1. Introduction

Childhood lead poisoning is a pervasive problem in the United States, with 1.7 million young children (8.9%) having more than 10 µg/dL of lead in their blood (Brody, 1994, Pirkle 1994). The Centers for Disease Control and Prevention and the American Academy of Pediatrics have established a blood lead level of 10 µg/dL as the indicator of adverse health effects, including reduced intelligence and neurobehavioral problems. Empirical evidence shows that housing-associated lead hazards are responsible for most childhood lead poisoning cases in the United States (CDC, 1991). In fact, lead-based paint is considered the most common source of high-dose lead poisoning among children in the U.S. (ATSDR, 1988). Title X of the Housing & Community Development Act defines "lead-based paint hazards" as any condition that causes childhood lead exposure from lead-contaminated dust or soil, or from lead-contaminated paint that is deteriorated or present in accessible, friction, or impact surfaces, and that would result in adverse human health effects (Title X, 1992). Since Congress passed Title X, researchers, regulators, and practitioners from the Federal government, state and local governments, and the private sector, have made great strides in developing the science, facilities, equipment, and expertise needed to reduce housing-associated lead hazards on a national scale.

It is generally believed that the most effective means of controlling housing-associated lead hazards is to identify the likely sources of lead on a case-by-case basis and carefully remove or control them. Numerous environmental interventions have been developed to control potential lead hazards in paint, soil, and dust (HUD, 1994a). Hazard control procedures and requirements vary widely and range from those that involve fairly complete lead removal or enclosure (abatement), to more limited hazard control strategies (interim controls) that require, for example, treating and repainting only those surfaces with peeling, chipping, or deteriorating lead-based paint. Rigorous cleanup follows both abatement and interior controls.

Although public health officials have recommended lead hazard control for the treatment of lead-poisoned children for more than forty years, there have been relatively few studies designed to evaluate the short- and long-term efficacy of these efforts. While it seems obvious that safely controlling housing-associated lead hazards should be more effective in preventing childhood lead poisoning than doing nothing at all, the scientific data to evaluate this intuition can only be obtained by thoroughly reviewing the literature. There is no single study or source of information that fully addresses this complex issue.

The primary objective of this report is to comprehensively review the literature and to describe and synthesize what is currently known about the short- and long-term efficacy of environmental interventions to control housing-associated lead hazards. Beginning with the premise that effective interventions are needed to reduce the prevalence of childhood lead-poisoning, researchers and policymakers should recognize the gaps in our knowledge and understand what is already known.

1.1 Overview of This Report

This report critically reviews the available research studies, as well as data collected from selected on-going lead hazard control programs. Some of these studies were designed to measure the efficacy of environmental interventions, while others were not.

Section 2 provides an overview of children's lead exposure pathways, and discusses past and current lead hazard control practices.

Section 3 discusses issues related to measuring the efficacy of lead hazard control interventions. The section notes that all of the published studies on the subject evaluate the impact of interventions on already lead-poisoned children, which is an evaluation of secondary prevention. The impact of interventions on primary
prevention, or preventing non-poisoned children from becoming lead poisoned, is not known and may be different than observed for already poisoned children. In addition, the section discusses the benefits and limitations of using dust or blood lead levels to evaluate the effectiveness of the interventions.

Section 4 provides definitions of terms used throughout this report. Since the terminology for abatement and lead hazards has changed over time, it is important to categorize the intervention used in past studies using the current terminology, and not simply use the terminology used in the manuscript. In addition, this section provides a definition of efficacy which is used to summarize the information provided by each study.

Section 5 describes a framework for summarizing each of the environmental and secondary prevention intervention studies that provide information to evaluate the effectiveness of housing-related lead hazard control activities. The interventions target the control of lead hazards in paint, dust, and/or soil. In each case, the study's objectives, methods, results, and conclusions are described and the implications of the findings and potential sources of bias are discussed.

Section 6 provides a limited assessment of potential sources of information from selected hazard control programs.

Section 7 provides a brief description of current research designed to measure intervention efficacy.

Section 8 summarizes the findings in Sections 5, 6, and 7 and includes summary tables.

Section 9 outlines future research needs.

Section 10 provides conclusions based on all of the previous sections.

Section 11 contains all references.

2. Overview of Lead-Based Paint Hazards in Housing

Residential lead-based paint has been sold in the United States for more than two hundred years (EDF, 1992). For the last 90 years, considerable evidence has accumulated to indicate that lead-based paint is a major source of childhood lead poisoning. Congress passed the Lead-Based Paint Poisoning Prevention Act in 1971 in an attempt to alleviate the hazards associated with lead-based paint (U.S., 1971). In 1978, the Consumer Products Safety Commission (CPSC) banned the addition of lead to interior and exterior residential paint (CPSC, 1977). In the 1987 and 1988 amendments to the Lead-Based Paint Poisoning Prevention Act, Congress directed the Department of Housing and Urban Development (HUD) to develop comprehensive and workable plans for the cost-effective inspection and abatement of lead-based paint in both public housing and privately-owned housing. As part of this directive, HUD was required to estimate the amount and characteristics of housing that contain lead-based paint and, in response, the agency sponsored a national survey of lead-based paint in housing (Clickner, 1992). In December 1990, HUD submitted to Congress a Comprehensive and Workable Plan for the Abatement of Lead-Based Paint in Privately-Owned Housing (HUD, 1991a) based on that survey.

The Comprehensive and Workable Plan stated that an estimated 57.4 million homes, representing 74 percent of all occupied housing units built before 1980, contain lead-based paint somewhere in the building. The study further determined that approximately 71 percent of all pre-1980 housing units occupied by families with young children contain lead-based paint. In an estimated 3.8 million units nationwide, children are potentially exposed to non-intact leaded paint or to high dust lead levels (HUD, 1991a).
2.1 Children's Lead Exposure Pathways

Ingestion of lead-contaminated house dust is thought to be the primary cause of childhood lead poisoning in the U.S. (CDC, 1991). Many children live in dwellings with high dust lead levels and routinely put dust-laden fingers, toys, and other objects into their mouths. Deteriorated or disturbed lead-based paint is a major internal (inside the residence) source of leaded dust and may give rise to relatively high risks of both acute and chronic lead poisoning. Leaded dust may also be tracked or blown into a residence from soil and external dust that is contaminated primarily by lead-based exterior paint and/or leaded gasoline used in the past (EPA, 1991). Lead-based paint, soil, and external dust contribute directly to a child's blood lead level if ingested. However, a more common scenario appears to be the contamination of house dust by these sources and the child's subsequent ingestion of the lead-contaminated dust (CDC, 1991).

In 1973, Needleman and Scanlon hypothesized that unintentional ingestion of house dust could be a significant source of lead in children (Needleman, 1973). In 1974, Vostal and Sayre conducted research to test the hypothesis that lead-containing house dust caused increased lead exposure of inner city children (Vostal, 1974; Sayre, 1974). Other studies followed and today it is accepted that, as exterior lead-based paint deteriorates or is disturbed, it contaminates soil and finds its way into a dwelling in the form of dust. Further, interior lead-based paint contributes in various ways to surface dust. The principal pathway of childhood lead exposure for most children is thought to be from lead-based paint and soil to house dust to hands or other objects and, finally, to ingestion (Bornschein 1985; Duggan 1985; Bellinger 1986).

The type and condition of housing is also predictive of children's blood lead levels. One study, which characterized five housing categories, found that over one-half of the blood lead variability in 18-month-old children was due to housing type and condition (Clark, 1985). The authors found that children living in deteriorated pre-World War II housing had significantly higher blood lead levels than children living in public, rehabilitated, or pre-WWII housing in satisfactory condition. Another study that followed children who were treated for lead poisoning and released back into different home environments found that the children's blood lead levels decreased during the year following diagnosis in a pattern consistent with Clark's findings (Chisolm, 1985). Chisolm observed a larger blood lead level decrease in children released to newer housing in good condition than in children released to older deteriorated housing. Presumably, the children released to the older housing continued to be exposed to loose paint and high dust lead levels.

2.2 Renovation, Remodeling, Abatement, and Lead Poisoning

The presence of lead-based paint in housing is a potential hazard to children not only when it deteriorates into dust, but when it is disturbed for renovations, remodeling, or abatement. The literature on this subject contains numerous case reports of children who were poisoned after these activities (Wolf, 1973; Rabinowitz, 1985; Curran, 1989; Marino, 1990; Shannon, 1992; Rey-Alvarez, 1987; Feldman, 1978). In most cases, the probable cause of the poisoning was the lack of knowledge about safe work practices and the potential hazards of leaded dust.

Over 20 years ago, the hazards associated with renovation and lead paint hazard control activities were noted. In 1973, Wolf wrote that "within the past two years, lead poisoning has been diagnosed in the children of two families involved in the restoration of their home." The first family conducted extensive renovation, while living in the home, that included burning and scraping old paint. "Aware of the risk of lead poisoning, the mother had the children's blood lead levels checked on several occasions during the remodeling. At first low, the [blood] lead concentrations increased" and one child had to be hospitalized. The children of the second family were kept out of the house for one week so that work could proceed at a faster pace. Two weeks after the family returned, the children's blood lead levels increased to toxic levels and they were hospitalized and treated for lead poisoning. Dust samples collected from between the floorboards in the house showed a lead
content greater than 1 percent (>10,000 µg/g). Although dust samples were not collected before abatement -- and, therefore, a definite conclusion cannot be drawn -- it is likely that the restoration work contaminated the house dust with lead. It is further plausible that the dust was not cleaned up adequately before the children were allowed to move back home and thus, their blood lead levels increased (Wolf, 1973).

More recent studies have shown that the process of uncontrolled abatements continue to be associated with increases in blood lead levels. In 1985, Rabinowitz et al. published a 2-year longitudinal study of 204 children. They observed that refinishing activities in the presence of lead-based paint were associated with a statistically significant increase in blood lead levels. The authors conclude that young children residing where lead paint is being resurfaced may be at special risk of increased lead exposure (Rabinowitz, 1985). Curran and Nunez describe a case study whereby a two-and-a-half-year-old boy was found to have a blood lead level of 79 µg/dL following extensive renovations in his home. The renovations included demolition and replacement of most of the walls and plumbing, which generated large quantities of dust (Curran, 1989). Marino et al. describe a series of four cases of childhood lead poisoning during renovation of a rural farmhouse (Marino, 1990). Shannon and Graef found that household renovation was the most common source of lead poisoning in 50 infants, aged 12 months or younger, enrolled in their clinic (Shannon, 1992). Finally, Rey-Alvarez and Menke-Hargrave document 13 case studies that illustrate the importance of vacating dwellings during the deleading process. They found that blood lead levels of already lead-poisoned children increased even further following the lead hazard reduction activities which were initiated for the benefit of that child (Rey-Alvarez, 1987).

Finally, lead dust hazards may extend beyond the home being renovated, and may affect the renovator's home. Feldman highlighted this concern when he wrote:

> A new industrial hazard has been developed in the attempt to delead old houses...serious problems may result from careless or inexperienced deleading practices. In addition to the hazards of the jobsite, the deleader may carry with him on his skin, hair, and clothing sufficient lead in paint and dust particles to continue his own exposure off the job and to contaminate his family members (Feldman, 1978).

Many cases of child (and adult) lead poisoning occurred from renovation and remodeling activities in the past and probably continue today where homeowners and untrained contractors disturb leaded surfaces. Furthermore, traditional practices of abating residential leaded paint have been associated with acute increases in levels of lead in house dust and the blood of children and workers (Chisolm, 1985; Farfel, 1991). The use, in the past, of lead abatement procedures that are today considered dangerous probably caused numerous undetected cases of lead poisoning. Paint removal methods such as open flame burning or torching, machine sanding, grinding, or abrasive blasting without special local exhaust controls, uncontained hydro-blasting or high pressure water wash, and heat guns operated above 1,100 degrees Fahrenheit have been shown to produce high airborne lead levels that may poison workers and contaminate dwellings with excessive amounts of lead dust (NIOSH, 1992; Jacobs, 1991; Rekus, 1988; Amitai, 1991; Fischbein, 1981; Farfel, 1990 and 1991). The Department of Housing and Urban Development and several states banned the use of a number of these methods for residential lead abatement because of the hazards they pose (HUD, 1994a). The EPA, which has produced an educational pamphlet on remodeling and renovation for homeowners, also discourages the use of these methods (EPA, 1994).

In addition to the direct hazards generated by specific abatement methods, lack of thorough cleanup, improper disposal of debris, inadequate worker and occupant protection, and contamination of furnishings with leaded dust was typical during traditional practices for abatement of residential lead-based paint (Chisolm, 1985;
Farfel, 1990). Today, innovative abatement and interim control methods have been developed to "safely" abate and control housing-associated lead hazards. The next section discusses some of these methods.

2.3 "Safe" Lead Hazard Control Practices

Lead abatement and interim control activities are generally not "safe" and should be performed only by trained personnel under controlled situations. However, numerous techniques have been developed in recent years to decrease both the risk of high dose lead exposure among workers, and the likelihood that leaded dust will contaminate the dwelling and its furnishings.

Removal methods have been designed to permanently control lead hazards without releasing large quantities of dust into the environment. These methods are described in the 1995 version of the HUD Guidelines for The Evaluation and Control of Lead-Based Paint Hazards in Housing (HUD, 1994a). The recommended control methods include:

- wet scraping techniques
- building component replacement
- heat guns operating below 1,100 ° Fahrenheit
- power sanders with high efficiency particle accumulator (HEPA) exhaust filters
- HEPA vacuum blasting equipment
- HEPA vacuum needle guns
- certain chemical removal methods

Structural enclosure methods and building component replacement are also abatement techniques that do not typically release uncontrolled leaded dust or fumes, unless heavy demolition is involved (HUD, 1994a).

While abatement is designed to make dwellings lead-safe by permanently controlling lead hazards, interim controls are designed to temporarily control lead hazards. Interim control activities include a combination of:

- stabilizing paint
- removing dust
- creating cleanable surfaces
- covering bare soil
- controlling lead hazards on friction, impact, and child-accessible surfaces

A combination of interim controls and limited abatement is often utilized as a cost-effective approach to reducing lead hazards. Conducting abatements when a dwelling is vacant or undergoing renovation (opportunistic abatement) may be the most cost-effective approach (HUD, 1994a).

For the purposes of this report, the term "hazard control" includes both abatement and interim controls. Local definitions of abatement are likely to differ from the way it is used here.

Regardless of the method(s) used, however, neither abatement nor interim control measures can be considered "safe" until the dwelling has been thoroughly cleaned and has passed clearance testing. Since most lead hazard control work generates some leaded dust, and since previous studies have indicated that cleaning can be accomplished if done carefully (HUD, 1991b), it is necessary for all lead hazard control activities to adhere to clearance procedures. Clearance testing, which involves visual inspection and environmental sampling by a trained certified professional, ensures that the lead hazard control work was actually completed as specified; the area is safe for unprotected workers to enter; and the area is safe for residents and young children to live in (HUD, 1994a).
The literature suggests that deteriorated or disturbed lead-based paint constitutes a major source of leaded dust in residential environments and that children are commonly exposed to the lead through normal hand-to-mouth contact. Uncontrolled removal of old paint and inadequate cleanup has caused numerous cases of child and adult lead poisoning in the past. Today, methods to safely remove or treat leaded surfaces exist and dust clearance procedures are standardized and feasible. This ensures that children do not move back into dwellings contaminated with lead by the treatment process itself. However, it is important to know which methods are most effective in controlling lead hazards in the home over the short- and long-term. The following sections present numerous studies to illuminate our current state of knowledge on this subject.

3. Measuring the Impact of Lead Hazard Control Interventions

While each study contributes to our understanding of the impact of lead hazard control interventions, each study has strengths and limitations that influence the interpretation of the findings. Before reviewing the studies, it is important to understand the difference between the primary and secondary prevention of lead poisoning, and some of the problems with using blood or dust lead levels to measure the effect of lead hazard control activities.

3.1 Primary Versus Secondary Prevention of Lead Poisoning

Except for one EPA study (Weitzman 1993), all of the currently published blood lead studies available measured blood lead levels among already poisoned children (above 25 µg/dL) to evaluate the impact of lead hazard control activities. The studies measure the effectiveness of secondary prevention of childhood lead poisoning. The effectiveness of lead hazard control interventions on the primary prevention of childhood lead poisoning may differ. In fact, lead hazard control activities may work better for the primary prevention of lead poisoning among siblings or future residents than as an intervention for already-poisoned children.

Children who are chronically exposed to lead may have large body burdens of lead. The internal lead burdens may slow the reduction of blood lead levels even after a child is moved into a lead-free environment. One study showed that chronically exposed children who were placed in lead-free housing following chelation for blood lead levels of 50 µg/dL or greater had an average blood lead level of 28 µg/dL one year after chelation (Chisolm, 1985). The study highlights that even in a relatively lead-free environment, the blood lead levels of chronically exposed children may not go below 25 µg/dL during the year following diagnosis. However, children born into environments free from lead hazards usually do not have large body burdens of lead. The increase in blood lead levels prevented by lead hazard control interventions may be larger than the decrease measured among already-poisoned children.

3.2 Using Dust or Blood Lead Levels as an Outcome Measure

The general assumption behind abatement and interim controls is that by eliminating or controlling the sources of lead in an environment, the dust lead level will be reduced, which will in turn reduce blood lead levels. Therefore, samples of both house dust and blood are typically collected to assess the short- and long-term efficacy of lead hazard control interventions.

It can be argued that lead levels in house dust are a more direct measure of efficacy than are lead levels in blood. Consider the following simplified pathway of lead exposure from a primary lead source (e.g., old paint) to a child's blood.
Sampling house dust for lead provides an estimate of the amount of lead present in the environment. Blood lead sampling provides an estimate of the biological impact of the absorbed dose of lead, after exposure has taken place. Lead hazard control work typically targets the primary sources of lead and/or house dust directly. Therefore, house dust is a more direct measure of efficacy than measuring blood lead levels alone because the presence of lead can be measured before the uncertainties associated with exposure and biological impact occur.

When using dust lead measurements to determine if an intervention is effective in reducing lead-based paint hazards, it is important that dust lead levels are measured both before and after the intervention takes place. Although dust lead levels after an intervention may be below the HUD clearance levels, they may in fact be higher than they were prior to the intervention. Without pre-intervention dust lead levels, this will not be recognized.

Dust lead measurements are also influenced by many factors not associated with lead hazard control interventions. For example, the dust lead loading level, which measures the amount of lead on a surface, is directly affected by the cleaning methods used and the frequency of cleaning in relation to the timing of sampling. In addition, the dust sampling method itself, and the laboratory analysis procedure, may influence estimates of environmental dust lead levels. Standardized dust wipe sampling procedures have been established by the Federal government and ASTM (American Society for Testing and Materials) to minimize the variation in dust lead measurements (HUD, 1994a) (ASTM, 1994). These standardized procedures should be followed by persons conducting efficacy studies.

Measuring a child's blood lead level may show whether the intervention made a difference for the child for whom the intervention was initiated. However, blood lead levels can be influenced by numerous factors that are not associated with the hazard control activities. First, they can be influenced by the levels of lead stored in the bone, which reflect the child’s past exposure to lead. Second, they can be influenced by exposure to lead hazards outside the home environment, such as hazards at the home of a relative or babysitter. Third, they can be influenced by behavioral changes that are independent of the environmental changes. For example, as children age, their mouthing behaviors change which may increase or decrease their exposure to the existing lead hazards. Children's blood lead levels tend to peak around two to three years of age. Fourth, they may be influenced by metabolic changes. Finally, blood lead levels may be influenced by seasonal changes which may result from increased exposure to leaded soil or dust, possibly due to opening windows more frequently and playing more out-of-doors during the warmer months of the year. Among 14,033 children screened in Milwaukee from 1990-1994, the average blood lead levels decreased approximately one-third from summer to winter. The seasonal fluctuations were especially keen among children with higher blood lead levels (personal communication, Brad Schultz).

In summary, when the blood lead levels of lead-poisoned children are evaluated over time, the levels can be affected by the season the child was tested, the child’s past exposure to lead, the increasing age of the child, as well as any educational or other interventions that coincide with the environmental intervention. Similarly, dust lead measurements can be affected by numerous events not related to the environmental interventions.

4. Definitions