so all the dust falling in the Nearby area would be available for exposure calculations.

Exhibit 3-14. Crosswalk between the Loadings Used in this Approach and the Loadings Provided in the OPPT Dust Study for Outdoor Soil

Loadings Used in this Approach	Loadings Provided in the OPPT Dust Study
No Plastic (Control Option A)	
Dripline loading – Renovation	Top of rule plastic *plus* Under rule plastic – Post Work
Dripline loading – Post-renovation	Top of rule plastic *plus* Under rule plastic – Post Work
Nearby loading – Renovation and Post-renovation	Top of containment plastic – Post Work
Plastic (Control Option B)	
Dripline loading – Renovation	Top of rule plastic – Post Work
Dripline loading – Post-renovation	Under rule plastic – Post Work
Nearby loading – Renovation and Post-renovation	Top of containment plastic – Post Work

For some outdoor measurements, wipe samples were not the only type of sample taken in the OPPT Dust Study. In some cases, bulk debris samples (i.e., samples containing excess debris that could not be collected with a dust wipe but were analyzed separately for their Pb content) were collected, analyzed, and included with some wipe sample results. Because Pb contained in bulk debris is accessible for exposure, this approach incorporates bulk debris results into the analysis as described below.

After setting all the data points that are below the limit of detection equal to one half the limit of detection, the dust samples are grouped by each unique combination of sampling area in yard, phase, and bulk debris type (i.e., with or without bulk debris). The geometric means are calculated and the minimum and maximum detected loadings are identified. For groups that differ only by bulk debris type (i.e., data groups with the same sample type, location, and Control Option that differ only in that one group included bulk debris while the other did not), a geometric mean is taken across the geometric means for the groups (i.e., geometric means of geometric means (GMM) are calculated). The geometric means or GMMs (where applicable) for each group are selected as the mid values for indoor dust loading. These mid values are used in the deterministic simulations to generate “best estimate” results (as described in Chapter 4). The maximum and minimum loadings serve as the high and low outdoor soil loading values, respectively, and are used to develop the outdoor soil loading input distributions used in the probabilistic modeling (as described in Chapter 4).

It is important to note that the OPPT Dust Study reports Pre Work (DS) and Post Work (DS) soil concentrations for each of the exterior RRP activities. These measurements are not used for two primary reasons. First, RRP activities were repeated at the various sites in the study, so only the first activity at a given property would give valid soil concentrations for that activity. The use of data from only these first activities would result in an extremely small number of observations, thus decreasing predictive power. Second, the results of using this approach must be applicable to a range of different locations in the United States. Using these soil concentrations would bias results towards the small number of locations where the OPPT Dust Study experiments were performed. As a result, outdoor soil concentrations associated with particular RRP activities are estimated using estimated background concentrations in combination with the OPPT Dust Study’s estimates of exterior dust loadings.

3.4.4 Multiple Activities Example

For the purpose of illustrating the methodology of this approach for estimating childhood exposures to multi-activity RRP events, an example scenario consisting of kitchen renovation, bathroom renovation, 10 door or window replacements, interior painting, HVAC (heating, ventilation, and air conditioning), wiring, plumbing, and installation of a security system is examined here. This section presents the approach for developing the Pb levels from the OPPT Dust Study for a multiple RRP activity scenario. Because the OPPT Dust Study does not include experiments for all of these RRP events, the example scenario is assumed to be most similar to two kitchen renovations, 10 window replacements, one interior flat component LBP removal scraping event, and four cut-outs.

3.4.4.1 Air

The approach for estimating activity-related air concentration for the multiple activities example is exactly the same as the activity-related air concentration estimation approach shown in Section 3.4.3.1. The process is simply repeated for each of the individual activities.

As in the single activities case, it is expected that the area adjacent to the Workspace and the Rest of Building will have higher Pb air concentrations in the Base Control Option and Control Option 1, which do not involve plastic sheeting, while the Workspace is expected to have higher Pb air concentrations in Control Options 2 and 3, because the plastic sheeting is intended to limit the movement of dust to areas outside the Workspace. This trend, however, may not generally be followed for all the renovation activities comprising any multiple activities cases since calculations will reflect any anomalies in the dust study data and sums are taken to create aggregates for estimation. In this particular multiple activities example, the exceptions occur most frequently for the window replacements case (discussed above), but other deviations are seen for the other activities as well.

3.4.4.2 Indoor Dust

The approach for estimating activity-related indoor dust loadings for a multiple activities case is exactly the same as the activity-related indoor dust loading estimation approach shown in Section 3.4.3.2. The process is simply repeated for each of the individual activities.

As in the single activities case, it is expected that post work values should be the highest, with post cleaning and post verification levels each subsequently decreasing. Again, however, deviations occur. Because the multiple activity weighs the window replacements activity ten times (that is, it assumes that ten window replacements are part of the multiple activity), the deviations noted for this case become exacerbated for the multiple activity example. In addition, other individual deviations also occur in the other activities.

3.4.4.3 Outdoor Soil

There are no outdoor activities in the multiple activities example, but the approach for estimating activity-related outdoor soil loadings for the multiple activities example is exactly the same as the outdoor soil loading estimation approach shown in Section 3.4.3.3. The process will simply be repeated for each individual activity.

3.5 Uncertainties and Limitations

The primary source of uncertainty in the background and activity-related data is limited sample size for the activity-related data. The need to parse the activity data into small groupings based on Control Options, sampling location, and exposure periods and phases, significantly limits the predictive power of the OPPT Dust Study data.

Another significant uncertainty is the lack of activity-related data that were specific to the control options and exposure periods and phases of this approach (e.g., separate experiments were not conducted for outdoor soil's Control Option A and B and Post Work (DS) samples were the only usable air concentration values for indoor air). This data limitation necessitates assumptions regarding the appropriate methods for estimating loadings.

The fact that loadings for the various control options are not always taken from the same job sites in the OPPT Dust Study is another important source of uncertainty. For example, one control option for window replacement may have been tested in one building while another control option for that activity might have been tested in another. This study design limits the comparability of the control options because differences in loading values might be explained by differing building characteristics rather than by control options.

An additional uncertainty is that the Post Work (DS) air concentrations from the OPPT Dust Study were often reported as non-detects. This occurred when either the measured value was deemed below the measurement threshold (not enough mass collected in the machine) or when the sampling time was too short. In this approach, all samples are used, except for a single sample with a sampling time of 5 minutes that was deemed too short to be representative and was excluded from the analysis (the next shortest sampling time was 80 minutes). Thus, there is uncertainty surrounding the smallest air concentrations based on experimental error.

A limitation of the approach is that blood lead models (i.e., IEUBK and Leggett) do not explicitly account for window sill loadings. As a result, this approach factors these loading samples into the dust loadings by adding 10 percent of the window sill loading to the maximum floor loading. It is recognized that this procedure adds uncertainty to the floor samples, but this approach was taken to ensure that potential childhood exposures to lead on window sills are factored into the analysis.

A source of uncertainty in this approach is the median air concentration (0.025 $\mu g/m^3$) used as the background Pb air concentration, which comes from site monitoring data in EPA's Air Quality Systems database (USEPA 2006c). It is likely biased high because Pb monitors are often located in areas with nearby Pb emission sources. Modeling conducted for this approach, however, indicates that background ambient air concentrations are a small contributor to overall blood Pb levels, so the effects of this potential bias are expected to be minimal.

Another limitation of this approach is that the indoor air concentrations are assumed to equal the outdoor air concentrations. It is unclear whether this assumption would tend to positively or negatively bias blood Pb level results since no comparative indoor air concentration data were found.

In this approach, it is assumed that indoor air, indoor dust, and outdoor soil are the three media that contain increased levels of Pb as the result of RRP activities. It is a recognized limitation of this analysis that the Pb concentration of outdoor air may also rise as the result of a renovation. Although the tendency of this limitation would be to underestimate total exposures, the increased ventilation in the outdoor environment as compared to indoor ventilation would likelymitigate the effect.

A further limitation of this approach is that in calculating the "mid" values for the dust loadings, geometric means are used to combine the available data into a single central tendency estimate. The use of geometric means implicitly assumes that the distribution of the loadings is lognormal. In general, the measurements tend to be positively skewed, indicating that lognormal is a better representation of the data than normal; this assumption, however, represents an uncertainty and may tend to produce either lower or higher mid estimates than if an arithmetic mean is used.

The fact that some measurements from the OPPT Dust Study are not incorporated in this approach is also a limitation. For example, measurements from the halls are not used since these areas have poorly specified and variable containment properties compared to enclosed rooms. In addition, some interior renovation activities had exterior samples which were taken to determine how much indoor dust was tracked into the outdoor environment. Little information about the yard location of the samples is available, however, so these samples are not incorporated in this approach. It is important to note, however, that this approach accomodates specified outdoor soil concentration.

4. ESTIMATES OF MEDIA CONCENTRATIONS

This chapter describes the approach for estimating Pb concentrations in the relevant exposure media, including air, indoor dust, outdoor soil, drinking water, and diet. It describes how the approaches for air, indoor dust, and outdoor soil build on the background and activity-related inputs developed as described in Chapter 3 and how these inputs are used to characterize air, indoor dust, and outdoor soil concentrations. It also describes how concentrations in drinking water and diet were characterized. The approaches for estimating indoor dust and outdoor soil concentrations include both deterministic and probabilistic components. The approaches for air, drinking water, and diet include only a deterministic component. Water and diet concentrations are assumed to be unaffected by renovation activities. In addition, the activity-related air concentrations have a lower effect on blood Pb levels than the activity-related dust and soil concentrations, partially because the dust and soil levels remain elevated longer and partially because the blood Pb models are more sensitive to dust and soil inputs using the range of dust, soil, and air concentrations measured during and after renovation activities.

Because of this increased sensitivity, the dust and soil concentrations include a probabilistic component to determine the range of responses to different ranges of dust and soil values. The deterministic components for air, indoor dust, and outdoor soil (described in Sections 4.1 through 4.3, respectively) estimate concentrations for a given scenario based on a single set of “best estimate” inputs and assumptions. The approaches for drinking water and diet rely upon national-level data to characterize concentrations. The probabilistic components for indoor dust and outdoor soil (described in Section 4.6) involve both sensitivity and Monte Carlo analyses. The sensitivity analysis characterizes the sensitivity of the estimated media concentrations to changes in each selected input, considering the expected variability of that input as well as potential influential characteristics like cleaning efficiency and the use of a loading concentration conversion, and its results provide insight into which inputs are most important. The Monte Carlo analysis characterizes the range of estimated media concentrations given the distributions of potential values for selected inputs. Its results help to better characterize the potential range of estimated media concentrations given the uncertainty and variability in the input values. To illustrate both the deterministic and probabilistic components of the approach, two example applications, one for a single RRP activity example and another for a multiple RRP activities example, are provided for air and indoor dust in Sections 4.1 and 4.2.[2] The chapter concludes with Section 4.7, which provides a discussion of the uncertainties and limitations of the approach.

Exhibit 4-1 provides a key for the different dimensions (e.g., control options, exposure phases) that are used in the formulas throughout this chapter.

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[2] Note that no examples are provided for outdoor soil, drinking water, and diet.

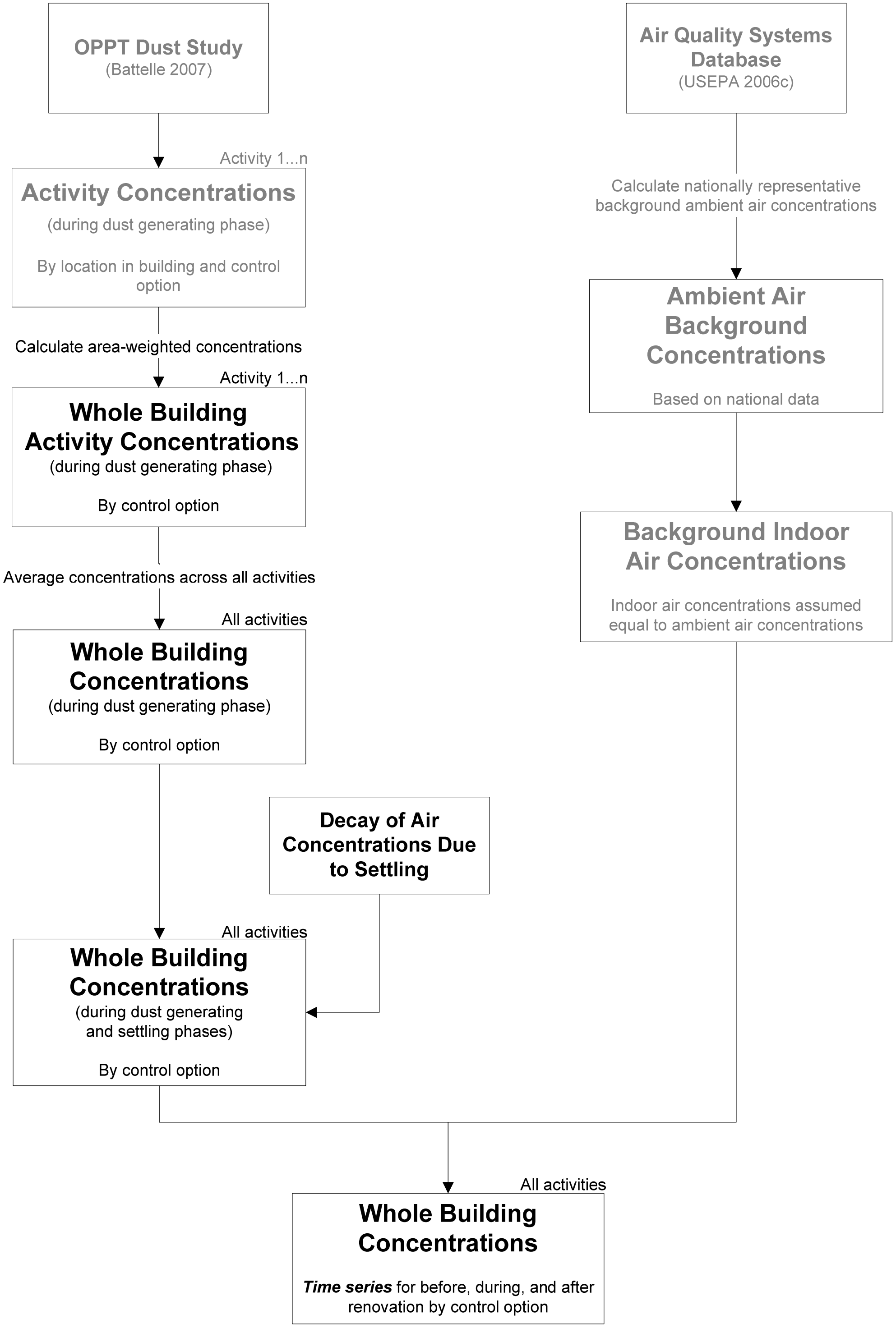
Exhibit 4-1. Dimension Types, Names, and IDs used in this Approach

Dimension Type	Dimension Name	Dimension ID
Location (LOC) ***Indoor***	Workspace	1
	Adjacent	2
	Rest of Building	3
Location (LOC) ***Outdoor***	Dripline	A
	Nearby	B
	Rest of Yard	C
Exposure Phase (PH) ***Indoor Dust***	Pre-Renovation (Background)	1
	Renovation (Dust Generating)	2
	Renovation (After Baseline Cleaning)	3
	Post-Renovation (Routine Cleaning)	4
	Post-Renovation (Background)	5
Phase (PH) ***Indoor Air***	Pre-Renovation (Background)	i
	Renovation (Dust Generating)	ii
	Renovation (Settling)	iii
	Renovation (Background)	iv
	Post-Renovation (Background)	v
Phase (PH) ***Outdoor Soil***	Pre-Renovation (Background)	A
	Renovation	B
	Post-Renovation	C
Control Option (CO) ***Indoor Dust and Air***	Base Control Option	0
	Control Option 1	1
	Control Option 2	2
	Control Option 3	3
Control Option (CO) ***Outdoor Soil***	Control Option A	A
	Control Option B	B
Activity (ACT)	Window replacement(s)	1
	Interior flat component LBP removal, scraping	2
	Renovating kitchen	3
	Cut-Outs	4
Sampling Method (SM)	Wipe	W
	Blue Nozzle	BN
Vintage (VIN)	< 1940	1
	1940 to 1959	2
	1960 to 1979	3

4.1 Air

Two types of air concentration data are required for this approach: ambient air concentrations (i.e., outdoor air) and indoor air concentrations. Ambient air concentrations are developed as described in Section 3.3.1.2. It is assumed that RRP activities do not contribute to ambient air concentration and thus the ambient concentrations used in this approach are based solely on background estimates. Indoor air concentrations are estimated as summarized in Exhibit 4-2. The elements of this process described in Chapter 3 are shown in grey and the elements described in this section are shown in black (note that this exhibit is identical to Exhibit 3-6, with the exception of which elements are in grey and black). Section 4.1.1 describes how the general approach illustrated in Exhibit 4-2 is applied to estimate indoor air concentrations during each phase of the different exposure periods. Estimated indoor air concentrations for the single RRP activity and multiple RRP activities examples are provided in Sections 4.1.2 and 4.1.3.

Exhibit 4-2. Approach for Estimating Indoor Air Concentrations



4.1.1 Approach

Exhibit 3-2 presents an overview of the different exposure periods, and phases comprising each exposure period, defined in this approach for characterizing indoor air concentrations. The specifics of the approach used to characterize indoor air concentrations for each of these exposure periods are provided in the following sections.

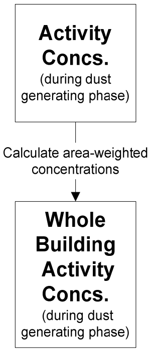
4.1.1.1 Pre-renovation

The Pre-renovation exposure period represents the period of exposure before initiation of the RRP activity or activities and thus consists of background contributions only. The approach for estimating background indoor air concentrations is described in Section 3.3.1.3.

4.1.1.2 Renovation

The Renovation exposure period represents the period of exposure beginning with the initiation of the RRP activity or activities and concluding with the completion of the renovation and any contractor cleaning. In this approach, there are three phases of the Renovation period for indoor air concentrations: the Dust Generating phase, the Settling phase, and the Background phase. The Dust Generating phase represents the portion of the renovation where RRP activities are creating leaded dust (e.g., during demolition). The Settling phase represents the period of time following completion of the Dust Generating activities during which the dust in air settles onto the floor. The Background phase represents the period of time from the end of the Settling phase until the end of the Renovation period. In this approach, there are four steps involved in estimating air concentrations for this exposure period: (1) calculate whole building RRP activity-related concentrations during the Dust Generating phase; (2) combine activity concentrations to calculate whole building concentrations for the Dust Generating phase; (3) estimate the Settling of dust in air during the Settling phase; and (4) calculate concentrations for background phase. These steps are described below.

Calculate Whole Building Activity Concentrations during the Dust Generating Phase



In this approach, the indoor air concentrations are developed (as described in Chapter 3) for three different locations in the building: Workspace, Adjacent Room, and Rest of the Building. These room-specific concentrations are combined into a single whole house concentration for each activity using the following equation:

$$\begin{aligned} ACONC_{PH=ii,CO,ACT} = \; & (PAW * ACONC_{LOC=1,PH=ii,CO,ACT}) + \\ & (PAA * ACONC_{LOC=2,PH=ii,CO,ACT}) + \\ & (PAR * ACONC_{LOC=3,PH=ii,CO,ACT}) \end{aligned} \qquad \textbf{(Eq. 4-1)}$$

where:

$ACONC_{PH=ii,CO,ACT}$ = Whole building average indoor air Pb concentrations during phase ii (i.e., Dust Generating phase), with Control Option *CO*, and Activity *ACT*, in $\mu g/m^3$

CO = Base, 1, 2, or 3

PAW = % Area of Building --- Workspace

$ACONC_{LOC=1,PH=ii,CO,ACT}$ = Indoor air Pb concentration in the Workspace (i.e., LOC=1) during phase ii (i.e., Dust Generating phase), with Control Option *CO*, and Activity *ACT*, in $\mu g/m^3$

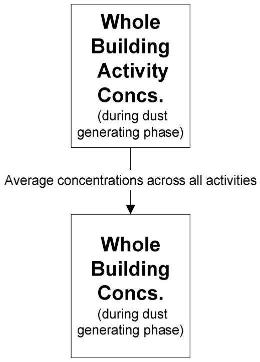
PAA = % Area of Building --- Adjacent Room

$ACONC_{LOC=2,PH=ii,CO,ACT}$ = Indoor air Pb concentration in the Adjacent Room (i.e., LOC=2) during phase ii (i.e., Dust Generating phase), with Control Option *CO*, and Activity *ACT*, in $\mu g/m^3$

PAR = % Area of Building --- Rest of Building (calculated as 1 - *PAW* - *PAA*)

$ACONC_{LOC=3,PH=ii,CO,ACT}$ = Indoor air Pb concentration in the Rest of Building (i.e., LOC=3) during phase ii (i.e., Dust Generating phase), with Control Option *CO*, and Activity *ACT*, in $\mu g/m^3$

Calculate Whole Building Concentrations across Activities during the Dust Generating Phase



After calculating whole building activity air concentrations, these concentrations are averaged together to estimate the whole building air concentrations using the following equation:

$$ACONC_{PH=ii,CO} = \frac{\sum_{ACT=1}^{n} ACONC_{PH=ii,CO,ACT}}{n}$$

(Eq. 4-2)

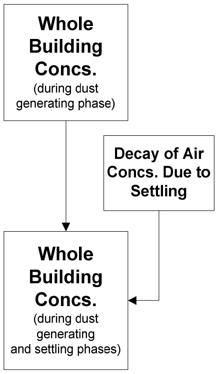
where:

$ACONC_{PH=ii,\ CO}$ = Whole building average indoor air Pb concentrations during phase *ii* (i.e., Dust Generating phase), with Control Option *CO*, in µg/m^3

$ACONC_{PH=ii,\ CO,\ ACT}$ = Whole building average indoor air Pb concentrations during phase *ii* (i.e., Dust Generating phase), with Control Option *CO*, and Activity *ACT*, in µg/m^3

n = number of activities

Calculate Concentrations during the Settling Phase



In this step, the indoor air concentrations during the Settling phase (which is always one week long) are estimated. Estimating these concentrations requires first estimating concentrations for each part of the phase and then calculating a time-weighted average of these concentrations to estimate the concentrations for the phase. Indoor air concentrations for the different parts of the phase are calculated as follows:

Part 1: As described in Chapter 3, indoor air concentrations for the Dust Generating phase were estimated using air sampling that began during the activity and continued until one hour after completion of the activity. Because this phase is defined as beginning at the completion of the Dust Generating phase activity, the last hour of this sampling is part of the Settling phase. As a result, the first part of the Settling phase is represented by concentrations for the Dust Generating phase (i.e., $ACONC_{PH=ii,\,CO}$) and is assumed to last one hour.

Part 2: The second part of the Settling phase is the time during which the dust suspended during the Dust Generating phase settles to the floor. The concentrations in this part are calculated using the following equation:

$$ACONC_{PH=iii@h,CO} = ACONC_{PH=ii,CO} * e^{(DecayConst*h)} \tag{Eq. 4-3}$$

where:

$ACONC_{PH=iii@h,CO}$ = Whole building average indoor air Pb concentrations at hour h of phase iii (i.e., Settling phase), with Control Option *CO*, in µg/m^3

h = Time since the initiation of the Part 2 of the Settling phase, in hours

$ACONC_{PH=ii,CO}$ = Whole building average indoor air Pb concentrations during phase ii (i.e., Dust Generating phase), with Control Option *CO*, in µg/m^3

DecayConst = Decay constant for Pb dust in air, based on most conservative value presented in Choe et al. (2000), in hours^{-1}

The calculation is repeated, incrementing *h* by one hour each time, until $ACONC_{PH=iii@h,CO}$ reaches the background concentration (generally around 15 hours). All of the values for $ACONC_{PH=iii@h,CO}$ are then averaged together to estimate the Part 2 concentration (i.e., $ACONC_{PH=iii@Part\ 2,CO}$).

Part 3: The final part of the Settling phase represents the time beginning when $ACONC_{PH=iii@h,CO}$ reaches background and continuing until the Settling phase reaches one week in duration. This part consists entirely of background contributions only. The approach for estimating background indoor air concentrations is described in Section 3.3.1.3.

The Settling phase concentration is estimated from the concentrations for Parts 1 through 3 using the following equation:

$$ACONC_{PH=iii,CO} = \frac{ACONC_{PH=iii@Part1,CO} * 1hr + ACONC_{PH=iii@Part2,CO} * Y + ACONC_{PH=iii@Part3,CO} * (167hr - Y)}{168hr}$$

(Eq. 4-4)

where:

$ACONC_{PH=iii,CO}$ = Whole building average indoor air Pb concentrations during phase *iii* (i.e., Settling phase), with Control Option *CO*, in µg/m^3

$ACONC_{PH=iii@Part1,CO}$ = Whole building average indoor air Pb concentrations during Part 1 of phase *iii* (i.e., Settling phase), with Control Option *CO*, in µg/m^3

$ACONC_{PH=iii@Part2,CO}$ = Whole building average indoor air Pb concentrations during Part 2 of phase *iii* (i.e., Settling phase), with Control Option *CO*, in µg/m^3

Y = Duration of Part 2 of phase *iii* (i.e., Settling phase), in hours

$ACONC_{PH=iii@Part3,CO}$ = Whole buildinig average indoor air Pb concentrations during Part 3 of phase *iii* (i.e., Settling phase), with Control Option *CO*, in µg/m^3

Calculate Concentrations for Background Phase

The Background phase of the Renovation period represents the time beginning at the conclusion of the Settling phase and continuing until the end of the Renovation period. This phase consists entirely of background contributions only. The approach for estimating background indoor air concentrations is described in Section 3.3.1.3.

4.1.1.3 Post-renovation

The Post-renovation period represents the time beginning at the conclusion of the Renovation period and continuing until the end of the exposure duration. This period consists entirely of background contributions only. The approach for estimating background indoor air concentrations is described in Section 3.3.1.3.

4.1.2 Example for Single RRP Activity

The approach presented in Section 4.1.1 was applied to the single RRP activity scenario by selecting experiments from the OPPT Dust Study for calculation. In the example, it uses in the input values presented in Exhibit A-4 in Appendix A. The indoor air concentrations for the Background (where Pre-renovation, Renovation (Background), and Post-renovation all use the same background value), Renovation (Dust Generating), and Renovation (Settling) for each of the three housing vintages for the single activity example are shown in Exhibit 4-3.

Exhibit 4-3. Indoor Air Concentrations for Single RRP Activity Example

Exposure Phase	Concentration (µg/m^3)			
	Base Control Option (no plastic; baseline cleaning)	Control Option 1 (no plastic; rule cleaning)	Control Option 2 (plastic; baseline cleaning)	Control Option 3 (plastic; rule cleaning)
Background	0.025	0.025	0.025	0.025
Post-renovation (Dust Generating)	3.06	3.57	6.30	5.14
Post-renovation (Settling)	0.24	0.29	0.52	0.41

4.1.3 Example for Multiple RRP Activities

The approach presented in Section 4.1.1 was applied to the multiple RRP activities scenario in a manner similar to a single RRP activity. For the multiple activities example, it uses the input values presented in Exhibit A-5 in Appendix A. The indoor air concentrations for the Background (where Pre-renovation, Renovation (Background), and Post-renovation all use the same background value), Renovation (Dust Generating), and Renovation (Settling) for each of the three housing vintages for the multiple activity example are shown in Exhibit 4-4.

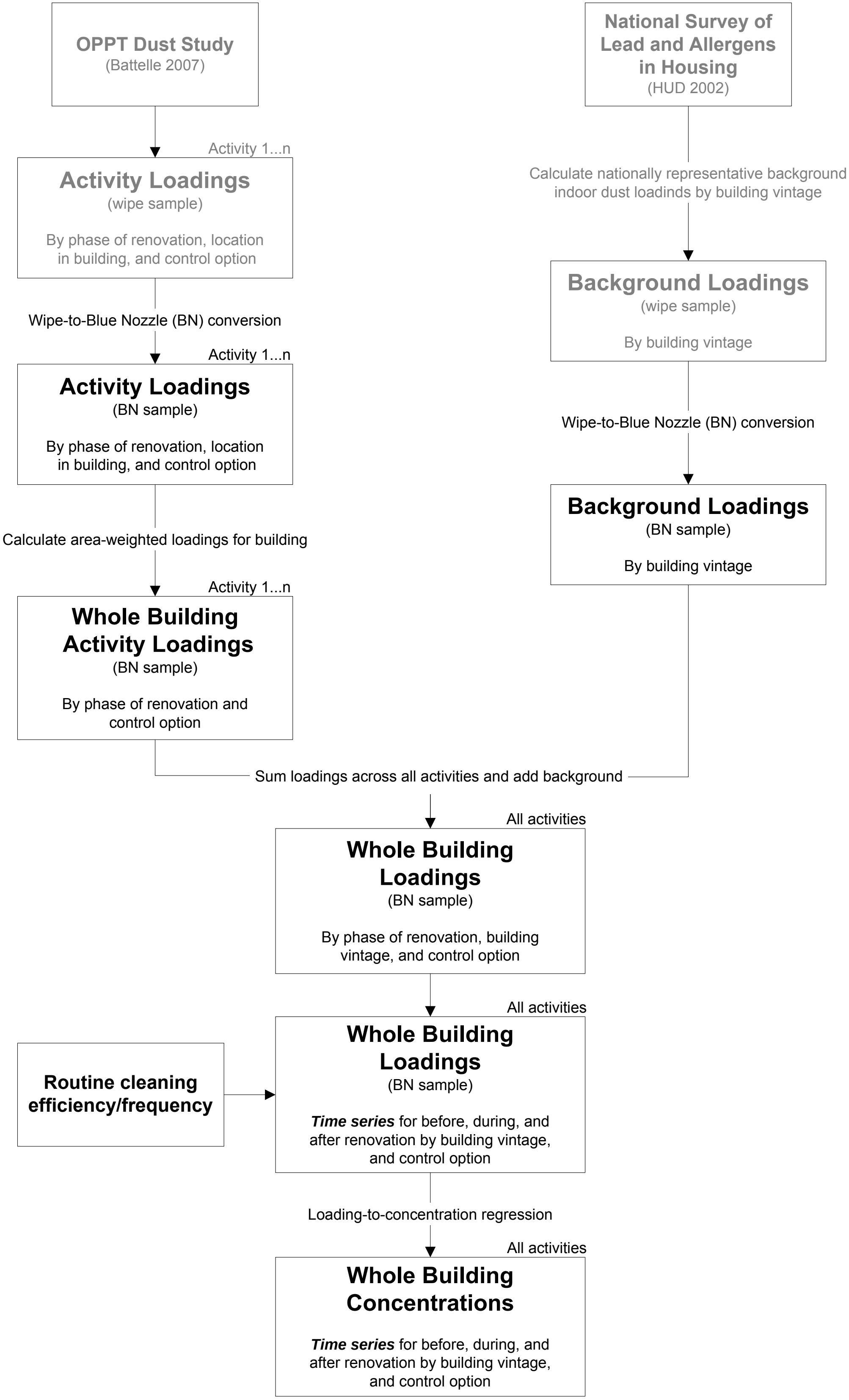
Exhibit 4-4. Indoor Air Concentrations for Multiple RRP Activities Example

Exposure Phase	Concentration (µg/m^3)			
	Base Control Option (no plastic; baseline cleaning)	Control Option 1 (no plastic; rule cleaning)	Control Option 2 (plastic; baseline cleaning)	Control Option 3 (plastic; rule cleaning)
Background	0.025	0.025	0.025	0.025
Post-renovation (Dust Generating)	3.45	3.72	5.19	4.41
Post-renovation (Settling)	0.26	0.30	0.42	0.34

4.2 Indoor Dust

Indoor dust concentrations are estimated in this approach as summarized in Exhibit 4-5. The elements of this process described in Chapter 3 are shown in grey and the elements described in this section are shown in black (note that this exhibit is identical to Exhibit 3-7, with the exception of which elements are in grey and black). Section 4.1.3 describes how the general approach illustrated in Exhibit 4-5 is applied to estimate indoor dust concentrations during each phase of the different exposure periods. Sections 4.2.2 and 4.2.3, respectively, provide estimated indoor dust concentrations for the single and multiple activity examples.

Exhibit 4-5. Approach for Estimating Indoor Dust Concentrations



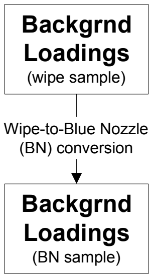
4.2.1 Approach

Exhibit 3-4 presents an overview of the different exposure periods, and phases comprising each exposure period, defined in this approach for characterizing indoor dust concentrations. The specifics of the approaches used to characterize indoor dust concentrations for each of these exposure periods are provided in the following sections.

4.2.1.1 Pre-renovation

The Pre-renovation exposure period represents the period of exposure before initiation of the RRP activity or activities and thus consists of background contributions only. There are two steps involved in estimating indoor dust concentrations for this period: (1) convert wipe sample indoor dust loadings to vacuum sample indoor dust loadings; and (2) convert vacuum sample indoor dust loadings to indoor dust concentrations. These steps are described below:

Convert Wipe Loadings to Vacuum Loadings



As described in Section 3.3.2, the background indoor dust loading values used for this approach are based on indoor dust wipe samples. Because the regression equations developed to convert indoor dust loadings to indoor dust concentrations require that loadings be provided in terms of Blue Nozzle (BN) vacuum samples, these wipe samples must be converted into BN samples. This conversion is performed using the following equation for uncarpeted floors from “Conversion Equations for Use in Section 403 Rulemaking” (USEPA 1997):

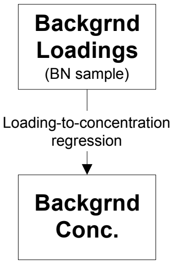
$$DLOAD_{BN,BG,VIN} = 0.185*(DLOAD_{W,BG,VIN})^{0.931} \qquad \textbf{(Eq. 4-5)}$$

where:

$DLOAD_{BN,BG,VIN}$ = Background (BG) indoor dust Pb BN sampling loading for building vintage VIN, µg/m^2

$DLOAD_{W,BG,VIN}$ = Background (BG) indoor dust Pb wipe sampling loading for building vintage VIN, µg/m^2

No equation is provided for converting loadings from carpet, so it is assumed this equation could be applied to both carpets and hard surfaces. This is recognized as a limitation of the approach.



Convert Loadings to Concentrations

For buildings of known vintage, the BN sample loading values are converted to indoor dust concentrations using the appropriate housing vintage-specific regression equation described in Appendix C, which is summarized below:

$$DCONC_{BG,VIN} = e^{(Intercept_{VIN} + Slope_{VIN}(\ln(DLOAD_{BN,BG})))} \qquad \textbf{(Eq. 4-6)}$$

where:

$DCONC_{BG,VIN}$ = Background (BG) indoor dust concentration for building vintage *VIN*, in µg/g

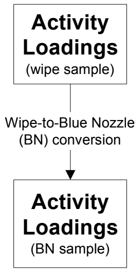
$DLOAD_{BN,BG}$ = Background (BG) indoor dust Pb BN sampling loading, in $\mu g/ft^2$

Although this regression introduces uncertainty, conversion remains a necessary step, since the blood Pb models are configured to accept concentrations and not loadings. Under an assumption that the HUD-derived relationships can be generalized, this regression represents the best known relationship available.

4.2.1.2 Renovation

The Renovation exposure period represents the period of exposure beginning with the initiation of the RRP activity or activities and concluding with the completion of the renovation and any contractor cleaning. There are two phases of the Renovation period for indoor dust concentrations: the Dust Generating phase and the After Baseline Cleaning phase. The Dust Generating phase represents the portion of the renovation where RRP activities are creating leaded dust (e.g., during demolition). The After Baseline Cleaning phase represents the remainder of the Renovation period and takes into account some basic cleaning after completion of the Dust Generating activities. The calculation process to estimate indoor dust concentrations for these phases is identical as explained in Chapter 3, but different loadings values are used to represent the different phases. The approach for estimating indoor dust concentrations for the Renovation period consists of four steps: (1) convert wipe sample indoor dust loadings to vacuum sample indoor dust loadings; (2) calculate whole building RRP activity-related vacuum indoor dust loadings; (3) calculate whole building total vacuum indoor dust loadings (including background); and (4) convert whole building total vacuum indoor dust loadings to whole building indoor dust concentrations. These steps are described below.

Convert Wipe Loadings to Vacuum Loadings



In this step, the activity-related and background indoor dust loading values, developed as described in Sections 3.4.3.2 (for single activity scenarios), 3.4.4.2 (for multiple activity scenarios), and 3.3.2 (for background), are converted from indoor dust wipe samples to indoor dust BN vacuum samples. This step is required because the regression equations developed to convert from indoor dust loadings to indoor dust concentrations require that loadings be provided in terms of BN vacuum samples. This conversion is performed for activity-related loadings using the following equation for uncarpeted floors based on "Conversion Equations for Use in Section 403 Rulemaking" (USEPA 1997):

$$DLOAD_{BN,LOC,PH,CO,ACT} = 0.185*(DLOAD_{W,LOC,PH,CO,ACT})^{0.931} \qquad \textbf{(Eq. 4-7)}$$

where:

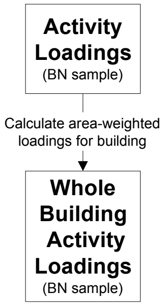
$DLOAD_{BN,LOC,PH,CO,ACT}$ = Indoor dust Pb BN sampling loading in location *LOC* during phase *PH*, with Control Option *CO*, and Activity *ACT*, in $\mu g/m^2$

$DLOAD_{W,LOC,PH,CO,ACT}$ = Indoor dust Pb wipe sampling loading in location *LOC* during phase *PH*, with Control Option *CO*, and Activity *ACT*, in $\mu g/m^2$

No equation is provided for converting loadings from carpet, so it is assumed this equation could be applied to both carpets and hard surfaces. This is recognized as a limitation of the approach.

Likewise, this conversion is performed for background loadings using Equation 4-1. Again, no equation is provided for converting loadings from carpet, so it is assumed this equation can be applied to both carpets and hard surfaces. This is recognized as a limitation of the approach.

Calculate Whole Building Activity Loadings



The indoor dust loadings are developed (as described in Chapter 3) for three different locations in the building: Workspace, Adjacent Room, and Rest of the building. These location-specific loadings are combined into a single whole house loading for each activity using the following equation:

$$DLOAD_{BN,PH,CO,ACT} = (PAW * DLOAD_{BN,LOC=1,PH,CO,ACT}) + (PAA * DLOAD_{BN,LOC=2,PH,CO,ACT}) + (PAR * DLOAD_{BN,LOC=3,PH,CO,ACT}) \quad \textbf{(Eq. 4-8)}$$

where:

$DLOAD_{BN,PH,CO,ACT}$ = Whole building average indoor dust Pb BN sampling loadings during phase *PH*, with Control Option *CO*, and Activity *ACT*, in µg/m^2

PAW = % Area of Building --- Workspace

$DLOAD_{BN,LOC=1,PH,CO,ACT}$ = Indoor dust Pb BN sampling loading in the Workspace (i.e., *LOC*=1) during phase *PH*, with Control Option *CO*, and Activity *ACT*, in µg/m^2

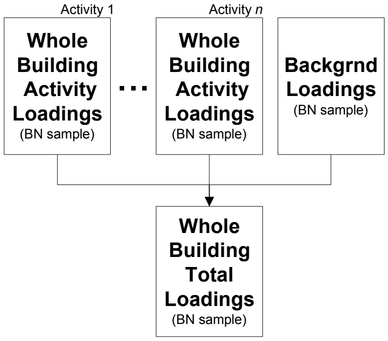
PAA = % Area of Building --- Adjacent Room

$DLOAD_{BN,LOC=2,PH,CO,ACT}$ = Indoor dust Pb BN sampling loading in the Adjacent Room (i.e., *LOC*=2) during phase *PH*, with Control Option *CO*, and Activity *ACT*, in µg/m^2

PAR = % Area of Building --- Rest of Building (calculated as 1-*PAW*-*PAA*)

$DLOAD_{BN,LOC=3,PH,CO,ACT}$ = Indoor dust Pb BN sampling loading in the Rest of Building (i.e., *LOC*=3) during phase *PH*, with Control Option *CO*, and Activity *ACT*, in µg/m^2

Calculate Whole Building Total Loadings



After calculating whole building average loadings for each activity, the next step is to sum the loadings across all RRP activities and then add the background loadings. This total loading represents the contributions from all activities as well as the contributions from background. Note that for scenarios with only one RRP activity, this step consists of simply summing the whole building loadings for that activity and the background loadings. The equation used to calculate this whole building total loading is provided below:

$$DLOAD_{BN,PH,CO,VIN} = \left(\sum_{ACT=1}^{n} DLOAD_{BN,PH,CO,ACT} \right) + DLOAD_{BN,BG,VIN} \qquad \textbf{(Eq. 4-9)}$$

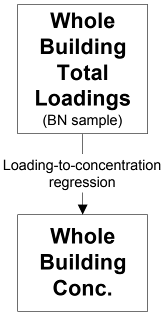
where:

$DLOAD_{BN,PH,CO,VIN}$ = Total whole building average indoor dust Pb BN sampling loadings during phase *PH*, with Control Option *CO*, and building vintage *VIN*, in µg/m^2

$DLOAD_{BN,PH,CO,ACT}$ = Average whole building indoor dust Pb BN sampling loadings during phase *PH*, with Control Option *CO*, and Activity *ACT*, in µg/m^2

$DLOAD_{BN,BG,VIN}$ = Background (BG) indoor dust Pb BN sampling loadingfor building vintage VIN, µg/m^2

Convert Loadings to Concentrations



The final step required to calculate indoor dust concentrations for both phases of the Renovation period is to convert the whole building total indoor dust loadings to indoor dust concentrations. For buildings of known vintage, the BN sample whole building total loading values are converted to indoor dust concentrations using the appropriate housing vintage-specific regression equation described in Appendix C, which is summarized below:

$$DCONC_{PH,CO,VIN} = e^{(Intercept_{VIN} + Slope_{VIN} * (\ln(DLOAD_{BN,PH,CO,VIN})))} \qquad \textbf{(Eq. 4-10)}$$

where:

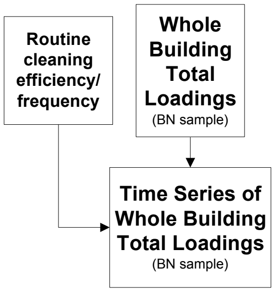
$DCONC_{PH,CO,VIN}$ = Total whole building average indoor dust concentration during phase *PH*, with Control Option *CO*, and building vintage *VIN*, in µg/g

$DLOAD_{BN,PH,CO,VIN}$ = Total whole building average indoor dust Pb BN sampling loadings during phase *PH*, with Control Option *CO*, and building vintage *VIN*, in µg/m^2

4.2.1.3 Post-renovation

The Post-renovation exposure period represents the period of exposure beginning with the completion of the renovation and any contractor cleaning and ending with the end of the time period for which exposures are being characterized. There are two phases of the Post-renovation period for indoor dust concentrations: the Routine Cleaning phase and the Background phase. The Routine Cleaning phase represents the period of time between the completion of the renovation and the time at which indoor dust concentrations return to background levels, and this phase accounts for the decrease in indoor dust concentrations that occurs due to routine cleaning of the building. The Background phase represents only contributions from background sources of indoor dust. The approach for estimating concentrations during the Post-renovation (Background) phase is identical to the approach used for the Pre-renovation period (presented in Section 4.2.1.1) and thus is not repeated here. The approach for estimating indoor dust concentrations for the Routine Cleaning phase consists of two steps: (1) calculating the change in indoor dust loadings based on routine cleaning; and (2) converting the resulting indoor dust loadings to indoor dust concentrations. These steps are described below.

Calculate Change in Loadings Based on Routine Cleaning



Indoor dust Pb loadings in the Routine Cleaning phase are a function of the loadings at the completion of the renovation and the frequency and efficiency of routine cleaning. Unlike previous phases which used a single loading to represent the entire phase, a time series of loadings is developed for this phase to account for the decrease in dust loadings that occurs over time with repeated routine cleanings. The indoor dust loading for cleaning iteration *X* is calculated using the following equation:

$$DLOAD_{BN,PH=4@X,CO,VIN} = DLOAD_{BN,PH=4@X-1,CO,VIN} * RoutineCleanEfficiency_{X} \quad \textbf{(Eq. 4-11)}$$

where:

$DLOAD_{BN,PH=4@X,CO,VIN}$ = Total whole building average indoor dust BN sample loading following cleaning *X* during phase 4 (i.e., routine cleaning phase), with Control Option *CO*, and building of vintage *VIN*, in µg/g

$DLOAD_{BN,PH=4@X-1,CO,VIN}$ = Total whole building average indoor dust BN sample loading following cleaning *X-1* for phase 4 (i.e., routine cleaning phase), with Control Option *CO*, and building of vintage *VIN*, in µg/g

$RoutineCleanEfficiency_{X}$ = Post-activity cleanup efficiency for the cleaning iteration *X*; calculated as a weighted average based on the percentage of the building that is carpeted (the remainder is assumed to be covered by hard surfaces), the cleaning efficiency for carpet (which is a function of how many times the carpet has been cleaned), and the cleaning efficiency for hard surfaces (which is a function of the Pb loading remaining after the previous cleaning).

The indoor dust loading for time T is calculated using the following equations:

$$DLOAD_{BN,PH=4@T,CO,VIN} = DLOAD_{BN,PH=4@X,CO,VIN} \qquad \textbf{(Eq. 4-12)}$$

$$X = T * CleanFrequency \qquad \textbf{(Eq. 4-13)}$$

where:

$DLOAD_{BN,PH=4@T,CO,VIN}$ = Total whole building average indoor dust BN sample loading for week T during phase 4 (i.e., routine cleaning phase), with Control Option CO, and building of vintage VIN, in µg/g

X = Cleaning iteration, unitless

T = Time, in weeks

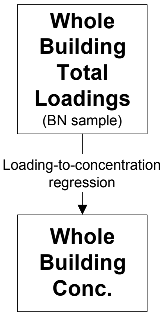
$DLOAD_{BN,PH=4@X,CO,VIN}$ = Total whole building average indoor dust BN sample loading following cleaning X during phase 4 (i.e., routine cleaning phase), with Control Option CO, and building of vintage VIN, in µg/g

$CleanFrequency$ = Frequency of routine cleaning, in cleanings/week

Note that $DLOAD_{BN,PH=4@X=0,CO,VIN}$ is assumed to be equal to $DLOAD_{BN,PH=4@T=0,CO,VIN}$, which is the initial loading for the Routine Cleaning phase and is developed as described in Chapter 3.

Convert Loadings to Concentrations

The final step required to calculate indoor dust concentrations for the routine cleaning phase is to convert the time series of whole building total indoor dust loadings to a time series of indoor dust concentrations. For buildings of known vintage, the Blue Nozzle (BN) sample whole building total loading values are converted to indoor dust concentrations using the vintage-specific regression equation described in Appendix C, which is summarized below:



$$DCONC_{PH=4@T,CO,VIN} = e^{(Intercept_{VIN} + Slope_{VIN} \ln(DLOAD_{BN,PH=4@T,CO,VIN})))} \qquad \textbf{(Eq. 4-14)}$$

where:

$DCONC_{PH=4@T,CO,VIN}$ = Total whole building average indoor dust concentration during week T of phase 4 (i.e., routine cleaning phase), with Control Option CO, and building vintage VIN, in µg/g

$DLOAD_{BN,PH=4@T,CO,VIN}$ = Total whole building average indoor dust Pb BN sampling loadings during week *T* of phase 4 (i.e., routine cleaning phase), with Control Option *CO*, and building vintage *VIN*, in µg/m^2

For buildings of unknown vintage, the following non-vintage-specific regression equation (described in Appendix C) is used to convert Blue Nozzle (BN) sample loadings to concentrations.

$$DCONC_{PH=4@T,CO} = e^{(Intercept_{VIN=unknown} + Slope_{VIN=unknown} \ln(DLOAD_{BN,PH=4@T,CO})))} \quad \textbf{(Eq. 4-15)}$$

where:

$DCONC_{PH=4@T,CO}$ = Total whole building average indoor dust concentration during week *T* of phase 4 (i.e., routine cleaning phase), with Control Option *CO*, and building of unknown vintage *VIN=unknown,* in µg/g

$DLOAD_{BN,PH=4@T,CO}$ = Total whole building average indoor dust Pb BN sampling loadings during week *T* of phase 4 (i.e., routine cleaning phase), with Control Option *CO*, and building of unknown vintage *VIN=unknown*, in µg/m^2

4.2.2 Example for Single RRP Activity

The approach presented above is applied to the single RRP activity scenario using the inputs provided in Exhibit A-6 in Appendix A. The indoor dust concentrations for the Background (where Pre-renovation and Post-renovation both use the same background value), Post-renovation (Dust Generating), Post-renovation (After Baseline Cleaning), and Post-renovation (Routine Cleaning, Week 0) for each of the three housing vintages for the single activity example are shown in Exhibit 4-6. This particular type of table can be used to examine patterns in time or across controls. In general, the concentrations seen in either example or in future calculations using this approach will reflect whatever relationships occur in the underlying OPPT Dust Study. In fact, at times in the underlying OPPT Dust Study, the concentration associated with Post-renovation (After Baseline Cleaning) is actually higher than the Post-renovation (Dust Generating) concentration, and the Post-renovation (Routine Cleaning, Week 0) is higher than the Post-renovation (After Baseline Cleaning) concentration.

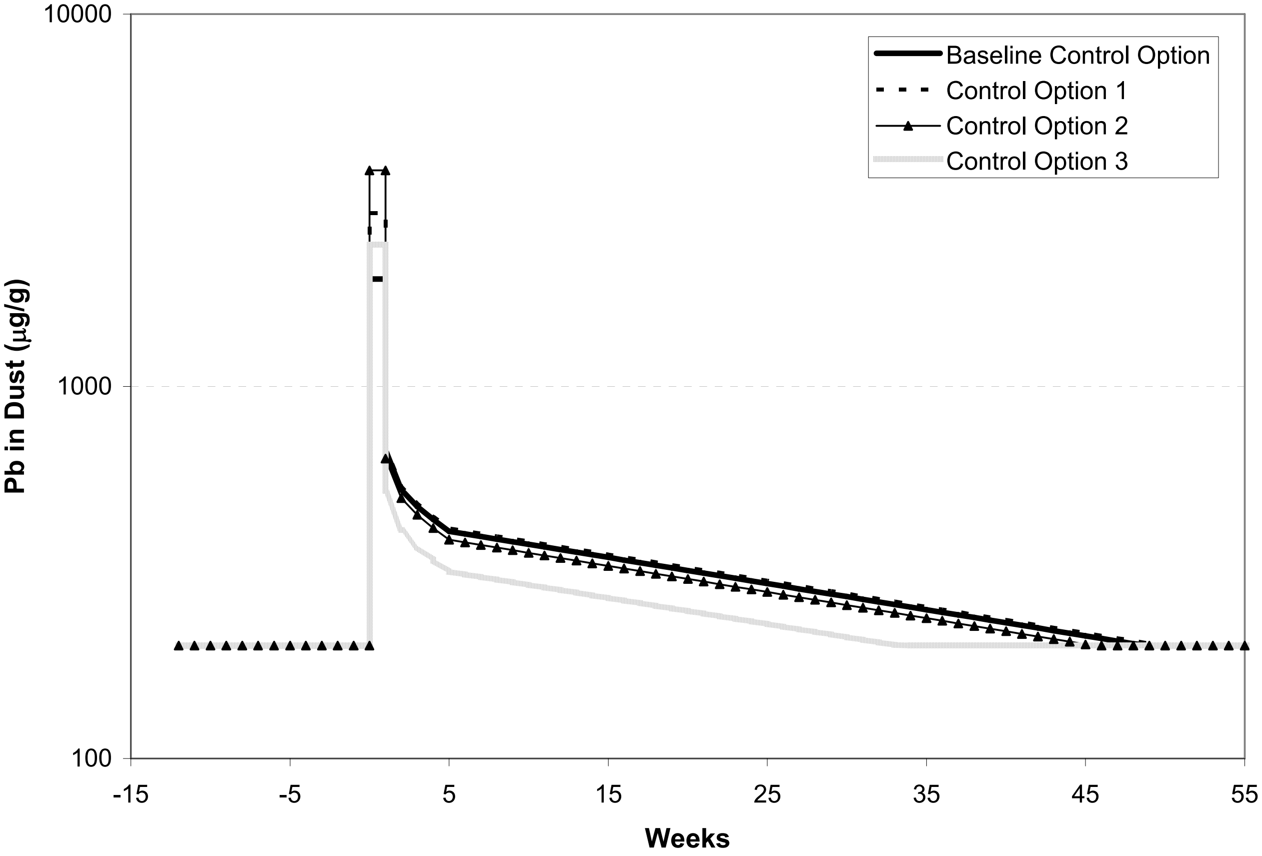
Exhibit 4-6. Whole-House Indoor Dust Concentrations for the Single RRP Activity Example for the Different Renovation Phases

Exposure Phase	Concentration (µg Pb/g dust)			
	Baseline Control Option	Control Option 1	Control Option 2	Control Option 3
Vintage <1940				
Pre-renovation (Background)	201	201	201	201
Renovation (Dust Generating)	1,941	2,923	3,800	2,406
Renovation (After Baseline Cleaning)	674	621	639	482
Post-renovation (Routine Cleaning, Week 0)	674	686	639	524
Vintage 1940 to 1959				
Pre-renovation (Background)	86	86	86	86
Renovation (Dust Generating)	1,029	1,534	1,983	1,269
Renovation (After Baseline Cleaning)	362	333	343	257
Post-renovation (Routine Cleaning, Week 0)	362	368	343	280
Vintage 1960 to 1979				
Pre-renovation (Background)	64	64	64	64
Renovation (Dust Generating)	551	760	933	652
Renovation (After Baseline Cleaning)	237	222	227	179
Post-renovation (Routine Cleaning, Week 0)	237	241	227	193

After Post-renovation (Routine Cleaning, Week 0), the routine cleaning decreases the concentrations over time. The values for the indoor dust concentrations at Post-renovation Week 0 (at the beginning of the routine cleaning phase) and Post-renovation Week 10 (in the middle of the routine cleaning phase) are given in tables by vintage in Appendix E. In addition, the Weeks to Background model metric gives the number of routine-cleaning weeks required to clean away the renovation “spike” and return to background indoor dust levels. The number of weeks tends to increase for later vintages, because the background value itself is lower in these later vintages and more cleaning weeks are required.

An example of a full time-series containing the Pre-renovation, Renovation, and Post-renovation phases for the < 1940 vintage for all Control Options is shown in Exhibit 4-7. Note that the actual time-series extends 312 weeks (6 years); it has been truncated in this figure for presentation purposes. The concentrations are plotted on a log scale and thus exponential decreases in concentration during the Post-renovation (Routine Cleaning) phase appear as straight lines.

Exhibit 4-7. Indoor Dust Concentrations Time Series for the Single Activity Example, < 1940 Vintage



4.2.3 Example for Multiple RRP Activities

The approach presented above was applied to the multiple RRP activities scenario using the inputs provided in Exhibit A-7 in Appendix A. The multiple indoor activities example includes a combination of four separate renovation activities, where the whole house loadings are summed across activities and then converted to concentrations. The indoor dust concentrations for the Background (where Pre-renovation and Post-renovation both use the same Background value), Post-renovation (Dust Generating), Post-renovation (After Baseline Cleaning), and Post-renovation (Routine Cleaning, Week 0) for each of the three housing vintages for the multiple activity example are shown in Exhibit 4-8. This particular type of table can be used to examine patterns in time or across controls.

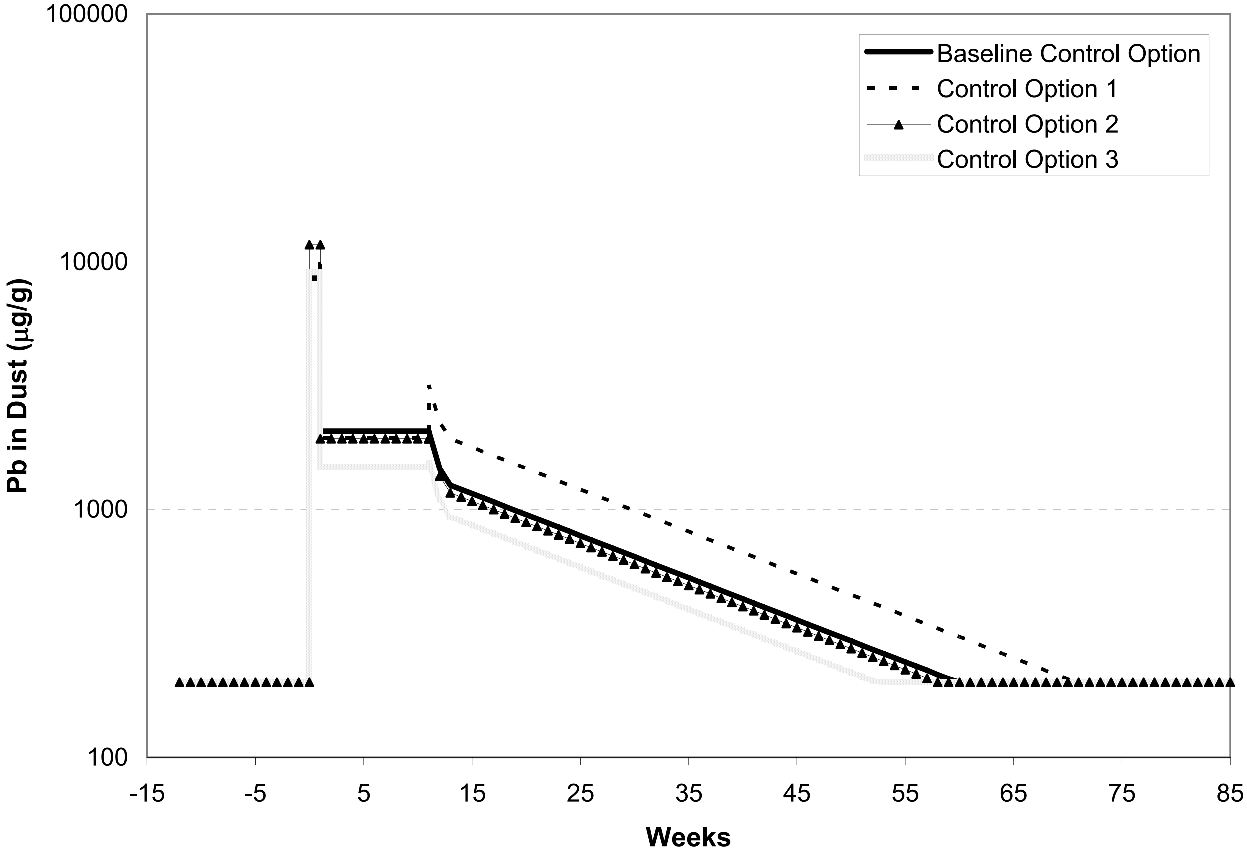
Exhibit 4-8. Whole-House Indoor Dust Concentrations for the Multiple Activities Example for the Different Renovation Phases

Exposure Phase	Concentration (µg Pb/g dust)			
	Baseline Control Option	Control Option 1	Control Option 2	Control Option 3
Vintage <1940				
Pre-renovation (Background)	201	201	201	201
Renovation (Dust Generating)	8,588	9,803	11,713	9,136
Renovation (After Baseline Cleaning)	2,075	1,950	1,932	1,483
Post-renovation (Routine Cleaning, Week 0)	2,075	3,185	1,932	1,549
Vintage 1940 to 1959				
Pre-renovation (Background)	86	86	86	86
Renovation (Dust Generating)	4,395	5,000	5,949	4,668
Renovation (After Baseline Cleaning)	1,098	1,033	1,024	790
Post-renovation (Routine Cleaning, Week 0)	1,098	1,669	1,024	824
Vintage 1960 to 1979				
Pre-renovation (Background)	64	64	64	64
Renovation (Dust Generating)	1,766	1,958	2,250	1,853
Renovation (After Baseline Cleaning)	581	553	549	446
Post-renovation (Routine Cleaning, Week 0)	581	813	549	461

The values for the indoor dust concentrations at Post-renovation Week 0 and Week 10 and the Weeks to Background metric are given in tables by vintage in Appendix E. In general, the concentrations and Weeks to Background are all higher in the multiple activities example compared to the single activity example. The Week 0 concentrations tend to increase for the multiple activities example by a factor of two to five.

An example of the full time series of dust concentrations for the < 1940 vintage for all Control Options is shown in Exhibit 4-9. Such plots permit diagnostics and comparisons across Control Options in light of the phases mapped in Exhibit 3-4. For example, in addition to the largest spike in concentration due to the Renovation (Dust Generating) phase, there is also the eleven week Post-renovation (post-baseline cleaning) phase. Control Option 1 suffers another spike in concentration at the end of this phase; this spike may occur because the post-verification OPPT Dust Study values lead to whole house concentrations higher than the post-cleaning values.

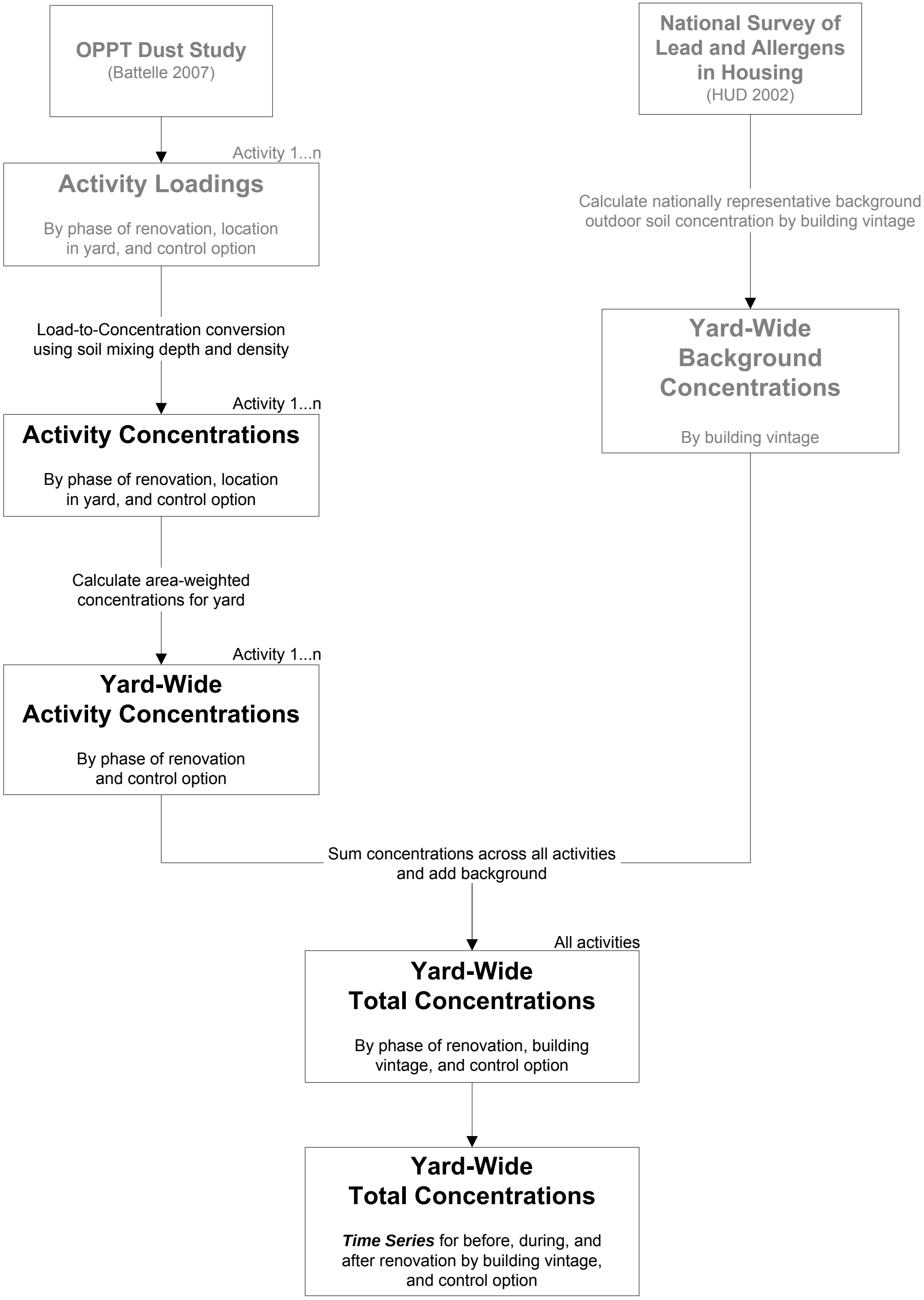
Exhibit 4-9. Indoor Dust Concentrations Time Series for the Multiple Activity Example and < 1940 Vintage



4.3 Outdoor Soil

The approach for estimating outdoor soil concentrations is summarized in Exhibit 4-10. The elements of this process described in Chapter 3 are shown in grey and the elements described in this section are shown in black (note that this exhibit is identical to Exhibit 3-8, with the exception of which elements are in grey and black). This section describes how the general approach illustrated in Exhibit 4-10 is applied to estimate indoor dust concentrations during each phase of the different exposure periods.

Exhibit 4-10. Approach for Estimating Outdoor Soil Concentrations



4.3.1 Pre-renovation

The Pre-renovation exposure period represents the period of exposure before initiation of the RRP activity or activities and thus consists of background contributions only. The approach for estimating background outdoor soil concentrations is described in Section 3.3.3.

4.3.2 Renovation

Outdoor soil concentrations during the Renovation exposure period are estimated in this approach based on the Pb loading associated with the activity-Control Option combination, the size of the yard, the size of the areas impacted by the activity, and the background concentration. There are two steps involved in calculating outdoor soil concentrations during the Renovation exposure period: (1) calculating soil concentrations in the different regions of the yard; and (2) calculating whole yard average concentrations. These steps are described below.

Calculate Concentrations in Different Regions of Yard

Concentrations are estimated for three sections of the yard; dripline (roughly adjacent to house or building); nearby area (adjacent to dripline); and remainder of yard. The concentration in the remainder of the yard is assumed to be equivalent to the background soil concentration, which is developed as described in Section 3.3.3.2. The concentrations in the dripline and nearby areas are calculated based on the estimated loadings from the activity or activities in the two areas and assumed soil characteristics. These concentrations are estimated using the following equation:

$$SCONC_{LOC,ACT,CO} = \frac{SLOAD_{LOC,ACT,CO} * 0.001 \frac{ft^2}{cm^2}}{SoilDepth * SoilDensity} \qquad \textbf{(Eq. 4-16)}$$

where:

$SCONC_{LOC,ACT,CO}$ = Outdoor soil concentration in location *LOC* (where *LOC* = dripline [A] or nearby area [B]) during Activity *ACT* for Control Option *CO*, in µg/g

$SLOAD_{LOC,ACT,CO}$ = Pb loading in location *LOC* (where *LOC* = dripline [A] or nearby area [B]) during Activity *ACT* for Control Option *CO*, in µg/ft^2

SoilDepth = Soil mixing depth, in cm

SoilDensity = Density of soil, in g/cm^3

Calculate Whole Yard Average Concentration

The whole yard soil concentration is calculated as an area-weighted average of the concentrations in the dripline, nearby area, and remainder of yard using the following equation:

$$SCONC_{ACT,CO} = PercArea_{LOC=A} * SCONC_{LOC=A,ACT,CO} + PercArea_{LOC=B} * SCONC_{LOC=B,ACT,CO} + \mathrm{PercArea}_{\mathrm{LOC=Rest}} * \mathrm{SCONC}_{\mathrm{BG}}$$

(Eq. 4-17)

where:

$PercArea_{LOC=A}$ = Percent of yard comprised of the dripline area (i.e., *LOC* = A)

$SCONC_{LOC=A,ACT,CO}$ = Outdoor soil concentration in dripline area (i.e., *LOC* = A) during Activity *ACT* for Control Option *CO*, in µg/g

$PercArea_{LOC=B}$ = Percent of yard comprised of the nearby area (i.e., *LOC* = B)

$SCONC_{LOC=B,ACT,CO}$ = Outdoor soil concentration in nearby area (i.e., *LOC* = B) during Activity *ACT* for Control Option *CO*, in µg/g

$PercArea_{LOC=Rest}$ = Percent of yard not comprised by the dripline and nearby areas (calculated as 1- $\mathrm{PercArea}_{\mathrm{LOC=A}}$ – $\mathrm{PercArea}_{\mathrm{LOC=B}}$)

$SCONC_{BG}$ = Background outdoor soil Pb concentration, in µg/g (see Section 3.3.3.2)

4.3.3 Post-renovation

For the No Plastic Control Option, it is assumed that there is no cleanup or degradation of Pb in outdoor soil; therefore, the Post-renovation exposure period concentrations are identical to the Renovation period concentrations. For the With Plastic Control Option, outdoor soil concentrations for all Control Options during the Post-renovation exposure period are estimated using the same approach used for the Renovation period, with the Post-renovation exposure period Pb loadings used instead of the Renovation period loadings.

4.4 Drinking Water

All of the exposed populations (i.e., children under six years of age) are assumed to consume drinking water with the same "typical" Pb exposure concentration. While there is a rather large amount of data in the literature, in many cases, the measurements represent “first-draw” samples, non-random (“priority”) samples, or samples from communities where Pb levels were known to be elevated. After reviewing the literature, the average drinking water concentration exposure was estimated to be 4.61 µg/L, based on data from two recent studies of residential water concentrations in U.S. and Canadian homes and apartments (Moir et al. 1996, Clayton et al. 1999). The range of values seen in these studies (0.84 to 16 µg/L) was considered to be representative of randomly sampled residential water in houses constructed since Pb pipe and solder were banned for residential use. The selected value is close to the “default” value (4.0 µg/L) recommended for use with the IEUBK blood Pb model when evaluating the blood Pb impacts of soil contamination (USEPA 1994). Much higher values have been encountered in homes with Pb piping and/or very corrosive water. For purposes of this approach, it is assumed that drinking water exposures are not impacted by RRP activities, and all of the exposed children are assumed to receive the same age-specific exposures.

4.5 Diet

It is expected that young children will be exposed to Pb in the foods they consume. In this approach, all exposed children are assumed to receive the age-specific estimates of dietary Pb intake developed by EPA’s Office of Solid Waste and Emergency Response (USEPA 2006c). EPA developed these estimates by analyzing food consumption data from the NHANES III survey conducted by the National Center for Health Statistics, and food residue data from the U.S. Food and Drug Administration’s (FDA) Total Dietary Study. The daily intake values published by EPA and summarized in Exhibit 4-11 are considerably lower than those developed using the same methodology in the 1980s and 1990s. Pb concentrations in food have decreased dramatically since the prohibition of Pb solder in food containers in 1982. For purposes of this approach, it is assumed that dietary exposures are not impacted by RRP activities.

Exhibit 4-11. Summary of Non-Water Dietary Pb Intake Estimates [a]

Age (months)	Updated Dietary Pb Intake Estimate (µg/day)
0 to 11	3.16
12 to 23	2.60
24 to 35	2.87
36 to 47	2.74
48 to 59	2.61
60 to 71	2.74
72 to 84	2.99

[a] Data derived from USEPA 2006b.

4.6 Sensitivity and Monte Carlo Analyses

4.6.1 Overview

Given the variability in characteristics of U.S. buildings covered by the proposed RRP rule and the uncertainty and variability in Pb dust loading data for the selected activities, it is important to characterize the impacts of this variability and uncertainty on the estimated dust concentrations. The approach selected involves two stages: (1) a sensitivity analysis designed to estimate the influence of the different inputs on the estimated dust concentrations; and (2) a Monte Carlo analysis that estimates the reasonable range of dust concentrations given the uncertainty and variability of these parameters. Both of these analyses were performed for both the single activity and multiple activities examples for all three building vintages (< 1940, 1940 to 1959, and 1960 to 1979). Complete tables of sensitivity and Monte Carlo analysis results for these examples can be found in Appendix E. Recall that indoor air and outdoor soil are not included in the sensitivity analysis. Air concentrations are taken directly from the OPPT Dust Study (Battelle 2007) and do not require additional calculations. Variability from that study was used in the Monte Carlo analyses. The outdoor soil concentrations used for the single indoor activity and multiple indoor activities examples are constant background values and thus are not varied in the uncertainty analyses. This approach, however, could be applied to outdoor soil concentrations for scenarios involving outdoor activities or indoor activities with outdoor loading estimates.

4.6.2 Sensitivity Analysis

4.6.2.1 Approach

A sensitivity analysis was performed to evaluate the sensitivity of the dust concentrations over time to changes in inputs within a reasonable range. The selected approach considers the relative impact of each input on estimated indoor dust concentrations, independent of the range of possible values. Two measures of sensitivity, elasticity and sensitivity score, were estimated for each input. Elasticity indicates “structural” sensitivity, while sensitivity score indicates “actual” sensitivity after accounting for the estimated variability in an input property. The elasticity is calculated as the percent change in a model output resulting from a one percent change in an input value. The elasticity provides information useful for understanding how the model operates and is used to compare with expected results, given knowledge of the model and the processes being simulated. The sensitivity score, which is calculated as the product of the elasticity and the coefficient of variation (CV), is useful in the context of assessing the influence of input properties, or how the variability of the input property affects the variability of the results.

For the sensitivity analysis, the inputs that are expected to most strongly influence the Post-renovation Week 0 and Week 10 concentrations and the Weeks to Background metric were selected. These inputs are listed in Exhibit 4-12.

Exhibit 4-12. Inputs Included in Sensitivity Analysis

Input Variable	Varies by
% Area of Building - Adjacent Room	Activity
% Area of Building – Workspace	Activity
% Area of Building - Carpet	None
Cleaning Frequency	None
Load-concentration Intercept	Vintage
Load-concentration Slope	Vintage
Background Loading - Indoor	Vintage
Adjacent Loading – Post Cleanup	Control Option and Activity
Adjacent Loading – Post Verification	Control Option and Activity
Rest of Building Loading – Post Cleanup	Control Option and Activity
Rest of Building Loading – Post Verification	Control Option and Activity
Workspace Loading – Post Cleanup	Control Option and Activity
Workspace Loading – Post Verification	Control Option and Activity

In each case, the input value was increased by 10 percent and the changes in the Post-renovation Week 0 and Week 10 concentrations and the Weeks to Background metric were assessed.

The sensitivity of estimated indoor dust concentrations to one additional input, routine cleaning efficiency, was assessed separately for feasibility reasons. Given the variable nature of the routine cleaning efficiency estimates, this input parameter could not be analyzed in the same way as the constant inputs. To analyze the sensitivity of the modeling results to this input, three additional sets of cleaning efficiencies for carpet and hard surface (representing minimum, maximum, and arithmetic mean efficiencies for a different data set than was used in the primary methodology) were developed (see Appendix B). Indoor dust concentrations for the single activity and the multiple activities examples included in the sensitivity analysis were then re-calculated using these efficiencies. The results using the three sets of cleaning efficiencies derived using the alternative methodology were then compared to the results using the primary methodology for the single activity and multiple activities examples and the percent change calculated.

The complete results of both parts of the sensitivity analysis with the examples are presented in Appendix E and summarized below.

4.6.2.2 Results – Sensitivity Analysis Excluding Cleaning Efficiency

The indoor dust concentrations are most sensitive to the Load-concentration Slope and Intercept. This suggests that this conversion equation is driving the concentration variability in this portion of parameter space. The Weeks to Background metric is relatively insensitive to this equation because the equation affects the loadings dependent on activities and the Background Loadings in a similar way.

The indoor dust concentrations at Week 0 and Week 10 are relatively insensitive to the other variables as measured by the elasticity. Control Options 1 and 3 have no sensitivity to the Post Cleaning loadings and Baseline Control and Control Option 4 have no sensitivity to the Post Verification loadings. This result derives from the fact that the Week 0 concentrations are either Post Cleaning or Post Verification, depending on the Control Option.

The Weeks to Background metric is most sensitive to the % Building Carpet, the Background Loading, and the Cleaning Frequency, because these are the primary drivers of the cleaning efficiency and the number of iterations required to reach background.

The Week 0 concentration, the Week 10 concentration, and the Weeks to Background tend to have higher elasticities in the earlier vintage, compared to the later vintages.

Elasticities are comparable across the single and multiple activities examples. The exception is the load-concentration slope, which has a higher elasticity in the multiple activities case.

The sensitivity analysis was performed by varying parameters about their mean value. Elasticities are not constant in all parts of parameter space because the model is non-linear. Thus, other variables may prove more important when modeled concentrations are far from the mean values. These variables will be discussed in Section 4.6.3.

4.6.2.3 Results – Cleaning Efficiency Sensitivity Analysis

The alternative cleaning efficiency results for hard floor tend to be lower than the primary cleaning efficiency results for the range of loadings explored in both the single and multiple activity examples. The cleaning efficiency remains at the lower bound of the alternative cleaning efficiency equation (1 percent) for all whole-building loadings in both the multiple and single activity examples in the 1960 to 1979 vintage.

Using the alternative cleaning efficiency equations tended to create higher initial carpet cleaning efficiencies and lower initial hard wood efficiencies. Comparing the primary cleaning efficiency results to the results derived from using the alternative cleaning efficiency's Mean equations in the Workspace compartment, carpet efficiency went from 53 percent to 67 percent and hard floor efficiency went from 13 percent to 1 percent in the first cleaning week. Because the buildings are assumed to be 72 percent carpet, the overall cleaning efficiency went up in the initial weeks, creating correspondingly lower concentrations.

A lower cutoff of 1 percent was imposed, however, on both equations in the alternative cleaning efficiency methodology (hard floor and carpet). Because of the particular value of the Pb loading, this meant the alternative methology's Mean equation always gave the lower cutoff (1%) for hard wood, whereas the primary methodology always saw a value of 13% (the Mid value for the particular loading range). Conversely, by the fourth iteration, carpet cleaning efficiencies in the Workspace were very small in both methodologies. Thus, the overall cleaning efficiencies were smaller in the alternative cleaning efficiency methodology in these later weeks. The Week 10 concentrations and the Weeks to Background metric were correspondingly higher for the alternate cleaning efficiency methodology. In particular, it took twice as long to return to background for the single activity example in the 1960 to 1979 vintage.

The scenario tested used the vintage with the lowest background concentration (the 1960 to 1979 vintage). Other scenarios which have higher background concentrations and higher Weeks to Background would be less sensitive to the cleaning efficiency.

4.6.3 Monte Carlo Analysis

4.6.3.1 Approach

The underlying variability in the input parameters leads to variability in the time series of indoor dust Pb concentrations. To capture this variability in the blood Pb and IQ estimates, Monte Carlo simulations were performed for both the single activity and multiple activities examples for all vintages and all Control Options. Because the full time series (rather than just Post-renovation Week 0 and Week 10) were needed as inputs to the blood Pb modeling, additional variables were added to the Monte Carlo analysis. In addition, the Load-concentration equation slope was not included because adequate upper and lower bounds could not be determined with any confidence. The Load-concentration equation intercept, however, is included. The variables included in the analysis are summarized in Exhibit 4-13.

An approximate distribution was obtained for each input parameter by choosing either a normal or lognormal distribution, selecting the Mid value as the mean (normal) or geometric mean (lognormal), and using the standard deviation (SD) provided in the data or calculated based on the low and high input parameter values (see Appendix D for details). The only exception is the Cleaning Frequency, which was modeled using a uniform distribution. In a given Monte Carlo iteration, a value was randomly selected (sampled) from these distributions for each input parameter. In general, these parameters were treated as independent variables. The exception is the % Area of Building – Adjacent, which must be less than 100 percent minus the % Area of Building – Workspace. If the sampled value did not satisfy this criterion, it was resampled until the criterion was met.

Based on the sampled input parameters, the resulting indoor dust concentrations time series were calculated. This process was repeated 20,000 times to adequately resolve the tails of the input parameter distributions.[3] Aggregating the 20,000 model output values for each week gives

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[3] A more complete description of the Monte Carlo tool is available in Appendix D.

information about the approximate distribution of the indoor dust concentration for that week. The maximum, 99th percentile, 95th percentile, 75th percentile, mean, median, 25th percentile, 5th percentile, and minimum values are reported for each metric in each Control Option (see Appendix E).

Exhibit 4-13. Input Variables Used in the Monte Carlo Analysis

Input Variable	Varies by
% Area of Building - Adjacent Room	Activity
% Area of Building – Workspace	Activity
% Area of Building - Carpet	None
Cleaning Frequency	None
Load-concentration Intercept	Vintage
Background Loading - Indoor	Vintage
Adjacent Loading – Post Work	Control Option and Activity
Adjacent Loading – Post Cleanup	Control Option and Activity
Adjacent Loading – Post Verification	Control Option and Activity
Rest of Building Loading – Post Work	Control Option and Activity
Rest of Building Loading – Post Cleanup	Control Option and Activity
Rest of Building Loading – Post Verification	Control Option and Activity
Workspace Loading – Post Work	Control Option and Activity
Workspace Loading – Post Cleanup	Control Option and Activity
Workspace Loading – Post Verification	Control Option and Activity

4.6.3.2 Monte Carlo Results

The percentiles, mean, maximum, and minimum values for the single activity and multiple activities examples for all vintages are shown in Appendix E for the Post-renovation Week 0 and Week 10 concentrations and the Weeks to Background metric. The overall range in the model metrics is large. For example, the Single Activity < 1940 vintage under the Baseline Control Option, the Week 0 concentrations have a maximum value of 12,577 µg/g, a minimum value of 33 µg/g, and a mean of 906 µg/g.

Exhibit 4-14 shows the 95th, 75th, 50th, 25th, and 5th percentiles for the Week 0 concentration for the < 1940 housing vintage in the single activity example across the different Control Options.

The curves indicate that while the 5th percentile cases are nearly uniform across Control Options, the 95th percentile see considerable spread, with the Base Control Option and Control Option 1 having higher 95th percentile concentrations than Control Option 2 and Control Option 3. This shape indicates that the distributions for the less strict Control Options (Base and Control Option 1) are wider than the Control Option 2 and Control Option 3 cases.

Exhibit 4-14. Monte Carlo Percentiles for Week 0 Concentration for the < 1940 Single Activity Example

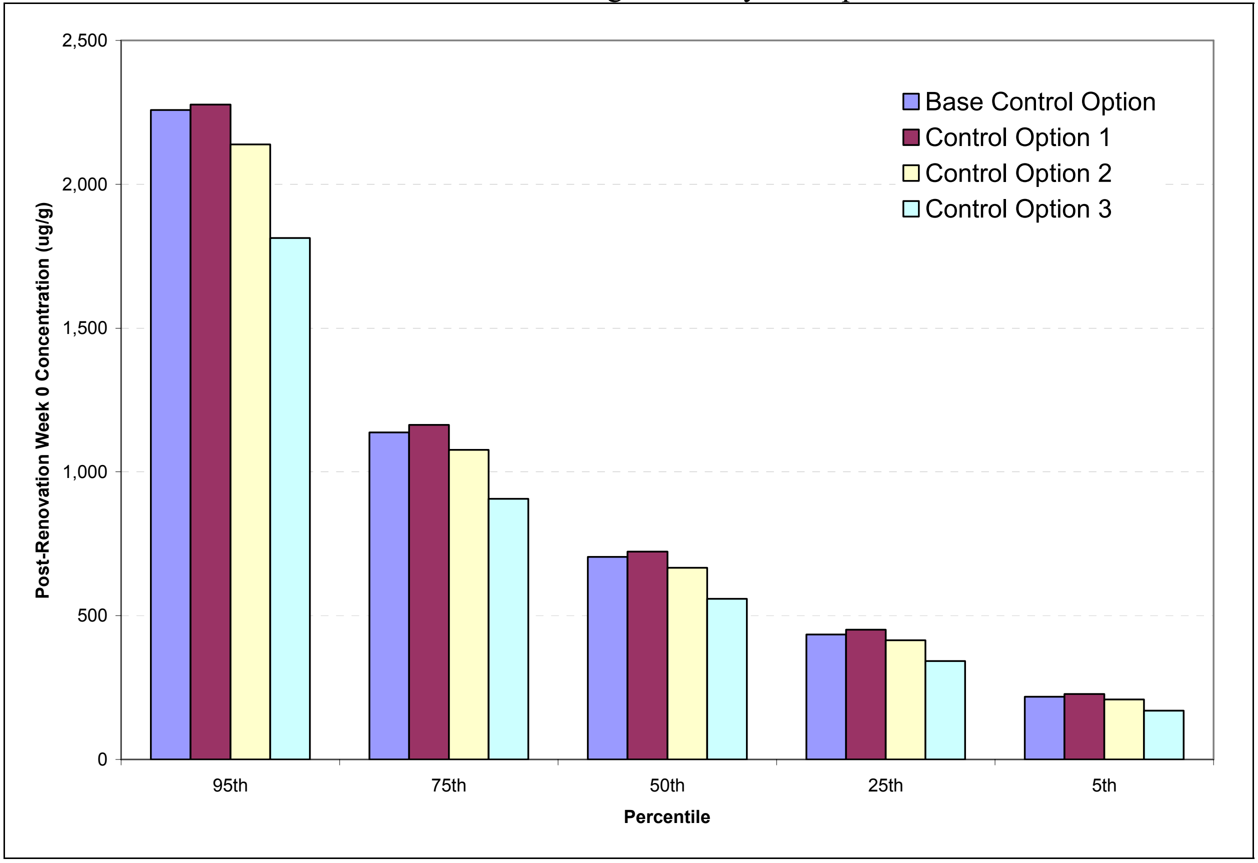
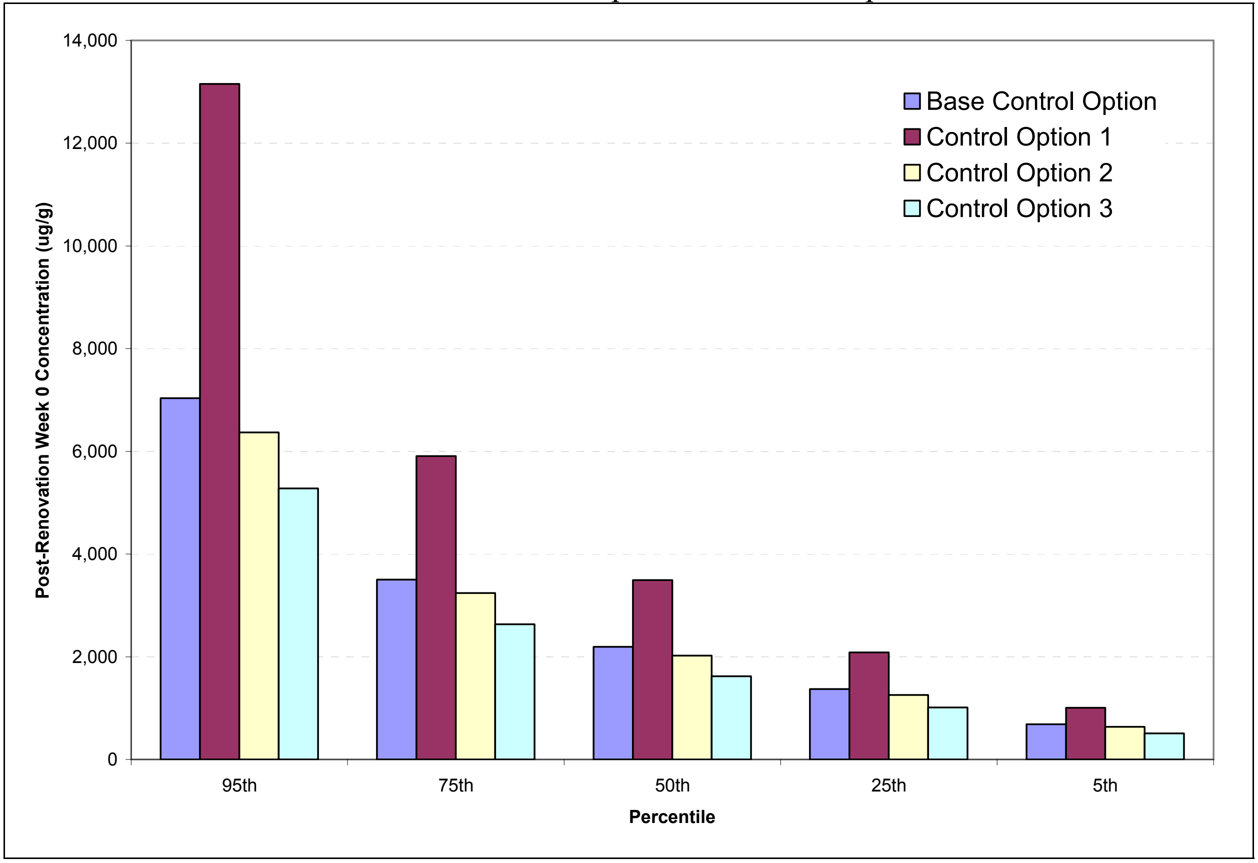


Exhibit 4-15 shows the 95th, 75th, 50th, 25th, and 5th percentiles for the Week 0 concentration for the < 1940 housing vintage in the multiple activities example across the different Control Options.

In this case, Control Option 1 is always substantially higher than the other Control Options for all percentiles. This phenomenon is caused by a high measurement of the tool room loading in the Three-Cutouts renovation activity in the OPPT Dust Study. Because the low, mid, and high estimates were all high for this case, all percentiles are much higher than the other Control Options.

Exhibit 4-15. Monte Carlo Percentiles for Week 0 Concentration for the < 1940 Multiple Activities Example



4.7 Uncertainties and Limitations

Whole house loadings are created by taking area averages across different rooms. These area averages are based on assumptions about the percent of the house occupied by each room for each renovation activity. These percentages are uncertain, however, since a window replacement, for example, could occur in either a living room (large "footprint") or a bathroom (small "footprint"). These percentages have been varied by overall activity (kitchen renovation versus window replacement versus three-cutouts, etc), but they have not been varied across different instances of the same activity (all window replacements use the same percentages). Thus, these assumptions introduce uncertainty into the overall whole house exposure levels.

Indoor dust loadings are summed across the different activities to represent total loadings from multiple renovation projects. This technique is applied to whole house loadings and assumes that the average loadings are additive since they occur in the same total surface area. This process, however, smears out any gradients that occur in different locations of the house due to the different activities. It also does not take into account the different "footprints" of different activities in different portions of the house.

Indoor air concentrations are averaged across the different activities to represent total air concentrations from multiple renovation projects. Unlike the dust concentrations, the air concentrations are averaged (rather than summed) to account for the fact that concentrations will never stay elevated for a full week (the smallest time increment in the exposure model) due to settling. Thus, averaging instead of summing acknowledges that different activities may lead to elevated air concentrations at different times during the week. This averaging represents uncertainty, however, since the actual duration of elevated air from each activity in each part of the house is not resolved.

Whole house concentrations are calculated for each exposure phase for each Control Option. These Control Options can only be compared cautiously, however, owing to the underlying methodology of the OPPT Dust Study. In the Dust Study, different Phases (or Control Options, according to the vocabulary of this approach) were generally completed in different houses. In general, the different Control Options for window replacements occurred in at least two different houses, while kitchen replacements occurred in completely mutually exclusive houses. If each house has different Pb content in the paint and other media, there is no reason to expect that a stricter Control Option (e.g., Control Option 3) in one house will give lower dust concentrations than a less strict Control Option (e.g., Base Control Option) in another house. Thus, the use of Dust Study data limits the degree of comparison possible between Control Options. The overall exposure level (and the subsequent blood Pb level and IQ reduction) for each Control Option relative to background, however, can be assessed.

Children are assumed to occupy the entire house or the entire yard equally during the renovation project. No effort is made to ensure that children remain outside the work area during the renovation. Thus, this approach gives a conservative estimate of exposure. This assumption is particularly suspect in the multiple activities example, when the project likely encompasses the entire house and the child likely would be removed to another house during the renovation. The current approach theoretically allows this alternative to be explored by setting the exposure to background levels during the Renovation period, but this alternative has not been explored in the current examples. For outdoor RRP activities especially, and for COFs, it is likely that a child could occupy only part of the space but, also, outdoor soil may contribute differentially to indoor exposures. This uncertainty will be handled by including an additional step prior to proceding to the calculations of chapter 5.

The conversion of loadings to concentrations introduces significant uncertainty into the modeled dust concentrations. The regression itself is based on limited data and the regression is recognized as a limitation of the study. In addition, the multiple activity example Dust Generating phase loadings are higher than the maximum loadings used in the regression, reflecting that the regression model is being extrapolated for this case, which introduces additional uncertainty. Finally, this conversion is being used for both carpeted and hard-floor surfaces, when the wipe samples only apply to hard floors. Although this regression introduces uncertainty, conversion remains a necessary step, since the blood Pb models are configured to accept concentrations and not loadings. Under an assumption that the HUD-derived relationships can be generalized, this regression represents the best known relationship available. An alternate approach to obtaining concentrations could be to use the loadings in concert with assumptions about the amounts (mass) of dust in the renovated spaces, the amount taken up on contact by the child, and the amounts transferred to the child’s mouth. Such an approach is adopted, for instance, in the draft All-Ages Lead Model (US EPA, 2005b), which is not being employed for blood Pb modeling in this analysis.

The routine cleaning efficiency data are another significant limitation of this approach. There are limited studies that are appropriate for this type of approach and even those that are appropriate have significant limitations. These data play an important role in determining how quickly the post-activity concentrations return to background for indoor activities. Thus, the long-term average exposure levels could be either over or under estimated as a result of the cleaning efficiency data. Because the renovation activity level concentrations are by far the largest "spike" in exposure, however, they are the most significant contributor to blood Pb levels and IQ loss, and long-term slight elevations relative to background are less important.

The cleaning efficiency is applied to the whole house loadings, rather than to individual rooms. By averaging out the room-to-room gradient, cleaning efficiency on hard floor (which is based on the loading level) may be either over or under estimated.

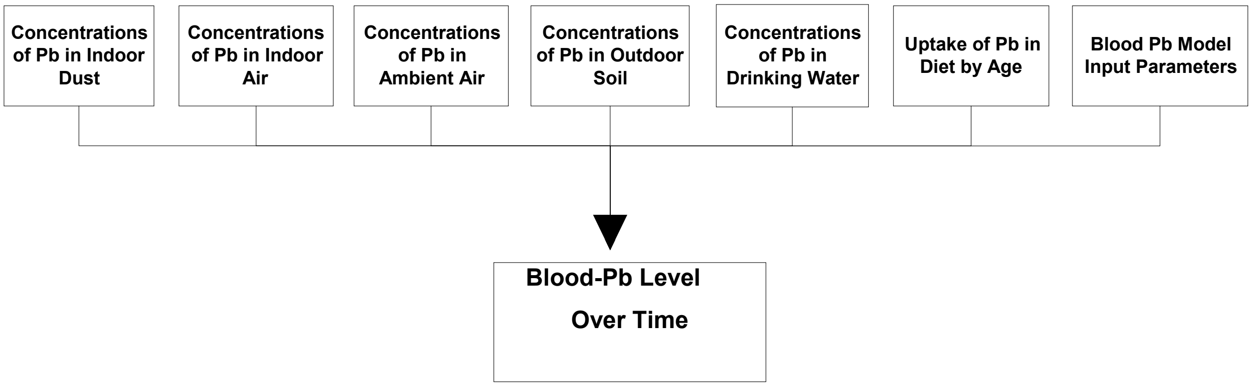
In order to calculate the range of dust concentrations for each week of the child's life, Monte Carlo runs are performed using assumptions about the underlying distribution of each input parameter. For each parameter, a low, mid, and high value is estimated, and a coefficient of variation is estimated from these values. In general, the low, mid, and high values came from only a limited number of data values, suggesting the distribution likely is not adequately captured. In addition, the calculation of coefficient of variation implements assumptions about the shape of the distribution (normal or log-normal) and the values represented by low and high (assumed to be two standard deviations from the mean). In both steps, significant uncertainty is introduced into the input parameters, suggesting that the estimates for the "tails" of the Monte Carlo dust predictions are highly uncertain. The median Monte Carlo estimates, based on the mid estimates, are more robust.

The Monte Carlo tool (see Appendix D) is run for 20,000 iterations. This number is likely sufficient to resolve the middle portions of the distributions. No tests are made, however, to determine if 20,000 iterations produces convergence in the tails of the distributions. Thus, there are additional uncertainties in the upper and lower percentiles for the Monte Carlo dust predictions.

5. ESTIMATES OF BLOOD PB LEVELS

This chapter describes the approaches and methods that can be used to evaluate children's blood Pb levels from RRP activities from the time of birth to age six. The general approach is shown in the flowchart in Exhibit 5-1. Pb concentrations in the activity-influenced exposure media (indoor air, indoor dust, and outdoor soil) and background exposure media (ambient air, drinking water, and diet), as well as Pb exposure and intake assumptions, serve as inputs for biokinetic blood Pb models (discussed in Section 5.2). It is recognized that some portion of Pb in the background exposure media may derive from RRP-activity-related sources, for example, if the exposed child consumes homegrown vegetables grown in Pb-contaminated garden soil. However, this proportion is assumed to be small for most of the exposure scenarios considered in this analysis.

Exhibit 5-1. Flow Chart Illustrating the Approach to Calculate Blood Pb Levels



In each exposure pathway, the relationship between exposure concentration and Pb uptake (absorbed dose) is defined by a range of factors related to physiological processes and to the chemical and physical properties of the exposure media. These factors include respiratory volume, soil and dust ingestion rates, and gastrointestinal (GI) absorption fractions for diet, water, and soil/dust, which determine how much Pb is absorbed from each medium. Values for these factors differ with age and across exposure media, as discussed in Section 5.2.

In this approach, blood Pb levels for six different hypothetical children are modeled from birth until six years of age. Exposure profiles are defined for each child so as to simulate the occurrence of the renovation project at the beginning of a different year of their life (birth, first birthday, second birthday, etc.). Prior to the renovation, these children experience background level exposures from all media, and after the renovation the dust and air concentrations are decreased due to routine cleaning and settling. Activity-related Pb exposure concentrations vary weekly depending on the activities and year of life being modeled.[4] Ambient air, drinking water,

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[4] For the examples presented in this document, outdoor soil concentrations remain constant throughout the simulations. This is a result of the types of activities being evaluated and the data sources (specifically, the OPPT Dust Study), which did not include contributions to outdoor soil concentrations from indoor activities. The

and dietary Pb exposures are assigned the same age-specific values in all of the exposure scenarios, as described in Section 5.2.

5.1 Selected Model(s)

Two different biokinetic models are applied to predict blood Pb levels in this approach: the Integrated Exposure Uptake Biokinetic (IEUBK) Model for Children (hereafter referred to as the IEUBK model) and the International Commission for Radiation Protection (ICRP) model (hereafter referred to as the Leggett model). Both models are well documented, widely used, and have been subject to a range of testing and calibration exercises (see Section 4.4 of USEPA 2006a).

A third model, which is empirical, uses a regression-based approach for predicting blood lead levels on the basis of environmental concentrations and other variables (Lanphear et al., 1998). There are, however, obstacles to using it for the estimation of blood lead from exposure during RRP activities. The biggest obstacle is the lack of a dynamic component or term. Because it predicts blood leads only at a single point in time, its results cannot easily be compared to the time-varying results of the biokinetic models. In addition, there is nothing in the development of the empirical model that predicts how it would respond to short-term variations in exposure, such as those anticipated with renovation activities. Thus, it has not been applied in the RRP analysis.

5.1.1 IEUBK Model

The IEUBK Lead Model Version 1.0 Build 263 (USEPA, 2005a) was used to model blood Pb levels for all exposure scenarios. The IEUBK model consists of three main modules: the exposure module, the uptake module, and the biokinetic module. The exposure module accepts exposure concentration inputs for each of six exposure media: air, food (excluding water), water, soil, indoor dust, and other. Exposure, intake, and uptake factors are combined with exposure concentrations in the various media to estimate Pb uptake through the inhalation and ingestion pathways. The IEUBK model provides default values for many input parameters that can be adjusted by the user as appropriate for specific applications. These parameters include medium-specific GI absorption fractions, and age-specific respiratory volumes, water intake, dietary intakes of specific food classes, and soil and dust ingestion rates. The selection of model input parameter values for this approach is discussed in Section 5.2.

The exposure module also includes default age-specific estimates of time spent outdoors, as well as age-specific estimates of outdoor and indoor air Pb concentrations, inhalation rates, and respiratory tract absorption fractions, all of which are used to estimate age-specific Pb inhalation uptakes. The inhalation pathway absorption fraction combines both the deposition pattern of inhaled Pb in the respiratory tract and absorption of deposited Pb, either directly from the respiratory tract or from the GI tract after mucociliary clearance. Ingestion uptake of Pb is calculated using absorption fractions that are specific to the ingested media (food, water, soil, or

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approach presented here, however, can easily accommodate characterization of assumed or measured contributions to outdoor soil, either from indoor or outdoor activities.

dust). Total GI Pb uptake is modeled as being composed of a saturable and an unsaturable component.

In the biokinetic component of the IEUBK model, the movement of absorbed Pb (from ingestion and inhalation) through various body “compartments” is simulated. The model is termed “biokinetic,” rather than “pharmacokinetic,” because transfers between compartments are controlled by first-order transfer coefficients (equivalent to first-order rate constants), rather than being perfusion-controlled. A more complete description of the derivation and structure of the IEUBK model can be found in USEPA (1994) and White et al. (1998).

The original purpose of the IEUBK model was to predict changes in long-term (annual average) blood Pb concentrations based on constant or slowly varying exposures (USEPA 1994). The approximate temporal resolution of the biokinetic component of the IEUBK is about one month (USEPA, 2006a). The IEUBK is thus not ideal for use in estimating the impacts of short-term variations in Pb exposures (such as the one-week peak exposures anticipated with renovation activities). In the approach outlined in this document, Pb exposures and blood Pb variability for each 7-day exposure period are modeled using the IEUBK’s batch capability. Lifetime average blood Pb concentrations (derived from the batch results) are used to estimate IQ loss, as explained in Chapter 6.

5.1.2 Leggett Model

Leggett (1993) developed a sophisticated biokinetic model for Pb exposures, intended primarily for use in radiological dosimetry, which has since been adopted as the standard model for that purpose by the International Commission for Radiation Protection (ICRP). The model is capable of predicting changes in blood Pb levels for exposed individuals over their entire lifespan (birth to 90 years old). The compartmental structure of the Leggett model is more complex than that of the IEUBK model, and was patterned after similar models developed by the ICRP to model the age-specific biokinetics of calcium-like radionuclides (Leggett, 1993).

Differences between the structures of the Leggett model and the IEUBK model include:

- The published version of the Leggett model lacks the multipathway exposure module of the IEUBK. The Leggett model accepts total respiratory and ingestion intakes (administered doses) as inputs and calculates Pb uptake using age-specific absorption factors.

- The central exchange compartment in the Leggett model is "diffusible plasma," rather than the plasma-extracellular fluid (ECF) compartment used in the IEUBK model.

- The trabecular and cortical bone compartments in the Leggett model are divided into two subcompartments each, one exchangeable, and one "non-exchangeable." Pb in the "non exchangeable" compartments of both types of bone can be remobilized, but only relatively slowly as a result of bone remodeling.

- Urinary excretion is modeled in the Leggett model as part of an integrated kidney compartment, rather than separately as in the IEUBK model.

- In the Leggett model, the liver is modeled as two compartments with rapid and moderately rapid Pb exchange, respectively. Other soft tissues are modeled as having three compartments with differing exchange rates. Pb in brain tissue is explicitly modeled.

Like the IEUBK model, the Leggett model is biokinetic, with exchange between compartments modeled using first-order "transfer rates" (equivalent to rate constants). The values for the transfer rates were estimated using a range of data from adult human radioactive tracer studies, autopsy data from adults and children, and data from animal studies related to the absorption, deposition, and excretion of Pb and chemically similar elements (Leggett, 1993).

Importantly, the Leggett model differs from the IEUBK model in that data from short-term studies (on the time-scale of hours to days) are used to estimate parameter values for the most rapid of the uptake and exchange processes, and thus the time resolution of the Leggett model is much finer than that of the IEUBK model. Without violating any of the assumptions used to derive the model the user may specify step lengths much shorter than those used in the IEUBK, depending on the degree of time resolution required in the blood Pb predictions. The Leggett model is capable of modeling the impacts of very short-term (even acute, one-time) Pb exposures.

Leggett developed estimates of biokinetic parameters for six age categories: newborn (0 to 100 days), 1 year, 5 years, 10 years, 15 years, and 25 years and older, with age-specific transfer parameters for children estimated by interpolation between the nearest values. Transfer factors for children were adjusted to take into account the more rapid bone turnover (calcium/Pb addition and resorption) in children compared with adults.

Predictions from the Leggett model have been compared with the deterministic predictions of blood Pb levels generated by the IEUBK model, using the IEUBK default inputs (Pounds and Leggett, 1998). In that comparison, the Leggett model predictions were substantially higher than those of the IEUBK model. As described in Section 5.4, the same pattern appears during the analysis of blood Pb impacts of the single and multiple RRP activities examples.

5.2 Derivation of Blood Pb Estimation Inputs

In order to obtain estimates of blood Pb, both the time series of the media inputs (air, indoor dust, outdoor soil, diet, and drinking water) and the "exposure factor" values that govern intake and absorption processes must be specified.

5.2.1 Time Series of Media Concentrations: Exposure to Renovation Activity at Different Ages

Indoor dust, air (ambient and indoor), outdoor soil, and water concentrations and dietary Pb intakes are the necessary exposure concentration inputs for the blood Pb models. Indoor dust and air concentrations were estimated for each exposure period and phase of the renovation activities, as discussed in Section 3.1. For the indoor single activity and multiple activities examples presented below, the outdoor soil Pb concentration was always assumed to remain at background levels throughout the life of each theoretical child. In addition, the drinking water and dietary concentrations were set at age-specific background levels in all the scenarios (see discussion below).

In order to determine the range of blood Pb levels associated with the range of exposure model parameters, the Monte Carlo time series estimates of indoor dust concentrations were used as inputs to the blood Pb models. For each week of the exposure model, the 5th percentile, median, mean, and 95th percentile dust Pb concentrations are calculated from the 20,000 Monte Carlo iterations. Each of the percentile values becomes a separate weekly time series for indoor dust concentrations, and is run separately using the same air, outdoor soil, water, and dietary Pb inputs.

Indoor air and indoor dust Pb concentrations are estimated in weekly increments. Each scenario involves estimating blood Pb concentration profiles for a child associated with the specified series of weekly exposure concentration estimates corresponding to the Renovation (Dust Generating), Renovation (After Baseline Cleaning), Post-renovation (Routine Cleaning), and Post-renovation (Background) phases (see Section 3.1 for phase descriptions). Depending on the activities and scenarios being evaluated, dust exposures could remain elevated above background for many weeks.

It is expected that these complex exposure scenarios will have different impacts on estimated blood Pb levels, depending on the age of the child when renovation occurs. In order to explore how the blood Pb levels change when the RRP activity occurs in a different year of a child's life, six different hypothetical children are modeled for each exposure period, as shown in Exhibit 5-2. Child 1 experiences the renovation beginning at birth. The remaining weeks after the renovation follow the weekly Post-renovation concentrations from the indoor dust and indoor air exposure modeling. Child 2 experiences Pre-renovation (Background) levels during the first year of life and the renovation occurs at the beginning of the second year of life, with the remaining weeks after renovation following the Post-renovation concentrations, and so on for Child 3, Child 4, Child 5, and Child 6.

Exhibit 5-2. Definition of Modeled Hypothetical Children and the Time in Their Life When They Experience the RRP Activity

		Child 1	**Child 2**	**Child 3**	**Child 4**	**Child 5**	**Child 6**
Time ↓	**Age 0 to 1 (Year 1)**	Renovation Occurs	Pre-renovation	Pre-renovation	Pre-renovation	Pre-renovation	Pre-renovation
	Age 1 to 2 (Year 2)	Post-renovation	Renovation Occurs	Pre-renovation	Pre-renovation	Pre-renovation	Pre-renovation
	Age 2 to 3 (Year 3)	Post-renovation	Post-renovation	Renovation Occurs	Pre-renovation	Pre-renovation	Pre-renovation
	Age 3 to 4 (Year 4)	Post-renovation	Post-renovation	Post-renovation	Renovation Occurs	Pre-renovation	Pre-renovation
	Age 4 to 5 (Year 5)	Post-renovation	Post-renovation	Post-renovation	Post-renovation	Renovation Occurs	Pre-renovation
	Age 5 to 6 (Year 6)	Post-renovation	Post-renovation	Post-renovation	Post-renovation	Post-renovation	Renovation Occurs

As noted above, the exposure concentrations and Pb intake from background pathways (i.e., those assumed not to be impacted by renovation–drinking water and non-water diet) were also parameter inputs to the blood Pb model. Drinking water concentrations were assigned a single, constant value for all ages (see Section 4.4). In addition to drinking water, it is expected that young children will be exposed to Pb in the foods they consume. The development of inputs for dietary exposures is presented in Section 4.5.

5.2.2 Parameter Inputs Related to Pb Intake and Absorption (Uptake)

As discussed previously, there are a number of model inputs that govern how the exposure concentrations are converted to absorbed Pb dose (uptake) estimates. These variables represent the physiological and behavioral characteristics of the exposed population and the chemical and physical properties of the exposure media that govern exposure and absorption by inhalation and ingestion.

5.2.2.1 IEUBK Model

Because substantial data have become available since the IEUBK automated default values were last updated, more recent information available in the literature was used to modify some of the IEUBK inputs. These modifications are also being used in other Agency analyses (e.g., AQCD for lead). A number of the values, listed in Exhibit 5-3, differ from the suggested default values in the most current version of the IEUBK (USEPA 2005a). Children’s daily ventilation rate estimates were based on the EPA Exposure Factors Handbook (US EPA, 2002a). The inhalation absorption fraction was set to 0.42, which falls within the range of 0.25 to 0.45 estimated in the past for areas not influenced by point sources (US EPA, 1989), and is the IEUBK default.

Estimated children’s direct water ingestion values were interpolated from values in EPA’s Children-Specific Exposure Factors Handbook (US EPA, 2002b); the GI absorption fraction of Pb from water (and diet) was retained at the IEUBK default value of 50 percent, and is consistent with OAQPS previous analyses of Pb uptake (US EPA, 1989). Age-specific dietary intake values for Pb were revised to reflect the latest analyses of FDA and NHANES III data on food consumption pattern and Pb residue levels (US EPA, 2006d).

Age-specific soil and indoor dust ingestion rates were retained at the IEUBK default values. Similarly, the weighting factor for soil and indoor dust ingestion was also left at 45 percent soil, despite limited data supporting this specific value (US EPA, 1989; US EPA, 1994). The IEUBK generic default value for GI absorption of Pb from soil and indoor dust (0.30, or 30 percent) was used. This value is generally consistent with more recently reported values, although individual estimates vary widely. Finally, for maternal blood Pb, the IEUBK default value of 2.5 ug/dL was used.

Exhibit 5-3. IEUBK Parameter Input Values Used in this Approach

Parameter	IEUBK Parameter Name	Leggett Variable ID	Parameter Value: IEUBK Default Age Ranges (Years) 0 to 1	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	Basis/Derivation
Inhalation									
Daily ventilation rate (m^3/day)	Ventilation rate	RSVOL	4	5.1	6	6.8	7.8	8.8	ICRP (2002), with interpolation for intermediate ages.
Absolute inhalation absorption fraction (unitless)	Lung absorption	AFLNG	0.42						USEPA (1989), Appendix A
Indoor air Pb concentration	Indoor air Pb concentration (percentage of outdoor)	BRETH	100%						IEUBK default, USEPA (1994)
Time spent outdoors	Time spent outdoors (hours/day)		1	2	3	4	4	4	
Drinking Water Ingestion									
Water consumption (L/day)	Water consumption (L/day)	H20CNS	0.34	0.31	0.31	0.33	0.36	0.39	Based on value for infants, 1 to 3 yr olds, 1 to10 yr olds (with trend lines used to interpolate intermediate age ranges) (USEPA 2002b).
Water Pb concentration (µg/L)	Pb concentration in drinking water (µg/L)	H20CONC	4.61						GM of values reported in studies of United States and Canadian populations (residential water) (Moir et al. 1996, Clayton et al. 1999, as cited in USEPA (2006b), Section 3.3 Table 3-10).
Absolute absorption (unitless)	Total percent accessible	H20A	50%						Assumed similar to dietary absorption (see "Total percent accessible" under Ingestion-Diet below).

Parameter	IEUBK Parameter Name	Leggett Variable ID	Parameter Value						Basis/Derivation
			IEUBK Default Age Ranges (Years)						
			0 to 1	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	
Diet									
Dietary Pb intake (µg/day)	Daily Pb intake (µg/day)	EAT	3.16	2.6	2.87	2.74	2.61	2.74	Estimates based on (a) Pb food residue data from U.S. Food and Drug Administration Total Diet Study (USFDA 2001), and (b) food consumption data from NHANES III (CDC 1997).
Absolute absorption (unitless)	Total percent accessible	FI	50%						Alexander et al. (1974) and Ziegler et al. (1978), as cited in USEPA 2006 (Section 4.2.1). These two dietary balance studies suggest that 40-50% of ingested Pb is absorbed by children (2 weeks to 8 years of age).
Soil/Indoor Dust Ingestion									
Soil/dust weighting factor (unitless)	Soil/dust ingestion weighting factor (percent soil)	SLDST	45%						This is the percent of total ingestion that is soil. Value reflects best judgment and consideration (results published by van Wijnen et al. (1990), as cited in (USEPA 1989). The van Wijnen et al. study looked at tracer studies of ingestion rates for rainy days and non –rainy days. It was assumed that rainy days were associated with all soil ingestion and non-rainy days were associated with a combination of soil and dust with the delta representing soil.

Parameter	**IEUBK Parameter Name**	**Leggett Variable ID**	**Parameter Value**						**Basis/Derivation**
			IEUBK Default Age Ranges (Years)						
			0 to 1	**1 to 2**	**2 to 3**	**3 to 4**	**4 to 5**	**5 to 6**	
Total dust + soil ingestion (mg/day)	Amount of soil/dust ingested daily (mg)	SLDSTING	85	135	135	135	100	90	USEPA 1989, which was based on multiple studies focusing on children.
Absolute GI absorption (soil and dust) (unitless)	Total percent accessible	SLAF, DSTAF	0.30 for both soil and dust						USEPA (1989) reflects evidence that Pb in dust and soil is as accessible as dietary Pb and that dust/soil ingestion may occur away from mealtimes (resulting in enhanced absorption relative to exposure during meal events).
Other									
Maternal blood Pb (µg/dL)	Maternal blood Pb concentration at childbirth, µg/dL		2.5						IEUBK default, USEPA (1994)

5.2.2.2. Leggett Model

Because the Leggett model accepts inhalation and ingestion uptakes rather than media concentrations, air, dust, water, and soil concentrations are converted to uptakes using the same parameters as outlined above for the IEUBK model. Specifically, Pb uptake by the inhalation pathway is calculated as follows:

$$BRTCRN = RSVOL * BRETH * AFLNG \tag*{\textbf{(Eq. 5-1)}}$$

where:

$BRTCRN$ = Pb uptake by inhalation (µg/day)
$RSVOL$ = age-specific respiratory volume (m^3/day)
$BRETH$ = modeled exposure concentration (µg/m^3)
$AFLNG$ = inhalation absorption fraction (unitless)

The Pb uptake through ingestion was calculated as:

$$EATCRN = FOODUP + H2OUP + SOILUP + DUSTUP \tag*{\textbf{(Eq. 5-2)}}$$
$$FOODUP = EAT * FI \tag*{\textbf{(Eq. 5-3)}}$$
$$H2OUP = H2OCNS * H2OCONC * H2OA \tag*{\textbf{(Eq. 5-4)}}$$
$$SOILUP = SLDSTING * SLDST * SOILPB * SLAF \tag*{\textbf{(Eq. 5-5)}}$$
$$\mathrm{DUSTUP = SLDSTING * (1\text{-}SLDST) * DUSTPB * DSTAF} \tag*{\textbf{(Eq. 5-6)}}$$

where:

$EATCRN$ = total uptake through ingestion (µg/day)
$FOODUP$ = uptake from food (µg/day)
EAT = daily Pb intake from non-water diet (µg/day)
FI = GI absorption fraction for diet (unitless)
$H2OUP$ = uptake from drinking (µg/day)
$H2OCNS$ = direct residential drinking water consumption (l/day)
$H2OCONC$ = average Pb concentration in drinking water (µg/day)
$H2OA$ = GI absorption fraction for water (unitless)
$SOILUP$ = daily Pb uptake from soil (µg/day)
$SLDSTING$ = daily soil + dust ingestion (g/day)
$SLDST$ = fraction of soil + dust ingestion that is soil
$SOILPB$ = average soil Pb concentration (µg/g)
$SLAF$ = absolute GI absorption fraction for soil Pb (unitless)
$DUSTU$ = daily Pb uptake from indoor dust (µg/day)
$DUSTPB$ = average indoor dust Pb concentration (µg/g)
$DSTAF$ = absolute GI absorption fraction for dust Pb (unitless)

The time-varying inhalation and ingestion uptakes (BRTCRN and EATCRN) were then put directly into the Leggett model. Note that the Leggett variable IDs are included in Exhibit 5-3 with their corresponding IEUBK input parameters.

5.3 Estimation of Blood Pb Levels for Two RRP Examples

5.3.1 IEUBK Model Implementation

To implement the IEUBK model for the indoor residential single activity and multiple activities examples, the weekly air and dust concentrations, the yearly dietary uptakes, and the constant soil and drinking water concentrations are input into the IEUBK model. As noted above, multiple percentile estimates of weekly dust concentration generated by Monte Carlo modeling are run for each scenario for 312 weeks (ages 0 to 6). Because the IEUBK is a steady state model, it was run in batch mode, with separate blood Pb calculations for each week of input data, where the input concentrations are assumed to capture the midpoint of that week, and for each of the six hypothetical children (Exhibit 5-2). The outputs are weekly blood Pb concentration estimates for each of these children. The weekly estimates then are averaged to produce two Pb metrics, quarterly averages and lifetime averages. Quarterly averages are created by averaging over each quarter of the child’s life, ages 0 to 6. The results are also averaged over the entire lifetime of each child to provide lifetime averages as input for the IQ estimation model.

5.3.2 Leggett Model

To implement the Leggett model, a module has been added to the original FORTRAN code (Pounds 2000) to allow the model to be run in batch mode. The intake and uptake equations are implemented separately for each example using Excel® spreadsheet calculations and macros. The ingestion and inhalation uptakes are input into the model assuming 100 percent absorption, since the absorption fraction was already implemented in the uptake calculations. The model is then run for each of the six theoretical children, with inhalation and ingestion uptakes varying weekly and using a time step of 0.01 days. The resulting blood Pb levels are output daily, and these values are in turn averaged over each quarter and over the entire lifetime of each child.

5.4 Examples

Below are estimated blood Pb levels associated with background exposures, and for the single and multiple activity RRP examples. For the single and multiple activity RRP examples, the data are presented for one- to two-year-old children (Child 2). Complete sets of tables for all theoretical children can be found in Appendix F. Each section describes the steps of analysis that could be undertaken to estimate blood Pb levels associated with any specific renovation activity or activities.

5.4.1 Estimated Blood Pb Levels Associated With Background Exposures

The blood Pb models were first run using constant background values for all media concentrations, without any RRP activities, for a child from birth to age six. The estimated background concentrations for dust and soil vary by building vintage. Thus, blood Pb levels associated with background exposures also vary with building age. Estimated median lifetime average blood Pb levels for the Leggett and IEUBK models and the 50th percentile blood lead levels reported in NHANES for children 1-5 years old by vintage are summarized in Exhibit 5-4. This comparison allows the use of NHANES data as a benchmark to evaluate the performance of the blood Pb models. However, this comparison is valid only to the extent that the exposure patterns of the NHANES study subjects (1-5 years old) match those of the modeled children (0-6 years old). In addition, it should be noted that the houses included in the NHANES survey do not all contain lead-based paint. As expected based on prior comparisons, the Leggett model blood Pb estimates are two to three times higher than the IEUBK values. The IEUBK values are closer to the NHANES values which can suggest that the Leggett model may be over-predicting the blood Pb values. The NHANES values more likely reflect steady state, as do the IEUBK values, whereas the Leggett values can accommodate current kinetics for RRP activities underway or recently completed.

Exhibit 5-4. Comparison of Background Lifetime Average Blood Pb Levels from the Leggett Model, IEUBK Model, and the NHANES Survey in μg/dL

Vintage	Leggett Model Median Estimate	IEUBK Model Median Estimate	NHANES 50th percentile
<1940	13.9	4.5	2.6
1940 to 1959	6.3	2.2	2.1 to 2.8
1960 to 1979	5.4	1.9	1.6 to 1.8

Exhibit 5-5 shows the background blood Pb levels estimated for one- to two-year-old children (Child 2) living in different age (vintage) houses. In addition to the medians, the exhibit shows the blood Pb estimates associated with the mean and the 5th and 95th percentile indoor dust exposure concentrations. In this case, the variation in background blood Pb levels across percentiles is due to the assumed distribution of the background indoor dust concentrations. The median values that are compared to the NHANES data are shown in bold. In general, the background values vary by a factor of two between the 95th percentile and 5th percentile cases. In addition, the IEUBK results are again consistently two to three times lower than the Leggett results.

Exhibit 5-5. Background Lifetime Average Blood Pb Levels for All Indoor Dust Concentration Percentiles in μg/dL

Percentile	Leggett			IEUBK		
	<1940	1940 to 1959	1960 to 1979	<1940	1940 to 1959	1960 to 1979
95th Percentile	25.3	11.5	9.7	7.9	3.8	3.3
Median	**13.9**	**6.3**	**5.3**	**4.5**	**2.2**	**1.9**
Mean	15.5	7.0	6.0	5.0	2.4	2.1
5th Percentile	10.8	5.0	4.3	3.6	1.8	1.5

5.4.2 Blood Pb Level Estimation for the Single and Multiple RRP Acitivity Examples

The time-varying RRP activity dust and air concentrations are then used as model inputs, along with the background soil, water, and dietary values, to estimate the blood Pb levels for each of the six children in the single activity example or the multiple activity example. These runs are performed separately for all four Control Options, for each building vintage, and for each of the dust concentration Monte Carlo metrics (5th percentile, median, mean, and 95th percentile).

The results can be presented as lifetime average Pb levels for each theoretical child. Exhibit 5-6 shows the lifetime average blood Pb levels for the child who experiences the single RRP activity example starting at their first birthday (Child 2). The blood Pb levels are summarized for all four Monte Carlo percentiles, for all housing vintages, and for all Control Options, with the median values in bold to represent the central tendency estimate. As expected, the blood Pb levels tend to decrease with newer buildings. In general, the 95th percentiles estimates are on the order of three times the 5th percentile values.

Exhibit 5-6. Lifetime Average Blood Pb Levels for Child 2,
Single Activity Example in μg/dL

Control Option and Percentile	**Leggett**			**IEUBK**		
	<1940	**1940 to 1959**	**1960 to 1979**	**<1940**	**1940 to 1959**	**1960 to 1979**
Base Control Option, 95th Percentile	28.16	14.77	12.94	8.74	4.71	4.19
Control Option 1, 95th Percentile	28.30	14.97	13.08	8.76	4.74	4.22
Control Option 2, 95th Percentile	28.16	14.80	12.87	8.67	4.66	4.15
Control Option 3, 95th Percentile	27.16	13.68	11.98	8.38	4.40	3.91
Base Control Option, Median	**15.38**	**7.27**	**6.05**	**4.94**	**2.49**	**2.09**
Control Option 1, Median	**15.51**	**7.36**	**6.10**	**4.97**	**2.51**	**2.11**
Control Option 2, Median	**15.41**	**7.32**	**6.07**	**4.93**	**2.49**	**2.10**
Control Option 3, Median	**14.92**	**7.01**	**5.89**	**4.81**	**2.41**	**2.04**
Base Control Option, Mean	17.39	8.30	7.06	5.50	2.81	2.42
Control Option 1, Mean	17.55	8.41	7.13	5.53	2.83	2.43
Control Option 2, Mean	17.45	8.36	7.07	5.49	2.81	2.41
Control Option 3, Mean	16.79	7.93	6.77	5.34	2.69	2.33
Base Control Option, 5th Percentile	11.23	5.25	4.50	3.75	1.84	1.59
Control Option 1, 5th Percentile	11.28	5.27	4.52	3.76	1.85	1.59
Control Option 2, 5th Percentile	11.28	5.29	4.54	3.76	1.85	1.60
Control Option 3, 5th Percentile	11.15	5.21	4.49	3.72	1.83	1.58

Exhibit 5-7 shows the lifetime average blood Pb levels for the child who experiences the multiple RRP activity example starting at their first birthday (Child 2). As in the single RRP activity example, these runs were performed separately for all four Control Options, for each building vintage, and for each of the indoor dust concentration percentiles from the Monte Carlo simulations. The absolute blood Pb levels associated with the multiple activities scenario are all higher than corresponding values in the single activities example. This is to be expected, since the exposure concentrations and durations typically will be higher when multiple renovation activities are undertaken. Because both models use the same background soil, diet, and water concentrations/uptakes, the differences in the air and dust concentrations only partly determine the overall blood Pb levels.

Exhibit 5-7. Lifetime Average Blood Pb Levels for Child 2, Multiple Activities Example in μg/dL

Control Option and Percentile	**Leggett**			**IEUBK**		
	<1940	**1940 to 1959**	**1960 to 1979**	**<1940**	**1940 to 1959**	**1960 to 1979**
Base Control Option, 95th Percentile	34.50	20.45	16.52	10.42	5.91	4.94
Control Option 1, 95th Percentile	37.38	23.16	18.47	11.67	6.82	5.54
Control Option 2, 95th Percentile	33.81	19.82	16.11	10.19	5.73	4.83
Control Option 3, 95th Percentile	31.77	17.94	14.81	9.59	5.27	4.50
Base Control Option, Median	**18.58**	**9.36**	**7.03**	**5.63**	**2.94**	**2.34**
Control Option 1, Median	**19.30**	**9.80**	**7.30**	**5.85**	**3.08**	**2.42**
Control Option 2, Median	**18.43**	**9.27**	**6.97**	**5.57**	**2.90**	**2.32**
Control Option 3, Median	**17.31**	**8.47**	**6.59**	**5.31**	**2.73**	**2.22**
Base Control Option, Mean	21.43	11.17	8.56	6.38	3.41	2.76
Control Option 1, Mean	22.78	12.16	9.16	6.83	3.70	2.95
Control Option 2, Mean	21.09	10.93	8.41	6.28	3.33	2.72
Control Option 3, Mean	19.78	9.94	7.85	5.97	3.12	2.58
Base Control Option, 5th Percentile	12.41	5.86	4.73	4.01	2.00	1.65
Control Option 1, 5th Percentile	12.54	5.93	4.78	4.05	2.03	1.67
Control Option 2, 5th Percentile	12.39	5.86	4.74	4.00	2.00	1.65
Control Option 3, 5th Percentile	11.96	5.63	4.65	3.91	1.94	1.63

5.4.3 Ways to Compare Blood Pb Changes in Association with Control Options

This section presents three ways of looking at the association of the various control options and changes in blood Pb including tabulating quantiles of the distribution of lifetime average blood Pb level changes relative to background, graphing changes in blood Pb levels across ages for the theoretical children, and tabulating changes in blood Pb for each numbered control option compared to the Base Control option. Increments in blood Pb levels associated with the renovation activities are calculated by subtracting the background values from the lifetime average blood Pb values. In the single activity example, background values are subtracted from those in Exhibit 5-6, and shown in Exhibit 5-8. For the multiple activity example, background values[5] are subtracted from those in Exhibit 5-7, and are shown in Exhibit 5-9.

Exhibit 5-8. Incremental Changes in Lifetime Average Blood Pb Levels due to the Renovation Activity for Child 2, Single Activity Example in µg/dL

Control Option and Percentile	**Leggett**			**IEUBK**		
	<1940	**1940 to 1959**	**1960 to 1979**	**<1940**	**1940 to 1959**	**1960 to 1979**
Base Control Option, 95th Percentile	2.82	3.29	3.21	0.89	0.87	0.90
Control Option 1, 95th Percentile	2.96	3.48	3.34	0.91	0.90	0.93
Control Option 2, 95th Percentile	2.82	3.32	3.13	0.82	0.82	0.85
Control Option 3, 95th Percentile	1.82	2.20	2.24	0.53	0.56	0.62
Base Control Option, Median	**1.51**	**0.98**	**0.71**	**0.40**	**0.30**	**0.22**
Control Option 1, Median	**1.65**	**1.07**	**0.75**	**0.42**	**0.32**	**0.23**
Control Option 2, Median	**1.55**	**1.03**	**0.73**	**0.39**	**0.30**	**0.22**
Control Option 3, Median	**1.05**	**0.73**	**0.54**	**0.27**	**0.21**	**0.17**
Base Control Option, Mean	1.85	1.30	1.08	0.47	0.38	0.33
Control Option 1, Mean	2.02	1.41	1.15	0.50	0.40	0.35
Control Option 2, Mean	1.91	1.35	1.09	0.45	0.38	0.33
Control Option 3, Mean	1.26	0.92	0.79	0.31	0.26	0.24
Base Control Option, 5th Percentile	0.46	0.28	0.17	0.13	0.09	0.05
Control Option 1, 5th Percentile	0.51	0.31	0.19	0.15	0.10	0.06
Control Option 2, 5th Percentile	0.51	0.33	0.22	0.15	0.10	0.07
Control Option 3, 5th Percentile	0.38	0.25	0.17	0.11	0.08	0.05

---

[5] Note that the background values in this multiple activities are marginally different than those presented in Exhibit 5-5. These small differences arise from small differences in the Monte Carlo sampling of the Background Loading between the single activity and multiple activities examples.

Exhibit 5-9. Incremental Changes in Blood Pb Levels due to the Renovation Activity for Child 2, Multiple Activities Example in μg/dL

Control Option and Percentile	Leggett			IEUBK		
	<1940	1940 to 1959	1960 to 1979	<1940	1940 to 1959	1960 to 1979
Base Control Option, 95th Percentile	9.33	9.03	6.76	2.63	2.09	1.64
Control Option 1, 95th Percentile	12.22	11.73	8.70	3.87	3.00	2.24
Control Option 2, 95th Percentile	8.64	8.39	6.34	2.39	1.91	1.53
Control Option 3, 95th Percentile	6.61	6.51	5.04	1.79	1.45	1.20
Base Control Option, Median	**4.75**	**3.08**	**1.68**	**1.09**	**0.75**	**0.46**
Control Option 1, Median	**5.47**	**3.52**	**1.95**	**1.31**	**0.89**	**0.55**
Control Option 2, Median	**4.61**	**2.99**	**1.62**	**1.03**	**0.72**	**0.44**
Control Option 3, Median	**3.49**	**2.19**	**1.24**	**0.77**	**0.54**	**0.35**
Base Control Option, Mean	5.90	4.17	2.56	1.35	0.98	0.67
Control Option 1, Mean	7.25	5.16	3.16	1.80	1.27	0.86
Control Option 2, Mean	5.56	3.92	2.42	1.25	0.90	0.63
Control Option 3, Mean	4.25	2.94	1.86	0.93	0.69	0.49
Base Control Option, 5th Percentile	1.63	0.89	0.40	0.40	0.25	0.12
Control Option 1, 5th Percentile	1.76	0.96	0.45	0.43	0.28	0.13
Control Option 2, 5th Percentile	1.61	0.89	0.41	0.39	0.25	0.12
Control Option 3, 5th Percentile	1.18	0.66	0.32	0.29	0.19	0.10

The time-series of the incremental changes in blood Pb levels associated with the single and multiple RRP activity examples for the Base Control Option for each of the six theoretical children are shown in Exhibit 5-10 and 5-11, respectively. Age-specific blood Pb levels associated with the background media concentrations have been subtracted from these curves. These time-series are represented using the quarterly-averaged blood Pb values, and averages over these curves for the entire six years are used to derive the the lifetime averages presented in Exhibit 5-10 and 5-11. Figures like Exhibit 5-10 and 5-11 permit comparisons of the pattern across ages with other similar figures for different control options when plotted on the same axes.

For each hypothetical child, there is a spike during the year of renovation followed by an elevated "tail" of continued blood Pb elevelation during the Renovation (Post Cleaning) phase. The increments in blood Pb levels estimated with the Leggett model (solid lines) are consistently higher than the IEUBK results (dashed lines) for all children. In addition, the Leggett results tend to sustain higher blood Pb levels relative to the background for a longer portion of the child's life. Such differences arise from differences in the biokinetic modules between the Leggett and IEUBK models. This could be either because the Pb excretion rates in the IEUBK are greater than in Leggett or because the partitioning of the Pb body burden in the IEUBK model is weighted more towards the non-blood compartments than in the Leggett model. In both models, children who are two years old when renovation occurs usually have the highest spike in blood Pb for a given increase in media concentrations. This result follows from changes in age-specific biokinetics and from the competing effects of generally decreasing dietary intakes with age and soil/dust intakes which peak in years 2, 3, and 4.

Exhibit 5-10. Time Series of Incremental Blood Pb Changes Due to
the RRP Activity for the < 1940 Vintage, Single Activity Example

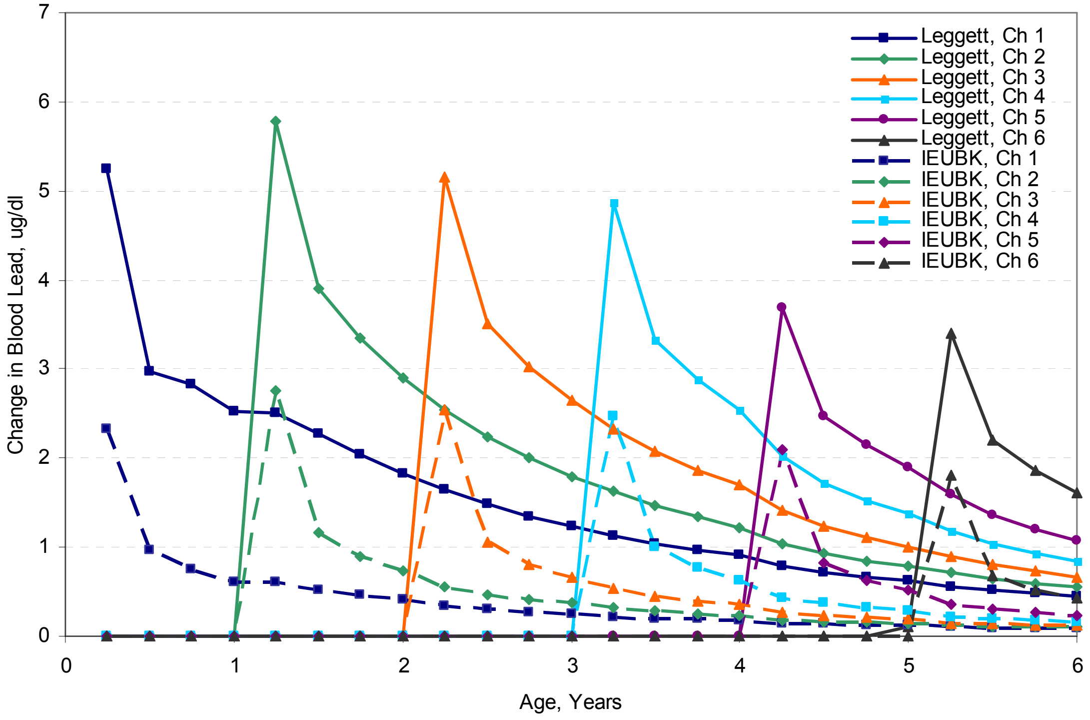
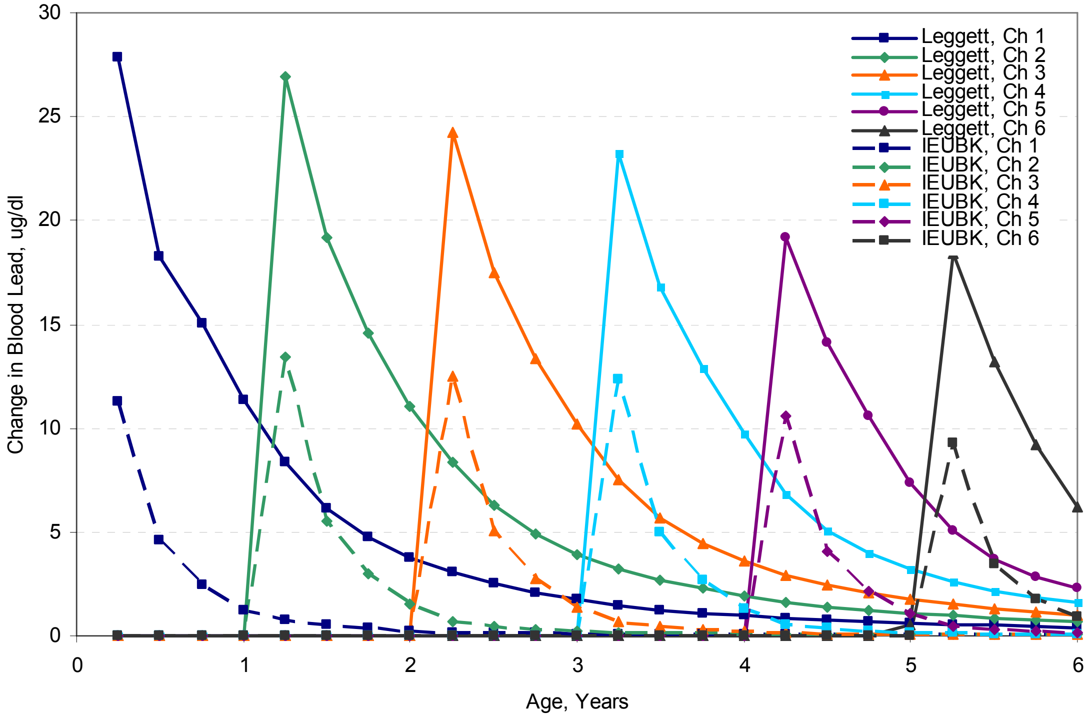


Exhibit 5-11. Time Series of Incremental Blood Pb Changes Due to the RRP Activity for the < 1940 Vintage, Multiple Activities Example



The difference in blood Pb between each of the Control Options and the Base Control Option for blood Pb estimates is shown in Exhibit 5-12 for the single RRP activity example, and in Exhibit 5-13 for the multiple RRP activity example. These were calculated using median indoor dust concentrations. Negative values in the table indicate that the Control Option represents a reduction in blood Pb levels compared to the Base Control Option and vice versa. Tables like Exhibits 5-12 and 5-13 translate figures like Exhibits 5-10 and 5-11 into summary measures that can be compared for analysis of proposed rule control options.

Exhibit 5-12. Changes in Blood Pb for each Control Option Compared to the Base Control Option for the Median Indoor Dust, Single Activity Example in µg/dL

Control Option and Percentile	**Leggett**			**IEUBK**		
	<1940	**1940 to 1959**	**1960 to 1979**	**<1940**	**1940 to 1959**	**1960 to 1979**
Control Option 1, Median	0.14	0.09	0.05	0.03	0.02	0.01
Control Option 2, Median	0.04	0.05	0.02	-0.01	0.00	0.00
Control Option 3, Median	-0.46	-0.26	-0.16	-0.13	-0.08	-0.05

Exhibit 5-13. Changes in Blood Pb for each Control Option Compared to the Base Control Option for the Median Indoor Dust, Multiple Activities Example in µg/dL

Control Option and Percentile	Leggett			IEUBK		
	<1940	1940 to 1959	1960 to 1979	<1940	1940 to 1959	1960 to 1979
Control Option 1, Median	0.72	0.44	0.27	0.22	0.14	0.09
Control Option 2, Median	-0.14	-0.09	-0.06	-0.06	-0.04	-0.02
Control Option 3, Median	-1.26	-0.89	-0.44	-0.32	-0.21	-0.12

5.5 Uncertainties and Limitations

It is likely that uncertainties in exposure concentration inputs contribute to the overall uncertainty in any blood Pb estimates. The difficulties involved in deriving estimates of indoor air and dust Pb concentrations for different renovation activities on the basis of limited data are discussed in Section 3 and 4 and Appendix A. Whatever uncertainties are involved in the estimation of exposure concentrations will be propagated through the exposure, intake, and uptake assessment, and through the biokinetic blood Pb modeling.

Exposure factor values used to estimate inputs to the biokinetic models (respiratory volume, water intake, GI absorption fractions, etc.) are anticipated to contribute a somewhat lesser degree of uncertainty to blood Pb estimates. Because exposure to indoor dust represents such a large proportion of total Pb uptake associated with indoor renovation activities, exposure factors in this pathway, such as dust ingestion rates and GI absorption, are likely to be the important contributors. Even with outdoor activities, a portion of outdoor soil is assumed to be available to a child indoors.

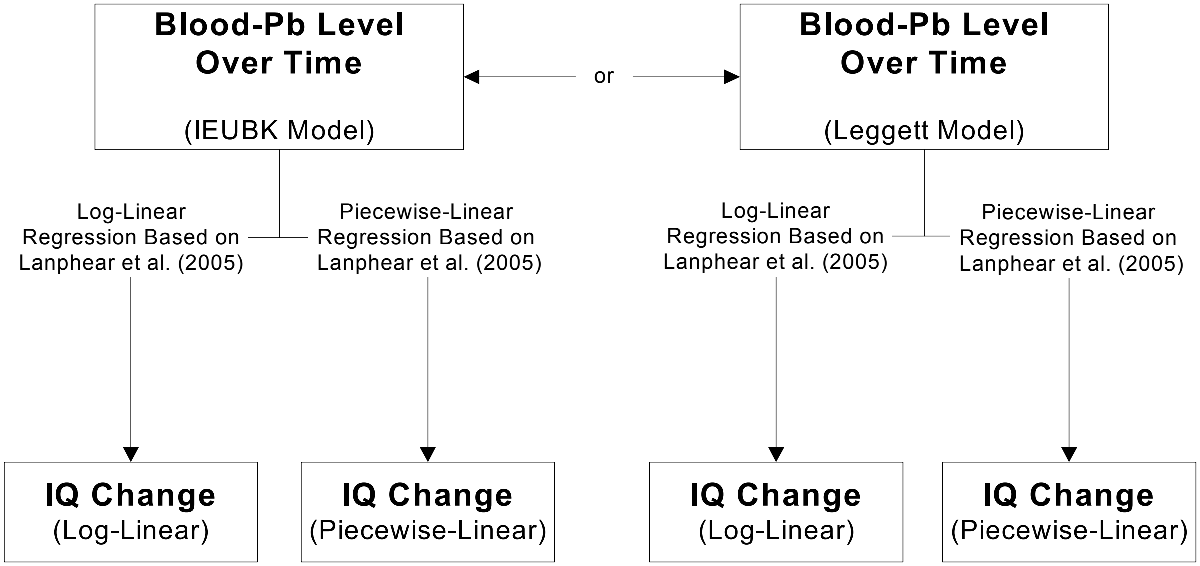
It is well-known that the IEUBK and Leggett biokinetic models tend to predict different blood Pb levels when given the same exposure inputs (Pounds and Leggett 1998, USEPA 2006d). The renovation examples reported here show that predictions by the Leggett model are about three times those predicted by the IEUBK. As discussed above, the relative performance of the two models suggests some possible explanations: (1) more rapid excretion of Pb (to urine and feces) from the IEUBK, or (2) differences in partitioning of Pb between blood and other body "compartments." The IEUBK seems to maintain a higher proportion of Pb in bone and other slowly-exchanging compartments, while Leggett keeps more Pb in the blood (erythrocyte) compartment for longer durations.

The difference in the predictions from the two biokinetic models illustrates the approximate contribution of "model uncertainty" to the overall uncertainty in blood Pb predictions. As discussed in Section 5.1.2, the supporting database for the Leggett model is somewhat more extensive than that for IEUBK, and the Leggett model is structurally more sophisticated than the IEUBK. In addition, applying the IEUBK to estimate the impacts of short-term fluctuations in Pb exposure (weekly in this analysis) is stretching the IEUBK to the limits of its temporal resolution. On the other hand, as shown in Exhibit 5-6, the IEUBK blood Pb predictions associated with what are considered to be typical Background exposures in the single activity case can result in central tendency blood Pb estimates that are much closer to the results obtained from large population surveys (NHANES) than the Leggett model. Regrettably, there are little data available concerning the patterns of Pb exposures of the NHANES participants.

6. ESTIMATES OF IQ CHANGE

Once the blood Pb levels are estimated from the media concentrations, these values are converted to IQ changes using regression equations, as shown in Exhibit 6-1. As discussed in Chapter 2, two such available sets of regression equations include those from Lanphear et al. (2005) and from Canfield et al. (2003). For the current approach, the Lanphear et al. (2005) models were selected because the population in that study was much larger, including subjects from several countries, from populations with different patterns of Pb exposure, and from a wide range of socioeconomic strata. The larger number of subjects in the Lanphear et al. (2005) study afforded a higher degree of precision in identifying and characterizing blood Pb-IQ relationships, and allowed the use of more sophisticated statistical models to evaluate the data.

Exhibit 6-1. Flow Chart Illustrating the Estimation of IQ Changes from Blood Pb Levels



6.1 Selected Model (Lanphear et al. 2005)

As discussed in Chapter 2, Lanphear et al. (2005) derived regression relationships between several blood Pb metrics and IQ test results based on linear, cubic spline, log-linear, and piecewise linear equations. Lanphear et al (2005) found that the log-linear model provided the strongest relationships for the data; this relationship was selected as the primary regression equation for the current approach. In addition, a piecewise-linear equation provided by Lanphear et al (2005) is used for purposes of comparison in the current approach to address the limitations and uncertainties associated with the log-linear model. For the blood Pb metric, the current approach selects the lifetime average blood Pb since it more fully takes into account the renovation activity exposures of children in all six age groups. The alternate option, using the concurrent average, would require averaging near the ages when IQ was measured for the test subjects used in the Lanphear et al (2005) regression. In this case, this would involve an average during the fifth or sixth year of life and would give relatively smaller blood Pb levels for the children who experience the renovation earlier in their lives and have nearly reached background by the sixth year, particularly with the IEUBK model.

The Lanphear et al. (2005) study included a relatively high proportion of children with low blood Pb levels. For example, approximately 18 percent of the children had blood Pb levels below 10 ug/dL and about eight percent had blood Pb levels that never exceeded 7.5 ug/dL. The statistical model with the strongest relationship between blood Pb and IQ levels in the Lanphear et al. (2005) data set is log-linear. This model has the property that the blood Pb-IQ slope increases rapidly at low blood Pb levels, and goes to infinity at zero blood Pb. Thus, it cannot be used to accurately predict IQ loss at very low blood Pb levels.

To address the limitations and uncertainties associated with the log-linear model, two strategies have been used. The first strategy uses a "cutpoint" of 1 ug/dL and does not estimate IQ change below that. The rationale for selecting this particular cutpoint is to apply the model within the range of the Lanphear et al. (2005) data; almost all of the observed blood Pb values in Lanphear et al (2005) were above 1 ug/dL. This methodology is intended to give a conservative estimate of IQ changes due to the relatively small changes in blood Pb in newer homes and in the 5th percentile dust lead concentration cases. The equation for the log-linear model used in the analysis is:

$$\left.\begin{array}{l} \text{IQ change} = 0 \text{ for PbB} < 1\ \mu\text{g/dL} \\[2em] \text{IQ change} = -3.04 * \ln(\text{blood Pb}/1\ \mu\text{g/dL}) \text{ for PbB} > 1\ \mu\text{g/dL} \end{array}\right\} \textbf{(Eq. 6-1)}$$

where:

PbB = Lifetime average of the blood Pb level

The second strategy adopts a piecewise linear model developed by Lanphear et al. (2005) with lifetime blood Pb data. This model has the advantage that while it captures the difference in slope between the lower and higher blood Pb ranges, the slope does not increase to infinity as blood Pb decreases. For the piecewise-linear model, the slope changes at 10 ug/dL, so the equation (Eq 6-2) is:

$$\left.\begin{array}{l} \text{IQ change} = 0 \text{ for PbB} < 1 \text{ ug/dL} \\ \text{IQ change} = -0.80 * (\text{PbB} - 1 \text{ ug/dL}) \text{ for } 1 < \text{PbB} < 10 \text{ ug/dL} \\ \text{IQ change} = -0.13 * (\text{PbB} - 10 \text{ ug/dL}) -7.2 \text{ for PbB} > 10 \text{ ug/dL} \end{array}\right\} \textbf{(Eq. 6-2)}$$

where:

PbB = Lifetime average of the blood Pb level

Since this model has a shallower slope, estimates based on like inputs will be uniformly smaller than those from the log-linear fit. The coefficients for this model, however, were developed by

Lanphear et al (2005) for concurrent levels and may differ from ones that might pertain to a preconceived linear fit to lifetime Lanphear et al (2005) data.

6.2 Examples

The lifetime average blood Pb for both the Leggett and IEUBK models were used to calculate estimated IQ changes for all vintages, all Control Options, and all indoor dust Monte Carlo percentiles (5th, median, mean, and 95th) for the single and multiple RRP activity examples using both the log-linear and piecewise linear models. These calculations are presented below for Child 2, and calculations for all children are presented in Appendix G.

6.2.1 Estimated IQ Changes Associated With Background Exposures

Exhibit 6-2 and 6-3 show the IQ changes associated with the background Pb exposure concentrations and their blood Pb estimates from the IEUBK and Leggett models, respectively. In this table, the sign convention is such that negative values represent reductions in IQ. In general, the Leggett model results follow similar trends to the IEUBK results, although with different magnitudes. As discussed above, the piecewise linear model results in smaller IQ changes than the log-linear model in every vintage.

Exhibit 6-2. IQ Changes Due to Background Pb Exposure Concentrations Calculated from Blood Pb Levels from the IEUBK Model

Percentile	Log-Linear			Piecewise Linear		
	<1940	1940 to 1959	1960 to 1979	<1940	1940 to 1959	1960 to 1979
95th Percentile	-6.3	-4.1	-3.6	-5.5	-2.3	-1.8
Median	-4.6	-2.4	-1.9	-2.8	-1.0	-0.7
Mean	-4.9	-2.7	-2.2	-3.2	-1.1	-0.9
5th Percentile	-3.9	-1.7	-1.3	-2.1	-0.6	-0.4

Exhibit 6-3. IQ Changes Due to Background Pb Exposure Concentrations Calculated from Blood Pb Levels from the Leggett Model

Percentile	Log-Linear			Piecewise Linear		
	<1940	1940 to 1959	1960 to 1979	<1940	1940 to 1959	1960 to 1979
95th Percentile	-9.8	-7.4	-6.9	-9.2	-7.4	-7.0
Median	-8.0	-5.6	-5.1	-7.7	-4.2	-3.5
Mean	-8.3	-5.9	-5.4	-7.9	-4.8	-4.0
5th Percentile	-7.2	-4.9	-4.5	-7.3	-3.2	-2.7

6.2.2 Estimated IQ Changes for the Single and Multiple RRP Activity Examples

Exhibits 6-4 and 6-5 show the IQ changes for Child 2 using blood Pb levels from the IEUBK and Leggett models, respectively, in the single activity example. The estimates derived using median dust concentrations are highlighted in bold. The reductions in IQ tend to be largest for the older homes, as expected. As in the background case, the predictions using the piecewise linear model tend to be lower than those using the log-linear model, although exceptions do occur for the higher indoor dust percentiles.

Exhibit 6-4. IQ Changes for Child 2 Using Blood Pb Values
from the IEUBK Model for the Single Activity Example

Control Option and Percentile	**Log-Linear**			**Piecewise Linear**		
	<1940	**1940 to 1959**	**1960 to 1979**	**<1940**	**1940 to 1959**	**1960 to 1979**
Base Control Option, 95th Percentile	-6.6	-4.7	-4.4	-6.2	-3.0	-2.6
Control Option 1, 95th Percentile	-6.6	-4.7	-4.4	-6.2	-3.0	-2.6
Control Option 2, 95th Percentile	-6.6	-4.7	-4.3	-6.1	-2.9	-2.5
Control Option 3, 95th Percentile	-6.5	-4.5	-4.1	-5.9	-2.7	-2.3
Base Control Option, Median	**-4.9**	**-2.8**	**-2.2**	**-3.2**	**-1.2**	**-0.9**
Control Option 1, Median	**-4.9**	**-2.8**	**-2.3**	**-3.2**	**-1.2**	**-0.9**
Control Option 2, Median	**-4.9**	**-2.8**	**-2.2**	**-3.1**	**-1.2**	**-0.9**
Control Option 3, Median	**-4.8**	**-2.7**	**-2.2**	**-3.1**	**-1.1**	**-0.8**
Base Control Option, Mean	-5.2	-3.1	-2.7	-3.6	-1.4	-1.1
Control Option 1, Mean	-5.2	-3.2	-2.7	-3.6	-1.5	-1.1
Control Option 2, Mean	-5.2	-3.1	-2.7	-3.6	-1.4	-1.1
Control Option 3, Mean	-5.1	-3.0	-2.6	-3.5	-1.4	-1.1
Base Control Option, 5th Percentile	-4.0	-1.9	-1.4	-2.2	-0.7	-0.5
Control Option 1, 5th Percentile	-4.0	-1.9	-1.4	-2.2	-0.7	-0.5
Control Option 2, 5th Percentile	-4.0	-1.9	-1.4	-2.2	-0.7	-0.5
Control Option 3, 5th Percentile	-4.0	-1.8	-1.4	-2.2	-0.7	-0.5

Exhibit 6-5. IQ Changes for Child 2 Using Blood Pb Values from the Leggett Model for the Single Activity Example

Control Option and Percentile	**Log-Linear**			**Piecewise Linear**		
	<1940	**1940 to 1959**	**1960 to 1979**	**<1940**	**1940 to 1959**	**1960 to 1979**
Base Control Option, 95th Percentile	-10.15	-8.19	-7.78	-9.56	-7.82	-7.58
Control Option 1, 95th Percentile	-10.16	-8.23	-7.82	-9.58	-7.85	-7.60
Control Option 2, 95th Percentile	-10.15	-8.19	-7.77	-9.56	-7.82	-7.57
Control Option 3, 95th Percentile	-10.04	-7.95	-7.55	-9.43	-7.68	-7.46
Base Control Option, Median	**-8.31**	**-6.03**	**-5.47**	**-7.90**	**-5.02**	**-4.04**
Control Option 1, Median	**-8.33**	**-6.07**	**-5.50**	**-7.92**	**-5.09**	**-4.08**
Control Option 2, Median	**-8.31**	**-6.05**	**-5.48**	**-7.90**	**-5.05**	**-4.06**
Control Option 3, Median	**-8.22**	**-5.92**	**-5.39**	**-7.84**	**-4.81**	**-3.91**
Base Control Option, Mean	**-8.68**	**-6.43**	**-5.94**	**-8.16**	**-5.84**	**-4.85**
Control Option 1, Mean	-8.71	-6.47	-5.97	-8.18	-5.93	-4.90
Control Option 2, Mean	-8.69	-6.45	-5.95	-8.17	-5.89	-4.86
Control Option 3, Mean	-8.57	-6.29	-5.81	-8.08	-5.54	-4.62
Base Control Option, 5th Percentile	-7.35	-5.04	-4.57	-7.36	-3.40	-2.80
Control Option 1, 5th Percentile	-7.37	-5.06	-4.58	-7.37	-3.42	-2.81
Control Option 2, 5th Percentile	-7.37	-5.07	-4.60	-7.37	-3.43	-2.83
Control Option 3, 5th Percentile	-7.33	-5.02	-4.57	-7.35	-3.37	-2.79

Exhibits 6-6 and 6-7 show the IQ changes for Child 2 using blood Pb levels from the IEUBK and Leggett models, respectively, in the multiple activity example. Again, the predictions using the piecewise linear model tend to be lower than those using the log-linear model, although exceptions do occur for the higher indoor dust percentiles.

Exhibit 6-6. IQ Changes for Child 2 Using Blood Pb Values from the IEUBK Model for the Multiple Activities Example

Control Option and Percentile	Log-Linear			Piecewise-Linear		
	<1940	1940 to 1959	1960 to 1979	<1940	1940 to 1959	1960 to 1979
Base Control Option, 95th Percentile	-7.1	-5.4	-4.9	-7.3	-3.9	-3.2
Control Option 1, 95th Percentile	-7.5	-5.8	-5.2	-7.4	-4.7	-3.6
Control Option 2, 95th Percentile	-7.1	-5.3	-4.8	-7.2	-3.8	-3.1
Control Option 3, 95th Percentile	-6.9	-5.1	-4.6	-6.9	-3.4	-2.8
Base Control Option, Median	**-5.3**	**-3.3**	**-2.6**	**-3.7**	**-1.6**	**-1.1**
Control Option 1, Median	**-5.4**	**-3.4**	**-2.7**	**-3.9**	**-1.7**	**-1.1**
Control Option 2, Median	**-5.2**	**-3.2**	**-2.6**	**-3.7**	**-1.5**	**-1.1**
Control Option 3, Median	**-5.1**	**-3.1**	**-2.4**	**-3.4**	**-1.4**	**-1.0**
Base Control Option, Mean	-5.6	-3.7	-3.1	-4.3	-1.9	-1.4
Control Option 1, Mean	-5.8	-4.0	-3.3	-4.7	-2.2	-1.6
Control Option 2, Mean	-5.6	-3.7	-3.0	-4.2	-1.9	-1.4
Control Option 3, Mean	-5.4	-3.5	-2.9	-4.0	-1.7	-1.3
Base Control Option, 5th Percentile	-4.2	-2.1	-1.5	-2.4	-0.8	-0.5
Control Option 1, 5th Percentile	-4.3	-2.1	-1.6	-2.4	-0.8	-0.5
Control Option 2, 5th Percentile	-4.2	-2.1	-1.5	-2.4	-0.8	-0.5
Control Option 3, 5th Percentile	-4.1	-2.0	-1.5	-2.3	-0.8	-0.5

Exhibit 6-7. IQ Changes for Child 2 Using Blood Pb Values from the Leggett Model for the Multiple Activities Example

Control Option and Percentile	**Log Linear**			**Piecewise Linear**		
	<1940	**1940 to 1959**	**1960 to 1979**	**<1940**	**1940 to 1959**	**1960 to 1979**
Base Control Option, 95th Percentile	-10.76	-9.18	-8.53	-10.38	-8.56	-8.05
Control Option 1, 95th Percentile	-11.01	-9.55	-8.86	-10.76	-8.91	-8.30
Control Option 2, 95th Percentile	-10.70	-9.08	-8.45	-10.29	-8.48	-7.99
Control Option 3, 95th Percentile	-10.51	-8.78	-8.19	-10.03	-8.23	-7.82
Base Control Option, Median	**-8.88**	**-6.80**	**-5.93**	**-8.32**	**-6.69**	**-4.82**
Control Option 1, Median	**-9.00**	**-6.94**	**-6.04**	**-8.41**	**-7.04**	**-5.04**
Control Option 2, Median	**-8.86**	**-6.77**	**-5.90**	**-8.30**	**-6.61**	**-4.78**
Control Option 3, Median	**-8.67**	**-6.49**	**-5.73**	**-8.15**	**-5.97**	**-4.47**
Base Control Option, Mean	**-9.32**	**-7.34**	**-6.53**	**-8.69**	**-7.35**	**-6.05**
Control Option 1, Mean	-9.50	-7.59	-6.73	-8.86	-7.48	-6.53
Control Option 2, Mean	-9.27	-7.27	-6.47	-8.64	-7.32	-5.93
Control Option 3, Mean	-9.07	-6.98	-6.26	-8.47	-7.15	-5.48
Base Control Option, 5th Percentile	-7.66	-5.37	-4.72	-7.51	-3.89	-2.98
Control Option 1, 5th Percentile	-7.69	-5.41	-4.75	-7.53	-3.94	-3.02
Control Option 2, 5th Percentile	-7.65	-5.37	-4.73	-7.51	-3.89	-2.99
Control Option 3, 5th Percentile	-7.54	-5.25	-4.67	-7.46	-3.70	-2.92

6.2.3 Ways to Compare IQ Changes in Association with Control Options

This section presents two ways of looking at the association of the various control options and changes in IQ including tabulating quantiles of the distribution of IQ changes relative to background, and tabulating changes in IQ for each numbered control option compared to the Base Control option. Increments in IQ levels associated with the renovation activities are calculated by subtracting the IQ levels associated with the background values from the IQ levels associated with the lifetime average blood Pb values of the activity-specific example.

Exhibits 6-8 and 6-9 show the incremental IQ reductions relative to background exposures associated with the single activity example using the IEUBK and Leggett models, respectively. Background values using the IEUBK model shown in Exhibit 6-2 are subtracted from those in Exhibit 6-4, and shown in Exhibit 6-8. Background values using the Leggett model shown in Exhibit 6-3 are subtracted from those in Exhibit 6-5, and shown in Exhibit 6-9. Exhibits 6-10 and 6-11 show the incremental IQ reductions relative to background exposures associated with the multiple activity example using the IEUBK and Leggett models, respectively. Background values using the IEUBK model shown in Exhibit 6-2 are subtracted from those in Exhibit 6-6, and shown in Exhibit 6-10. Background values using the Leggett model shown in Exhibit 6-3 are subtracted from those in Exhibit 6-7, and shown in Exhibit 6-11. For these examples, unlike blood Pb levels, these incremental changes do not decrease with newer houses. Although the blood Pb levels follow this trend, the IQ regression equations give steeper slopes for lower blood Pb levels. Thus, the same change relative to background in blood Pb for the pre-1940 vintage (higher blood Pb levels) will give a lower associated IQ loss than the same change in blood Pb for 1960-1979 vintage homes (lower blood Pb levels). These two competing effects (incremental blood Pb increasing with increasing vintage offset by IQ slope decreases with increasing vintage) combine such that the middle vintage sometimes has the highest predicted incremental IQ change.

Exhibit 6-8. Incremental Changes in IQ for Child 2 Using Blood Pb Levels from the IEUBK Model for the Single Activity Example

Control Option and Percentile	**Log-Linear**			**Piecewise Linear**		
	<1940	**1940 to 1959**	**1960 to 1979**	**<1940**	**1940 to 1959**	**1960 to 1979**
Base Control Option, 95th Percentile	-0.3	-0.6	-0.7	-0.7	-0.7	-0.7
Control Option 1, 95th Percentile	-0.3	-0.6	-0.8	-0.7	-0.7	-0.7
Control Option 2, 95th Percentile	-0.3	-0.6	-0.7	-0.7	-0.7	-0.7
Control Option 3, 95th Percentile	-0.2	-0.4	-0.5	-0.4	-0.4	-0.5
Base Control Option, Median	**-0.3**	**-0.4**	**-0.3**	**-0.3**	**-0.2**	**-0.2**
Control Option 1, Median	**-0.3**	**-0.4**	**-0.4**	**-0.3**	**-0.3**	**-0.2**
Control Option 2, Median	**-0.3**	**-0.4**	**-0.3**	**-0.3**	**-0.2**	**-0.2**
Control Option 3, Median	**-0.2**	**-0.3**	**-0.3**	**-0.2**	**-0.2**	**-0.1**
Base Control Option, Mean	-0.3	-0.4	-0.4	-0.4	-0.3	-0.3
Control Option 1, Mean	-0.3	-0.5	-0.5	-0.4	-0.3	-0.3
Control Option 2, Mean	-0.3	-0.4	-0.4	-0.4	-0.3	-0.3
Control Option 3, Mean	-0.2	-0.3	-0.3	-0.2	-0.2	-0.2
Base Control Option, 5th Percentile	-0.1	-0.1	-0.1	-0.1	-0.1	0.0
Control Option 1, 5th Percentile	-0.1	-0.2	-0.1	-0.1	-0.1	0.0
Control Option 2, 5th Percentile	-0.1	-0.2	-0.1	-0.1	-0.1	-0.1
Control Option 3, 5th Percentile	-0.1	-0.1	-0.1	-0.1	-0.1	0.0

Exhibit 6-9. Incremental Changes in IQ for Child 2 Using Blood Pb Levels from the Leggett Model for the Single Activity Example

Control Option and Percentile	**Log Linear**			**Piecewise Linear**		
	<1940	**1940 to 1959**	**1960 to 1979**	**<1940**	**1940 to 1959**	**1960 to 1979**
Base Control Option, 95th Percentile	-0.32	-0.77	-0.87	-0.37	-0.43	-0.60
Control Option 1, 95th Percentile	-0.34	-0.81	-0.90	-0.39	-0.45	-0.61
Control Option 2, 95th Percentile	-0.32	-0.77	-0.85	-0.37	-0.43	-0.59
Control Option 3, 95th Percentile	-0.21	-0.53	-0.63	-0.24	-0.29	-0.47
Base Control Option, Median	**-0.31**	**-0.44**	**-0.38**	**-0.34**	**-0.52**	**-0.50**
Control Option 1, Median	**-0.34**	**-0.48**	**-0.40**	**-0.21**	**-0.86**	**-0.60**
Control Option 2, Median	**-0.32**	**-0.46**	**-0.39**	**-0.20**	**-0.82**	**-0.58**
Control Option 3, Median	**-0.22**	**-0.33**	**-0.29**	**-0.14**	**-0.58**	**-0.43**
Base Control Option, Mean	-0.34	-0.52	-0.50	-0.24	-1.04	-0.86
Control Option 1, Mean	-0.37	-0.56	-0.53	-0.26	-1.12	-0.92
Control Option 2, Mean	-0.35	-0.54	-0.51	-0.25	-1.08	-0.87
Control Option 3, Mean	-0.24	-0.38	-0.38	-0.16	-0.74	-0.63
Base Control Option, 5th Percentile	-0.13	-0.17	-0.12	-0.06	-0.23	-0.14
Control Option 1, 5th Percentile	-0.14	-0.18	-0.13	-0.07	-0.25	-0.15
Control Option 2, 5th Percentile	-0.14	-0.19	-0.15	-0.07	-0.26	-0.17
Control Option 3, 5th Percentile	-0.11	-0.15	-0.11	-0.05	-0.20	-0.13

Exhibit 6-10. Incremental Changes in IQ for Child 2 Using Blood Pb Levels from the IEUBK Model for the Multiple Activity Example

Control Option and Percentile	**Log-Linear**			**Piecewise-Linear**		
	<1940	**1940 to 1959**	**1960 to 1979**	**<1940**	**1940 to 1959**	**1960 to 1979**
Base Control Option, 95th Percentile	-0.9	-1.3	-1.2	-1.8	-1.7	-1.3
Control Option 1, 95th Percentile	-1.2	-1.8	-1.6	-2.0	-2.4	-1.8
Control Option 2, 95th Percentile	-0.8	-1.2	-1.2	-1.8	-1.5	-1.2
Control Option 3, 95th Percentile	-0.6	-1.0	-0.9	-1.4	-1.2	-1.0
Base Control Option, Median	**-0.7**	**-0.9**	**-0.7**	**-0.9**	**-0.6**	**-0.4**
Control Option 1, Median	**-0.8**	**-1.0**	**-0.8**	**-1.1**	**-0.7**	**-0.4**
Control Option 2, Median	**-0.6**	**-0.9**	**-0.6**	**-0.8**	**-0.6**	**-0.4**
Control Option 3, Median	**-0.5**	**-0.7**	**-0.5**	**-0.6**	**-0.4**	**-0.3**
Base Control Option, Mean	-0.7	-1.0	-0.8	-1.1	-0.8	-0.5
Control Option 1, Mean	-0.9	-1.3	-1.0	-1.4	-1.0	-0.7
Control Option 2, Mean	-0.7	-1.0	-0.8	-1.0	-0.7	-0.5
Control Option 3, Mean	-0.5	-0.8	-0.6	-0.7	-0.5	-0.4
Base Control Option, 5th Percentile	-0.3	-0.4	-0.2	-0.3	-0.2	-0.1
Control Option 1, 5th Percentile	-0.3	-0.4	-0.3	-0.3	-0.2	-0.1
Control Option 2, 5th Percentile	-0.3	-0.4	-0.2	-0.3	-0.2	-0.1
Control Option 3, 5th Percentile	-0.2	-0.3	-0.2	-0.2	-0.2	-0.1

Exhibit 6-11. Incremental Changes in IQ for Child 2 Using Blood Pb Levels from the Leggett Model for the Multiple Activities Example

Control Option and Percentile	Log Linear			Piecewise Linear		
	<1940	1940 to 1959	1960 to 1979	<1940	1940 to 1959	1960 to 1979
Base Control Option, 95th Percentile	-0.96	-1.77	-1.60	-1.21	-1.17	-1.04
Control Option 1, 95th Percentile	-1.20	-2.15	-1.94	-1.59	-1.53	-1.29
Control Option 2, 95th Percentile	-0.90	-1.67	-1.52	-1.12	-1.09	-0.98
Control Option 3, 95th Percentile	-0.71	-1.37	-1.26	-0.86	-0.85	-0.81
Base Control Option, Median	**-0.90**	**-1.21**	**-0.83**	**-0.62**	**-2.46**	**-1.34**
Control Option 1, Median	**-1.01**	**-1.35**	**-0.94**	**-0.71**	**-2.81**	**-1.56**
Control Option 2, Median	**-0.87**	**-1.18**	**-0.81**	**-0.60**	**-2.39**	**-1.30**
Control Option 3, Median	**-0.68**	**-0.91**	**-0.63**	**-0.45**	**-1.75**	**-0.99**
Base Control Option, Mean	-0.98	-1.42	-1.08	-0.77	-2.55	-2.05
Control Option 1, Mean	-1.16	-1.68	-1.29	-0.94	-2.68	-2.53
Control Option 2, Mean	-0.93	-1.35	-1.03	-0.72	-2.52	-1.94
Control Option 3, Mean	-0.74	-1.06	-0.82	-0.45	-1.75	-0.99
Base Control Option, 5th Percentile	-0.43	-0.50	-0.27	-0.21	-0.71	-0.32
Control Option 1, 5th Percentile	-0.46	-0.54	-0.30	-0.23	-0.77	-0.36
Control Option 2, 5th Percentile	-0.42	-0.50	-0.28	-0.21	-0.71	-0.33
Control Option 3, 5th Percentile	-0.32	-0.38	-0.22	-0.15	-0.53	-0.26

Exhibits 6-12 and 6-13 show the IQ change associated with each Control Option compared with the Base Control Option using blood Pb levels from the IEUBK and Leggett models, respectively, for the single activity example. Exhibits 6-14 and 6-15 show the IQ change associated with each Control Option compared with the Base Control Option using blood Pb levels from the IEUBK and Leggett models, respectively, for the multiple activity example. In these tables, a positive number indicates that the Control Option gives a smaller IQ change, and thus provides a benefit compared to the Base Control Option. These tables provide summary measures that can be compared for analysis of proposed rule control options.

Exhibit 6-12. Comparison of IQ Changes for Child 2 Across Control Options for the Median Case Using Blood Pb Levels from the IEUBK Model for the Single Activity Example

Control Option	Log-Linear			Piecewise Linear		
	<1940	1940 to 1959	1960 to 1979	<1940	1940 to 1959	1960 to 1979
Control Option 1, Median	-0.02	-0.03	-0.02	-0.02	-0.02	-0.01
Control Option 2, Median	0.01	0.00	-0.01	0.01	0.00	0.00
Control Option 3, Median	0.08	0.10	0.08	0.10	0.07	0.04

Exhibit 6-13. Comparison of IQ Changes for Child 2 Across Control Options for the Median Case Using Blood Pb Levels from the Leggett Model for the Single Activity Example

Control Option	Log-Linear			Piecewise Linear		
	<1940	1940 to 1959	1960 to 1979	<1940	1940 to 1959	1960 to 1979
Control Option 1, Median	-0.03	-0.04	-0.02	0.01	0.01	0.01
Control Option 2, Median	-0.01	-0.02	-0.01	0.00	-0.04	-0.02
Control Option 3, Median	0.09	0.11	0.08	0.06	0.21	0.13

Exhibit 6-14. Comparison of IQ Changes for Child 2 Across Control Options for the Median Case Using Blood Pb Levels from the IEUBK Model for the Multiple Activities Example

Control Option	Log-Linear			Piecewise-Linear		
	<1940	1940 to 1959	1960 to 1979	<1940	1940 to 1959	1960 to 1979
Control Option 1, Median	-0.12	-0.14	-0.11	-0.18	-0.11	-0.07
Control Option 2, Median	0.03	0.04	0.02	0.05	0.03	0.02
Control Option 3, Median	0.18	0.23	0.16	0.26	0.17	0.09

Exhibit 6-15. Comparison of IQ Changes for Child 2 Across Control Options for the Median Case Using Blood Pb Levels from the Leggett Model for the Multiple Activities Example

Control Option	Log-Linear			Piecewise-Linear		
	<1940	1940 to 1959	1960 to 1979	<1940	1940 to 1959	1960 to 1979
Control Option 1, Median	-0.12	-0.14	-0.12	0.01	0.01	0.01
Control Option 2, Median	0.02	0.03	0.02	0.02	0.07	0.04
Control Option 3, Median	0.21	0.30	0.20	0.16	0.71	0.35

6.3 Uncertainties and Limitations

The estimates in IQ change are based on the blood Pb estimates described in Section 5. Substantial uncertainty is associated with the blood Pb estimates due to uncertainties fin the exposure data and models. Thus, overall uncertainty is carried throughout the approach and ultimately to the estimates of IQ change.

Lanphear et al. (2005) compared model shapes and Pb metrics. The log-linear model provides the strongest relationship as shown by the magnitude of its slope coefficient. Yet some estimates of that coefficient have 95 percent confidence limits that differ by a factor of about 2.5. In the same paper, they show prediction limits on regression estimates that span a range of about 10 IQ points across the entire range of observed blood Pb levels. The estimated blood Pb-IQ slope parameters also differ depending on the blood Pb metric (peak, concurrent, or lifetime) that is used to fit the models. In this approach, estimated changes in lifetime blood Pb levels are used to estimate IQ changes. The use of the lifetime blood Pb-IQ model for this approach is intended to reduce the effects of age-specific differences occurring in exposure conditions when there can be time lapses between Pb exposure and Pb measurement.

As discussed in Section 6.1, strategies can be taken to address the limitations and uncertainties associated with the log-linear IQ model. These include the use of a “cutpoint” and the use of the piecewise linear model. A “cutpoint” of one ug/dL maintains predictions within the range of the data used to derive the Lanphear et al. (2005) model. The piecewise linear comparison captures the difference in slope between the lower and higher blood Pb ranges.

7. Discussion of Uncertainties and Their Impact on Results

This chapter summarizes the overall uncertainties and limitations of the approach for generating estimates of children's IQ changes associated with exposures to Pb dust from RRP-related activities inside residences. In addition, this chapter identifies those aspects of the approach that will be modified for application to child-occupied facilities. This chapter does not repeat the detailed descriptions of the uncertainties and limitations associated with the different components of the analysis provided in Sections 3.5 (for background and activity-related inputs), 4.7 (for characterization of exposure media concentrations), 5.5 (for blood Pb modeling), and 6.3 (for children's IQ change characterization). Instead, it places the uncertainties and limitations of each component in the more general context of its contributions to overall result uncertainty.

There are two primary categories of uncertainties and limitations associated with this approach: uncertainty and limitations associated with the selected input data and assumptions, which are discussed in Section 7.1; and model uncertainty and general limitations of the modeling approaches, which are discussed in Section 7.2. Section 7.3 provides conclusions about the overall quality of the approach.

7.1 Input Data and Assumptions

Any model-based approach is limited by the quality of its input data. The approach described here is fairly data intensive and thus understanding the limitations and uncertainties associated with the input data and assumptions is critical. In addition, any uncertainties and limitations of the data will be propagated throughout the remainder of the downstream calculations and thus can have implications for several different parts of the approach.

For this approach, the input data most likely to significantly impact the results primarily are related to the characterization of exposure media concentrations. The most significant limitation is the source of the activity-related Pb loading data, the OPPT Dust Study (Battelle 2007). As discussed in Chapter 3, several sources of activity data were evaluated and this source was selected based primarily on the fact that its design most closely corresponded to the needs of this approach. However, it is limited by a fairly small sample size, particularly in light of the number of different scenarios evaluated using this approach. One of the most significant limitations of the small sample size is that the four Control Options evaluated were never all evaluated at the same building for the same activity. This is significant because it limits the ability to compare results across control strategies because many of the factors that impact the generated Pb loadings (e.g., Pb content of paint) can vary significantly across the different buildings. This limitation is illustrated by the fact that the estimated Pb levels, particularly for indoor air, are often not consistent with expectations (e.g., more stringent controls often result in higher indoor air concentrations). The sample size, in combination with the method used to estimate input distributions, also limits the ability to extrapolate from these results to other locations. The distributions of Pb loadings used in the Monte Carlo analysis were developed strictly from the OPPT Dust Study samples and thus likely do not capture the full range of potential loadings.

The cleaning efficiency data used in the approach are also highly uncertain and have the potential to affect Post-renovation period indoor dust concentrations. The available data on routine cleaning efficiency are very limited, and the data identified for this approach were not developed with this use in mind. In addition, these data do not cover the full range of Pb loadings evaluated using this approach, particularly on the lower end, and thus involve a number of assumptions and some extrapolation when used in this way. As demonstrated in the sensitivity analysis, these data have the potential to have substantial impacts on Post-renovation period indoor dust concentrations. However, the impacts on the estimated blood Pb levels and IQ changes may be limited because these data appear to be more heavily influenced by renovation period concentrations, which are unaffected by routine cleaning efficiency.

This approach uses a single concentration for each building and yard for each time, rather than characterizing the concentration gradients within the building and yard. This assumption effectively assumes that children spend their time equally throughout the building and yard and does not account for the fact that children may spend more or less time in locations with higher concentrations. Although this assumption may be fairly reasonable for capturing average exposures for most residences, it may be problematic for COFs because children in schools and daycare centers are likely to spend the large majority of their time in a fairly limited percentage of the building. In addition, it does not do a very good job at capturing the high- and low-end tails of the exposure concentration distributions. For COFs loadings will be estimated for three different room types (workspace, adjacent, rest of COF), rather than obtaining a single COF average, and a single workspace room will be assumed.

As illustrated in the results in Chapters 5 and 6, background indoor dust concentrations are the most significant contributors to overall blood Pb levels and IQ changes for the examples evaluated in this document. These data are based on fairly recent HUD data and are believed to be representative of typical US housing with LBP. Other studies generally had somewhat higher overall background levels and thus the selected concentrations may somewhat underestimate background contributions.

7.2 Modeling Approaches

There are four primary model-related uncertainties and limitations associated with this approach: the indoor dust loading-to-concentration conversion, the selection of blood Pb models, the selection of concentration-response functions for IQ change, and the selection of a cutpoint for the concentration-response functions. The dust loading-to-concentration conversion, which is described in detail in Appendix C, is based on a fairly limited data set that is not specific to renovation activities. In addition, the estimated dust loadings for the multiple activities example are higher than the range of loadings from which the load-to-concentration relationship was developed and there is significant uncertainty in extending this relationship beyond the data or to another data set. This conversion has an impact on both estimated activity-related and background indoor dust concentrations.

The selection of blood Pb models is a critical element of this approach because it provides the link between the exposure media concentrations and the measures of IQ change. Two biokinetic models were considered for this approach: the IEUBK and Leggett models. The Leggett model appears to be a more appropriate model for RRP activities because it can accommodate shorter time steps and can account for the impact of previous exposures. However, the results from the Leggett model appear to be higher than would be expected (i.e., it generates results that in some cases do not seem to be supported by observed levels), even for the scenario with only background contributions. The IEUBK model appears to generate results more consistent with expectations, but has limitations of its own. For example, it is a steady-state model designed to characterize blood Pb levels for long-term exposures, not peak exposures such as those associated with RRP activities. In addition, both models require indoor dust concentrations, instead of loadings, which introduces the need for the loading-to-concentration conversion discussed above. The blood Pb levels estimated from the two biokinetic models differ by a factor of two to three; this may provide some insight into the range of model uncertainty in the blood Pb models, but does not capture the full range of uncertainty associated with the blood Pb estimates (which include the uncertainties and limitations of all upstream steps).

Log-linear and piecewise linear models have been considered for proceeding from blood Pb to IQ change, using Lanphear et al. (2005). In implementing either model, a cutpoint of 1 ug/dL was used in estimating IQ change. The log-linear model is interpreted to give the change in IQ relative to the IQ at the cutpoint. A cutpoint of 1 ug/dL was chosen to ensure that no blood Pb-IQ relationship was used beyond the range of blood Pb levels used to derive it. Data in the lower blood Pb ranges are fairly limited and the regression model near the limit of the data is necessarily uncertain. Implementing a higher cutoff than the 1 ug/dL would decrease the change in IQ associated with *all* blood Pb estimates, and thus the IQ changes are very sensitive to the cutpoint used.

7.3 Conclusions

Overall, this approach appears to give useful estimates. Because of the complexity of the methods and models used to estimate blood Pb and IQ loss, the overall degree of uncertainty in estimates of changes in IQ cannot be estimated. However, it is important to note that any systematic modeling errors apply more or less equally to estimates of change in IQ for the Base Control case and for the alternate Control Options.

It is important to note that this approach has limitations in terms of its applicability to some types of COFs, particularly those that are significantly different from residences (e.g., schools, daycare centers). This approach uses whole building indoor dust and air concentrations and whole yard outdoor soil concentrations to characterize exposures. This essentially equates to assuming children are just as likely to spend time in a given room in the house or location in the yard as they are in any other room or location in the yard. This assumption is likely to be more reasonable for residences than for schools and daycare centers, where children under six years of age are likely to be restricted to a limited number of locations in the building. However, it will be relatively straightforward to modify this approach to better accommodate COFs by adjusting the media concentrations to account for where children spend their time when in a COF.

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