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Assessing remedial effectiveness through the blood lead:soil/dust lead relationship at the Bunker Hill Superfund Site in the Silver Valley of Idaho

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Abstract

The 21 square mile Bunker Hill Superfund Site in northern Idaho includes several thousand acres of contaminated hillsides and floodplain, a 365-acre abandoned lead/zinc smelter and is home to more than 7000 people in 5 residential communities. Childhood lead poisoning was epidemic in the 1970s with >75% of children exceeding 40 μg/dl blood lead. Health response activities have been ongoing for three decades. In 1991, a blood lead goal of 95% of children with levels less than 10 μg/dl was adopted. The cleanup strategy, based on biokinetic pathways models, was to reduce house dust lead exposure through elimination of soil-borne sources. An interim health intervention program, that included monitoring blood lead and exposures levels, was instituted to reduce exposures through parental education during the cleanup. In 1989 and 2001, 56% and 3% of children, respectively, exceeded the blood lead criteria. More than 4000 paired blood lead/environmental exposure observations were collected during this period. Several analyses of these data were accomplished. Slope factors derived for the relationship between blood lead, soil and dust concentrations are age-dependent and similar to literature reported values. Repeat measures analysis assessing year to year changes found that the remediation effort (without intervention) had approximately a 7.5 μg/dl effect in reducing a 2-year-old child's mean blood lead level over the course of the last ten years. Those receiving intervention had an additional 2–15 μg/dl decrease. Structural equations models indicate that from 40 to 50% of the blood lead absorbed from soils and dusts is through house dust with approximately 30% directly from community-wide soils and 30% from the home yard and immediate neighborhood. Both mean blood lead levels and percent of children to exceed 10 μg/dl have paralleled soil/dust lead intake rates estimated from the pathways model. Application of the IEUBK model for lead indicates that recommended USEPA default parameters overestimate mean blood lead levels, although the magnitude of over-prediction is diminished in recent years. Application of the site-

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specific model, using the soil and dust partitions suggested in the pathways model and an effective bioavailability of 18%, accurately predicts mean blood lead levels and percent of children to exceed 10 μg/dl throughout the 11-year cleanup period. This reduced response rate application of the IEUBK is consistent with the analysis used to originally develop the cleanup criteria and indicates the blood lead goal will be achieved.

Keywords: Blood lead; Superfund; Dose-response; Soil lead; Dust lead; Biokinetic model; Exposure pathways; Remedial effectiveness; Cleanup

1. Introduction/site history

The Bunker Hill Superfund Site (BHSS) encompasses approximately 21 square miles in the Silver Valley of northern Idaho and includes a 365-acre abandoned lead/zinc mining and smelting industrial complex and numerous confined and unconfined waste deposits. The site is home to more than 7000 people in 5 residential communities (Fig. 1). A century of mineral industry releases resulted in ubiquitous heavy metal contamination of soils and dusts across several thousand acres. Typical lead concentrations of wastes and soils within the smelter complex were measured up to 100 000 mg/kg (10%). Tailings deposits in the Coeur d'Alene River flood plain averaged more than 20 000 mg/kg (2%) lead and zinc. Residential yard soils and house dust both averaged 2000–5000 mg/kg lead in the 1980s.

Lead poisoning was epidemic in these cities in the 1970s. Fig. 2 provides perspective regarding childhood blood lead levels in the last three decades. During 1973–1974, the smelter was operated without controls following a fire in the main baghouse. Excessive smelter emissions and deposition of fine, high-lead particulate in air, soil and dusts were the principal exposure routes to children. Within one mile of the complex, air lead levels exceeded 20 μg/m^3, home yard soils and house dust averaged 7000 mg/kg and 1.2% lead, respectively. Mean blood lead levels among preschool children in Smelterville were near 70 μg/dl. Dozens of children were diagnosed with clinical lead poisoning and several were hospitalized and chelated with EDTA. Emergency response actions in 1974–1975 substantially reduced absorption by 1976. However, mean blood lead levels in preschool children remained near 40 μg/dl until smelter closure in 1981 (Idaho Department of Health and Welfare, 1976; Landrigan et al., 1976; Yankel et al., 1977; Walter et al., 1980; Panhandle Health District, 1986).

A comprehensive survey of lead poisoning and exposures conducted in 1983 showed continued excess absorption among area children, including those born since the smelter closure. Mean blood lead levels among preschoolers were near 21 μg/dl. Incidental ingestion of residual contamination in community soils and dusts, via ordinary hand-to-mouth behavior and play activities, was considered the primary route of exposure. Several co-factors were found to influence the soil/dust pathway and were related to excess absorption. Significant co-factors included parental income and socio-economic status, parental education level, home hygiene practices, smokers in the home, nutritional status of the child, use of locally grown produce, play area cover (grass vs. exposed surfaces), number of hours spent outside, pica behavior and child's age (Panhandle Health District, 1986; TerraGraphics, 1987). The results of the 1983 study provided a reasonably complete picture of the sources, pathways, and risk co-factors important to lead poisoning in the area similar to that noted in other populations (Charney et al., 1980; Stark et al., 1982; Bornschein et al., 1985, 1986; US Environmental Protection Agency, 1986; Bellinger et al., 1986).

In 1985, a comprehensive plan of intervention and risk reduction was established to minimize lead absorption during the remedial investigation and cleanup phases of the Superfund project. A combination of in-home intervention, public awareness efforts, and targeted remedial activities was implemented through two major health response actions, the *Lead Health Intervention*

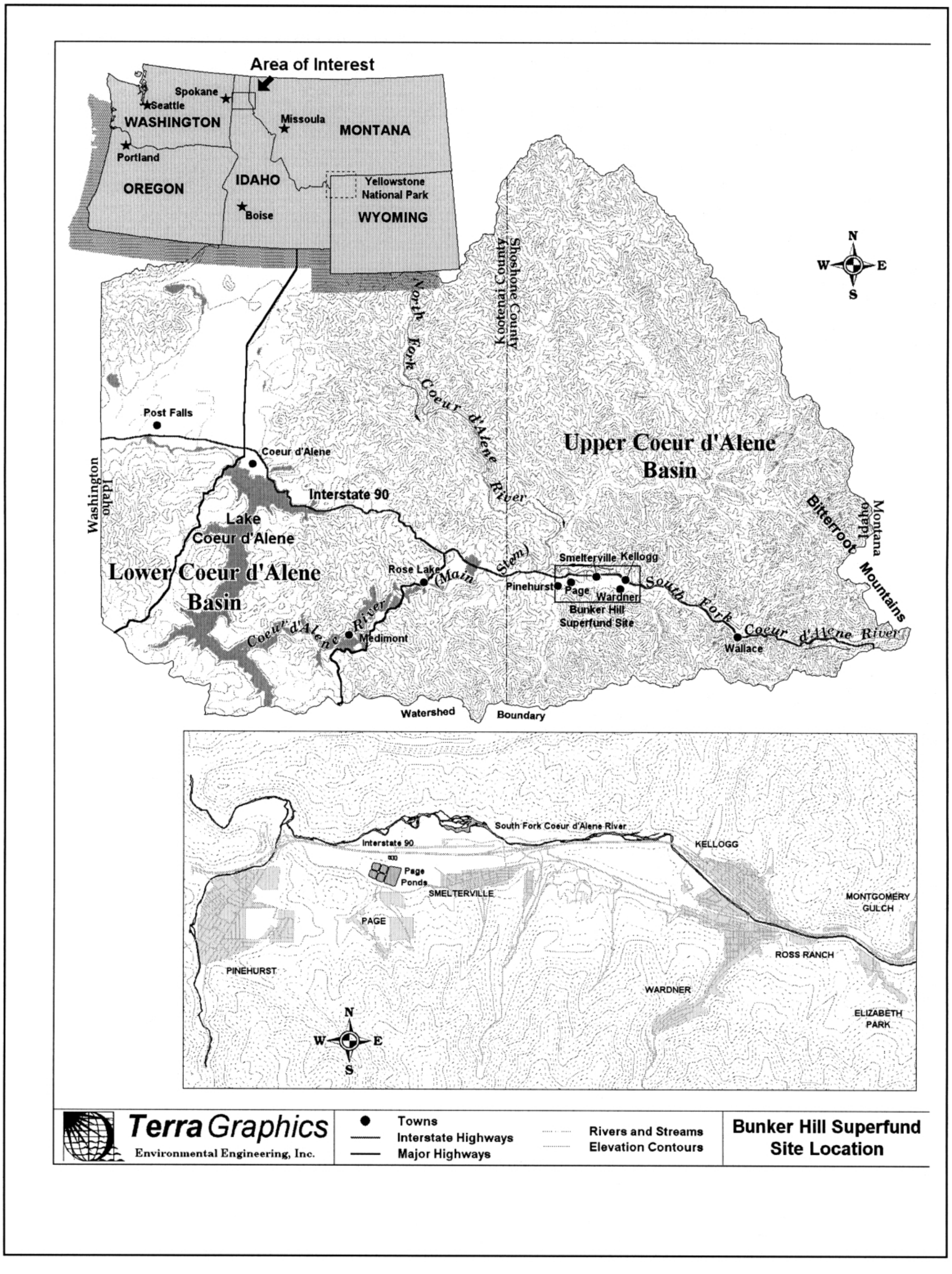


Fig. 1. Location map of Bunker Hill Superfund Site.

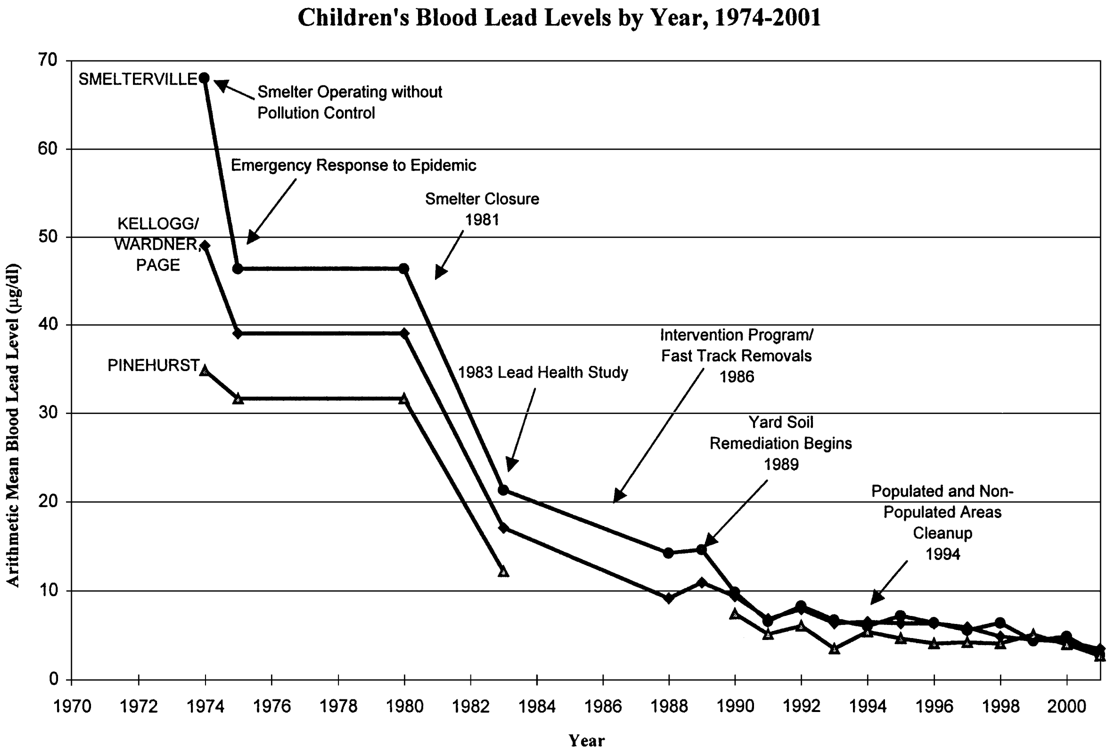


Fig. 2. Children's blood lead levels by year, 1974–2001.

Program (*LHIP*) and the *Residential Soil Cleanup*. Both were implemented at the community and individual home level (TerraGraphics, 1997, 2000a). The LHIP seeks to reduce intake of lead by modifying people's behavior by educating parents and children to ingest less dirt through improved hygiene. The program involves an annual door-to-door blood lead survey and nursing follow-up, and public education modules for local schools, parent and service groups and health care providers. The annual blood lead survey allows health department representatives direct contact with the majority of community parents to remind them of the health risks and precautions that can be taken to reduce the incidence and severity of lead poisoning. Home visits, individualized counseling, and, if appropriate, recommendation for medical follow-up are provided to children above the intervention blood lead level (Panhandle Health District, 1999). Analysis and discussion of *intervention* in the following sections refers to LHIP activities as opposed to remedial actions.

2. Blood lead levels, cleanup activities and environmental exposures

2.1. Site-wide blood lead levels

Table 1 summarizes site-wide LHIP blood lead data since 1988. More than 4000 blood lead samples have been drawn from children. In total, 372 children were targeted for follow up services and 317 (85%) were completed, with more than 75% of those children showing significant blood lead reductions. Overall blood lead levels have dropped 50–60%, with the greatest decreases corresponding with initial home yard remediation efforts in 1989–1991 (TerraGraphics, 1997, 2000a; Panhandle Health District, 2001). Table 1 also shows that the site-wide incidence of blood lead

Table 1
Lead health intervention blood lead summary 1988–2001

Year	Number of children tested	Geometric mean blood lead level (μg/dl)	Percent ≥ 15 μg/dl	Percent ≥ 10 μg/dl	Number targeted for Follow-up[a]	Number of Follow-ups completed
1988[b]	230	8.5	15%	45%	9	7
1989[b]	275	9.9**	26%	56%	8	8
1990	362	7.8**	10%	29%	3	2
1991	365	5.5**	3.6%	14%	6	6
1992	415	6.5**	7.2%	21%	31	30
1993	445	4.4**	2.2%	15%	66	56
1994	416	5.1**	3.6%	17%	71	53
1995	406	5.0	4.9%	15%	62	58
1996	397	4.7	3.3%	12%	49	38
1997	337	4.5	1.8%	11%	36	32
1998	375	4.0*	1.3%	8.3%	31	27
1999	370	3.9[c]	0.8%	6.2%	23	23
2000	320	3.5[c]	1.6%	5.3%	17	15
2001	322	2.7[c]	1.2%	3.1%	12	12

[a] Follow-up criteria ≥25 μg/dl in 1988–1990, ≥20 μg/dl in 1991, ≥15 μg/dl in 1992, ≥10 μg/dl 1993–2001.
[b] Does not include Pinehurst.
[c] 1999–2001 not included in multiple comparisons analysis.
$^{**}P \leq 0.001$ significant change from previous year. $^{*}P \leq 0.05$ significant change from previous year.

levels greater than or equal to 10 μg/dl has decreased from 56% in 1989 to 3% in 2001. Marked decreases occurred in 1989–1990, with excessive levels dropping to 29% in 1990 and to 14% by 1991. Conversely, the higher blood lead levels observed in 1992 resulted in significant increases in the number and percentage of children exhibiting lead poisoning. Site-wide, the incidence of high blood lead levels returned to approximately 15% in 1993 and stabilized near that level for the next 3 years. Site-wide high levels decreased to near 11% to 12% in 1996–1997, 8% in 1998, 6% in 1999 and 3% by 2001 (TerraGraphics, 2000a,b).

2.2. Cleanup activities

Remedial actions were designed to reduce intake of lead through cleanup, control and elimination of lead sources. Cleanup activities were undertaken in residential, former industrial and contaminated hillsides and flood plain areas. The residential remedial program effectively replaces contaminated surface soils and dusts with clean dirt. The remedial strategy with respect to soils in the residential areas is to replace all yards having soil lead concentrations greater than 1000 mg/kg and achieve a geometric mean yard soil lead concentration of less than 350 mg/kg for each community on Site. The first criterion also applies to commercial properties, parks, playgrounds and rights-of-way (ROWs) remediated during the area-wide yard removal effort. The combined efforts were expected to decrease mean house dust levels to less than 500 mg/kg in each community (US Environmental Protection Agency, 1991, 1992; CH2M-Hill, 1991).

Prior to implementation of the Record of Decision (ROD) in 1994, the cleanup was implemented in a series of high-risk removals and phased remedial actions that first targeted homes of young children and pregnant women throughout the BHSS. After the 1994 ROD, remedial efforts focused on particular geographic portions of the site, cleaning all residential, commercial, public properties, and ROWs in specific areas. During the latter period, the high-risk program continued and the yard of any child living on contaminated property during the health survey was also remediated. The nature and implementation schedule of this approach had a profound effect on soil and dust lead exposures and consequent blood lead levels as the cleanup progressed. Table 2 summa-

Table 2
Site-wide yard soil remediation progress, 1988–1998

Year	Number of yards remediated	Percent of contaminated yards remediated	Children surveyed on contaminated yards (%)	Geomean yard soil exposure (mg/kg)** (SOILPOST)	Geomean community soil concentration (mg/kg)** (GCITSOMN)	Geomean neighborhood (200 ft) soil concentration (mg/kg)** (NEIGH200)	Geomean vacuum dust lead exposure (mg/kg)** (DUST)
1988	0	0%	87%	2292	1528	2119	1324
1989	111	6%	83%	2069	1528	2151	1383
1990	160	15%	43%	581**	1239**	1196**	1080
1991	88	19%	25%	312**	1029**	975**	984
1992	100	25%	24%	300	895*	846*	798*
1993	39	27%	19%	268	794*	764*	720
1994	159	36%	18%	250	754	707	621*
1995	165	44%	29%	255	623**	693	554
1996	169	54%	19%	234	487**	533**	526
1997	192	64%	9%	198	382**	469*	536
1998	172	73%	4%	182	297**	325**	547

* $P \leq 0.05$ significant change from previous year.
** $P \leq 0.0001$ significant change from previous year.

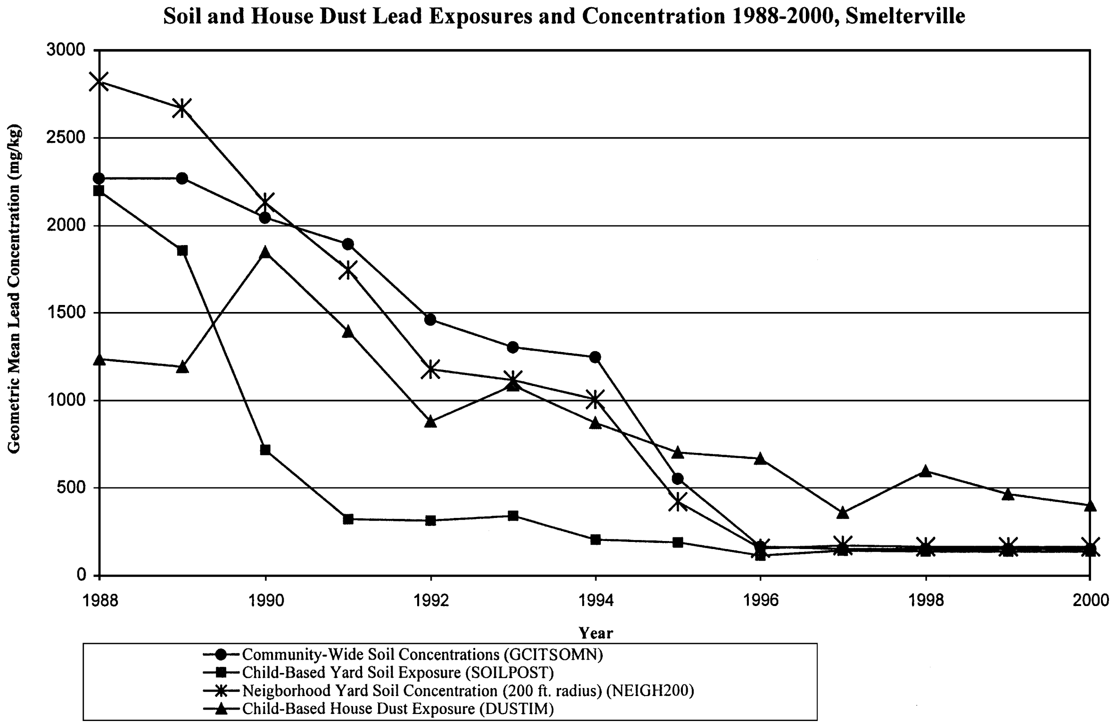


Fig. 3. Soil and house dust lead exposures and concentration 1988–2000, Smelterville.

rizes progress on the yard remediation program and soil and dust lead levels by year. More than 1800 yards on-site were estimated as being above the action level of 1000 mg/kg lead on the site in 1988. Most of these homes were located in Kellogg and Smelterville, where 85–90% of yards exceeded action levels. The remainder are in the outlying communities of Pinehurst, Wardner, Page and other unincorporated residential areas.

2.3. *Environmental exposures*

Due to the complicated nature of the cleanup and population mobility, four different soil and dust exposure variables are tracked and used in assessing remedial effectiveness. Fig. 3 illustrates these measurements for Smelterville where cleanup activities were completed in 1997. The geometric mean *community-wide soil lead concentration* (GCITSOMN) for all home yards represents the overall soils in each town, the child-based mean *yard soil lead exposure* (SOILPOST) and *house dust exposure* (*DUST*) represent individual homes occupied by children 9 years of age or less, and *neighborhood soil concentration* (*NEIGH200*) are estimated by GIS techniques aggregating all soil lead observations within various radii around each home. These different concentration measures demonstrate the complex effect of the residential soil cleanup on individual soil and dust exposures over the course of remedial activities.

The cleanup was accomplished in a prioritized manner that varied from year to year. In the early years, soil remediation was targeted at high-risk homes or those yards with the highest lead levels at homes occupied by the youngest children, pregnant women, or those children with high-blood lead levels. In later years, neighborhood-wide cleanups were accomplished for all homes in a specific geographic area. As a result, exposures to home yard soils changed abruptly for most individuals in the early years and then fluctuated as newcomers arrived. Neighborhood-exposures to soils declined slowly until the area-wide strategy reached that location and then were markedly reduced, and community-wide exposures declined steadily for a decade until completion of the program. Dust lead levels gradually decreased over time in response to all of these measures and cleanup activities in the non-residential portions of the BHSS. Because the area-wide or neighborhood remedial strategy was accomplished in different communities in different years, these patterns in soil exposure reductions also vary by community.

In order to assess the significance of the remedial actions in reducing soil exposures it was necessary to examine changes year-by-year and community-by-community for the home, neighborhood and community-wide environment. Only *site-wide* soil lead levels are presented in Table 2 and significant changes are noted for a number of years. Geometric mean *yard soil lead exposure* (SOILPOST) at homes where children resided decreased from more than 2200 mg/kg in 1988 to 581 mg/kg in 1990 and 312 mg/kg in 1991. This reduction corresponds with the first 2 years of the high-risk yard soil removal program. Little or no change was noted in mean yard soil exposure to individuals from 1991 to 1996 as newcomers moving to contaminated homes offset reductions achieved in the high-risk removal program. Since 1996, significant decreases in yard soil lead levels were again noted with area-wide cleanup activity in Kellogg and Smelterville. Significant reductions in *community-wide soil lead concentration* (GCIT-SOMN) were noted site-wide in Table 2 for all years except 1993–1994. In that year, protracted negotiations between the governments and the site PRPs delayed the cleanup and only 39 homes were remediated site-wide. Generally, mean concentrations decreased approximately 120 mg/kg annually with large reductions associated with area-wide removal efforts. In contrast to the individual yard soil exposure variable, significant changes in the mean 200-foot radius *neighborhood soil exposure* (NEIGH200) are noted throughout the last decade. Site-wide, significant differences in neighborhood concentrations occurred in every year except 1993–1995. In 1994–1996, remedial efforts concentrated in Smelterville where a significant reduction from a geometric mean of 1006 mg/kg to 150 mg/kg was achieved ($p=0.0001$).

Geometric mean *house dust exposures* (DUST) for Smelterville are illustrated in Fig. 3 and site wide in Table 2. Historic house dust samples were obtained from the resident's vacuum cleaner and are only from homes occupied by children. As a result, these concentrations may not be representative of all homes in the community. House dust lead exposures in Smelterville and Kellogg have decreased more than 50%, from means in the 1200–1800 mg/kg range in 1988–1990, to approximately 400–500 mg/kg in 1999. Most of the decrease seems to have occurred from 1990 to 1992, with gradual, but continuing, decreases noted through 1996. House dust lead concentrations are correlated with all three soil variables and decrease as the residential yards, rights-of-way, and commercial properties soil cleanup progresses. The variety of sources and mitigating factors affecting house dust lead levels makes it more difficult to identify and assess significant changes in exposures. Year-to-year differences are not as pronounced as those for soil exposures. A more gradual decrease has occurred in house dust lead content during the course of remediation. For successive years, only 1991–1992 and 1993–1994 showed a significant difference in site-wide levels with the effect most apparent in Kellogg. The site-wide overall decrease for the decade for house dust lead was highly significant ($P=0.0001$) with more than 50% reduction in mean concentrations accomplished since 1990. Similarly the decade-long reduction for each of the other soil variables was significant at the $P=0.0001$ level.

3. Remedial effectiveness analysis

3.1. Representativeness of the database

Prior to and during the entire health intervention and Superfund effort, an extensive database has been maintained that relates children's blood lead levels, media contaminant concentrations, environmental exposures, health intervention and remedial activities on an individual basis. The database contains individual medical, health, and property information, and is maintained as confidential health records. Only summary and non-confidential data are released publicly. This database has been used to track remedial progress and health response through the course of the cleanup. The relationship between blood lead, soil, and dust lead levels and the effectiveness of the remedial actions at the BHSS were examined by a variety of techniques in the 5-year review for the BHSS. These methods were suggested by a number of contributors and the analyses accomplished were a collaborative effort (TerraGraphics, 2000a). Some of these techniques are data intensive and sensitive to experimental design and variable distribution assumptions underlying the models. The surveys providing the data were not experiments and were not specifically designed to accommodate the analysis techniques applied. Caution should be exercised in reviewing the results. The cleanup was targeted, remediating priority homes of the youngest children with highest exposures and blood lead levels first. The soil exposure variables used to track remedial progress are correlated. The biological data are obtained from the annual blood lead surveys of the LHIP. These blood lead samples are solicited for the expressed purpose of identifying individual children with high blood lead levels. The objective is to obtain a sample from as many at-risk children as possible, particularly among the socio-economically disadvantaged portion of the population by paying $20 to each child providing blood. These children are identified in a confidential manner and provided follow-up services designed to effect blood lead reductions. It is neither a random sample nor a controlled solicitation. The program is strictly voluntary because earlier surveys identified as academic or experimental studies met with local opposition and reduced participation. Compelling testing would involve special legislation or application of child abuse laws. Any participation bias introduced is through self-selection by the population.

The potential for self-selection bias was examined in 1998 and the degree of participation and parental reasons for refusing on behalf of their children are summarized in Table 3. Detailed analysis of school records for 1988–1998 indicate that the door-to-door surveys identified 73% of all 9-month through 9-year-old children. Approximately two-thirds of these children participated in the LHIP. This resulted in the LHIP obtaining samples from 50% of the total population estimated from school records, or 68% of those actually identified in the door-to-door effort. Refusals have increased in recent years as environmental exposure, blood lead levels, and the number of children at-risk have declined (pers. comm. School Districts 391, 392, 393, 1999). The surveyors' notes were reviewed and the parents' reasons for refusal categorized into common responses. Over the last decade, 5 basic reasons were given for non-participation. Some parents indicated that their children exhibited low levels in past tests and see no reason to secure another sample. This reason applied to 5 to 11 children per year through 1995. Since 1996, this number has increased significantly to as many as 26 children in 1998. Many parents are concerned with the trauma associated with a venous blood lead draw and do not want to subject their children to this procedure. The number of children refusing for trauma reasons has varied from 7 to 24 children per year. Over the 10-year period, parents of from 19 to 81 children per year have indicated that the LHIP and/or blood lead testing is no longer necessary. Many residents state the opinion that these efforts are government overreaction to relatively minor contamination problems. The number of refusals attributed to this reason increased to 81 children in 1998.

These results suggest that the LHIP successfully tests more than half the at-risk population each year. Each year approximately half of the participating children have blood lead measurements from the previous year indicating that substantially more than half the total population has been tested at least once. Those children not identified in the summer surveys likely relocated since the school year ended and their exposure profile is unknown. The majority of those refusing to participate indicate they are informed and cognizant of the problems, and believe their children have low levels due to past testing or limited or insignificant exposures. This suggests that any participation bias that may have occurred is likely toward higher blood lead levels. As a result, this database is large enough and sufficiently representative of the population to support analysis of the blood lead to soil/dust lead relationship and the effectiveness of the remedial actions.

Table 3
Summary of participation rates for the annual blood lead survey, 1988–1998

Year	Estimated eligible population	Total number of children identified in survey	Number of children repeating participation from the previous year	Percent of identified population providing samples	Total number of survey refusals	Number of identified children from the eligible population that refuse participation				
						Reasons				
						PREVTESTED	TRAUMA	UNNECESS	REFUSAL	SHRTABSNT
1988	n/a	344	n/a	67%	63					
1989	n/a	373	105	74%	58					
1990	871	556	139	65%	111	8	16	39	33	15
1991	833	536	197	68%	121	8	22	36	36	19
1992	807	595	201	70%	127	11	11	69	12	24
1993	771	633	224	70%	144	5	24	27	58	30
1994	767	550	216	76%	81	10	18	26	10	17
1995	762	617	206	66%	148	8	7	22	96	15
1996	769	571	205	70%	114	20	14	49	21	10
1997	770	470	162	72%	85	20	13	19	27	6
1998	729	641	172	59%	165	26	17	81	26	15
1990–1998 avg.		73%	49%	68%	21%					

PREVTESTED = child was previously tested, and parents did not feel it was necessary again. TRAUMA = child had a bad experience with needles/doctors/etc., and parents did not want to subject child to testing. UNNECESS = parent did not feel program was necessary. REFUSAL = parent did not express specific reason. SHRTABSNT = family had only been in area a short time, or were moving out of area soon. n/a = no data available.

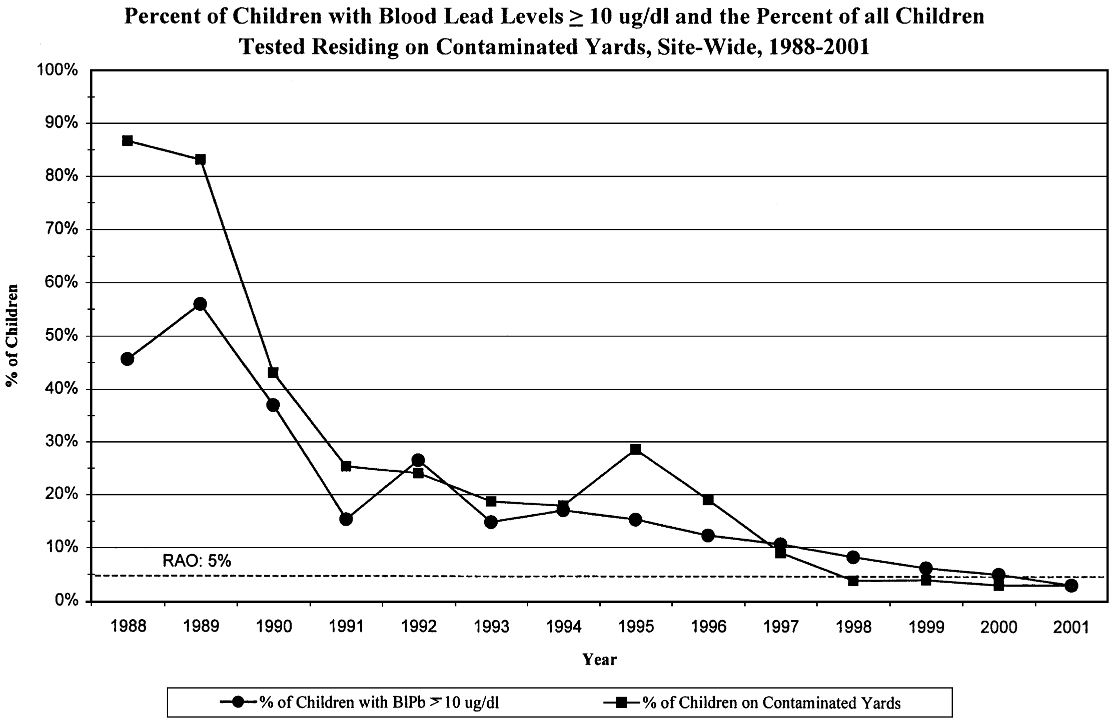


Fig. 4. Percent of children with blood lead levels > 10 μg/dl and the percent of all children tested residing on contaminated yards, site-wide, 1988–2001.

3.2. Excessive blood levels and children on contaminated yards

A correspondence has long been noted between the incidence of high blood lead levels and the percentage of children found living on contaminated yards as shown in Fig. 4. Understanding this relationship is critical to evaluating remedial effectiveness at the BHSS. Table 2 shows the progress in reducing soil exposures and the percentage of children living on contaminated yards above the action level at the time of each survey. Remediation status for each year is updated after the blood lead survey. As a result, the values in Table 2 and Figs. 3 and 4 reflect children whose exposures were reduced by living on yards remediated at least one year earlier. Prior to the yard remediation program (1988–1989), more than 80% of children site-wide were living on yards above the 1000 mg/kg action level. In 1990 and 1991 that number was decreased to 43% and 25%, respectively. From 1992 to 1996 the percentage of children living on contaminated yards fluctuated from 18% to 29%, despite remediation of an additional 551 homes in the community including all of those identified as children's residences during the preceding annual survey. Following area wide cleanups after 1996, significant progress was again achieved with less than 4% of children on contaminated yards by 1999.

A complicating factor in securing yard soil exposure reductions was associated with the low-income population's mobility and short-term residence status. Over the 11 years, 30% to 50% of all children in Kellogg resided at their current address less than one year. In-migration was particularly high in 1989 and from 1992–1995 as economic booms in an adjacent county forced many poor families to seek lower rents in the BHSS. Nearly 50% of the children were new to their homes each year and many parents were unaware of the contamination problems. Because the earlier remediation program focused on homes where children already lived, a significant portion of the newcomers moved onto contaminated yards, substantially increasing the total number of children at-risk in the community. For example, in 1995 59 children (or 50% of the 'newcomers') moved onto contaminated yards in Kellogg, more than in any year since 1989, increasing the percentage of children in high-risk homes from 18% to 29%, despite an additional 159 homes with children present being cleaned up in the interim. Considerable reductions in children on contaminated yards was achieved after 1996 when area-wide cleanups provided clean homes for newcomers. Site-wide, this percentage decreased from 19% in 1996, to 9% in 1997, to 4% in 1998. Only Kellogg had significant percentages of children on yards exceeding 1000 mg/kg lead since 1996 (27% in 1996, 13% in 1997 and 6% in 1998) (TerraGraphics, 2000a).

3.3. Assessing blood lead effects through linear regression analysis

Backward selection, step-wise multiple regression was applied with various combinations of attributes, exposure and log-transformed variables, including imputed variables to address missing house dust observations. Previous studies have noted the absence of a vacuum cleaner as an important risk co-factor. MISSDUST is a dummy variable equal to 0 if a vacuum bag dust sample is present and 1 if missing. DUSTIMP is the imputed dust lead concentration for homes with missing values. If a dust sample was present, DUSTIMP assumes that concentration value (DUST). If the sample was missing, DUSTIMP assumes the geometric mean house dust concentration for the community and year that the blood lead was drawn (Walter et al., 1980). The selected final model is presented in Table 4a. Age, log transformed house dust, individual yard soil, neighborhood (within 200-foot radius) and community soil lead concentrations all remained significant ($P<0.0001$, $R^2=0.22$–0.24) against both log transformed and untransformed blood lead levels. Dust lead concentrations best contribute as the log transformed imputed variable (LNDUSTIMP). Transforming soil lead variables added little to model or parameter significance, but was used to normalize the distribution (LNSOPOST). Log transforming-dependent blood lead showed little increase in R^2.

Age-specific effects were assessed by developing age group interaction terms for each independent variable and subsequently removing non-significant interactions from the model. Examination of the results summarized in Table 4b suggests significant age-specific responses for the source variables. Both models show a non-significant intercept. Age remains significant with a slope indicating approximately a 0.4 μg/dl per year decrease for children with constant exposure. The log of house dust lead is the most significant variable for all age groups with slope values translating to approximately 0.9 μg/dl blood lead per 1000 mg/kg dust lead in the range of concentrations observed at the site. The variable MISSDUST does not vary greatly with age and suggests a 0.6 μg/dl higher blood lead level in homes without a vacuum cleaner. The community soil concentration variable, GCITSOMN shows a slope value of approximately 1.5 μg/dl per 1000 mg/kg, peaking at 2.0 μg/dl per 1000 mg/kg for AGEGROUP5–6 and decreasing to 1.1 μg/dl per 1000 mg/kg for older children. For neighborhood soils, the slope is approximately 1.0 μg/dl per 1000 mg/kg for the youngest age group, and near 0.7 μg/dl per 1000 mg/kg for the 3 older age groups. The yard soil variable is not significant for the youngest or the oldest age groups, but shows slopes of 0.3–0.4 μg/dl per 1000 mg/kg for 2–6-year-old children. These age specific effects could reflect the importance of indoor exposures and the soil to house dust pathway for younger children shifting toward soil as they grow older, or could be artifactual due to the intercorrelation among these sources. Reported literature slope factors values describing the relationships between environmental lead concentrations and body lead burdens in young children range from 0.6 μg/dl to 15.5 μg/dl per 1000 mg/kg (Angle et al., 1984; Brunekreef, 1984; Bornschein et al., 1985, 1986; US Environmental Protection Agency, 1986; Laxin et al., 1987; Derosa et al., 1991; Xintaras, 1992; Weitzman et al.,

Table 4
(a) Log-transformed imputed dust model form and (b) Log-transformed dust model form

(a)
Dependent variable: BLPOST
$R^2 = 0.222$ ($P < 0.0001$)

Parameter	Estimate	Pr > F	Standardized estimate
Intercept	0.131	0.8770	0.000
AGE	−0.471	0.0001	−0.254
LNDUSTIMP	0.811	0.0001	0.112
MISSDUST	0.654	0.0001	0.068
LNSOPOST	0.238	0.0001	0.071
NEIGH200	0.736	0.0001	0.135
GCITSOMN	1.514	0.0001	0.175

AGE	Child age
LNDUSTIMP	Imputed log transformed dust concentration (mg/kg)
MISSDUST	Missing vacuum sample indicator (unitless)
LNSOPOST	Log transformed yard soil lead concentration
GCITSOMN	Geometric mean city soil lead concentration
NEIGH200	Geometric mean yard soil lead concentration within a 200-foot radius

(b)
Log-transformed dust model form
Dependent variable: BLPOST
$R^2 = 0.233$ ($P < 0.0001$)

Parameter	Estimate	Pr > F
Intercept	1.324	0.1369
AGE	−0.413	0.0001
LNDUSTIMP*AGEGROUP0–1	0.701	0.0001
LNDUSTIMP*AGEGROUP2–4	0.740	0.0001
LNDUSTIMP*AGEGROUP5–6	0.703	0.0001
LNDUSTIMP*AGEGROUP7–9	0.823	0.0001
AGEGROUP0–1*GCITSOMN	1.576	0.0097
AGEGROUP2–4*GCITSOMN	1.857	0.0001
AGEGROUP5–6*GCITSOMN	1.965	0.0001
AGEGROUP7–9*GCITSOMN	1.132	0.0003
MISSDUST	0.615	0.0001
AGEGROUP0–1*NEIGH200	0.978	0.0089
AGEGROUP2–4*NEIGH200	0.674	0.0003
AGEGROUP5–6*NEIGH200	0.729	0.0024
AGEGROUP7–9*NEIGH200	0.660	0.0004
AGEGROUP2–4*SOILPOST	0.367	0.0001
AGEGROUP5–6*SOILPOST	0.276	0.0076

AGE	Child age
LNDUSTIMP	Imputed log transformed dust concentration (mg/kg)
MISSDUST	Missing vacuum sample indicator (unitless)
GCITSOMN	Geometric mean city soil lead concentration
NEIGH200	Geometric mean yard soil lead concentration within a 200-foot radius
SOILPOST	Yard soil lead concentration (mg/kg)
AGEGROUP	Years

1993; Aschengrau et al., 1994; Burgoon et al., 1995; Lewin et al., 1999). The BHSS analysis suggests from 0.3 to 2.5 μg/dl per 1000 mg/kg for the yard, neighborhood and community soil sources. These results are additive in this model form and result in an overall ratio of near 4.0 μg/dl per 1000 mg/kg lead in soil, and coincide with the lower range of reported literature values.

3.4. Assessing intervention effectiveness through mixed models group effects analysis

Mixed model regression analysis examines both fixed and random effects among different treatment schemes. Mixed models are typically applied to several types of data sources including designed experiments, sampling surveys, and observational studies (Littell et al., 1996). These models were applied to assess repeat measures of blood lead levels acquired in the course of the LHIP. Many of the differences among children are controlled if the same child (corrected for age effects) is examined from year to year, and any blood lead changes related to modifications in that particular child's environment can be examined. For the initial analysis, the population of individuals that had repeat blood observations in consecutive years was divided into three treatment groups, based on specific actions undertaken in the previous year. The groups were REM (remediated)—those who received home yard remediation, INT (intervention)—those receiving LHIP intervention services and CTL (control)—the no-action group. Each group was divided by year as indicated by the suffix -PRE (preceding year) and -POST (survey year). Each group was examined by year for changes between PRE and POST blood lead levels and for differences between PRE and POST changes.

Table 5a,b summarizes results for the years 1988–1989 to 1997–1998. The combined results, shown in the bottom row of each table, suggest for the entire period that there was a significant PRE and POST blood lead difference for each of the groups. The differences in the PRE and POST levels were also significantly different from each other. The no-action CTL group decreased by a mean of 0.4 μg/dl, the REM group by 2.5 μg/dl and the INT group by 4.8 μg/dl. The REM group decrease exceeded the CTL group decrease by 2.1 μg/dl and the INT group decrease exceeded the CTL group by 4.4 μg/dl. All of the differences were significant at the $P=0.0001$ level. For the *No-action CTL Group*, blood lead levels decreased from a high of 11.8 μg/dl in 1989 to 4.5 μg/dl in 1998. The CTL group did not receive direct intervention or home-specific remediation services in that year. This group, however, is a beneficiary of remediation in other years, the community-wide and neighborhood reductions in exposure associated with cleanup activities and other unrelated exposure decreases. The *Remediation REM Group* are those children whose yards were replaced in the summer of the REMPRE year and have spent one year on the new soils. Generally, both PRE and POST blood lead levels were higher in the REM group vs. the no-action CTL children. This increase is likely due to the selection bias toward younger children on high lead soils, particularly in the earlier years. Significant decreases ($P<0.05$) in blood lead levels for the REM group were greater in the early years, i.e. 3.2 μg/dl to 4.6 μg/dl in 1989–1993 and 1.3 μg/dl to 2.3 μg/dl in 1994–1998. A significant increase was noted in 1993–1994 (1.6 μg/dl) when few homes were remediated. Blood lead changes in the REM group were significantly different from the CTL group, approximately 1.0 μg/dl greater for most years with *P*-values near 0.05. For the *Intervention INT Group*, both PRE and POST intervention blood lead levels are much higher in comparison to other groups. Decreases in PRE and POST blood lead levels are substantial and ranged from 12 μg/dl to 15 μg/dl in the period 1988–1992, but only represented six children. Notably smaller but significant effects, i.e. 2.0 μg/dl to 6.0 μg/dl, have been observed since 1993. In all cases, these changes are significant both within and among groups.

The decrease in the PRE and POST blood lead change for the INT group observed in 1993 is due to both decreasing absorption levels associated with age and exposure reductions and modifications in the intervention trigger level. As the remedial program proceeded, both environmental exposures and absorption decreased and fewer

Table 5
Summary of annual blood lead change and group differences by year and treatment group. (a) Pre and post blood lead levels (μg/dl) and (b) Blood lead differences in group means by year (μg/dl)

(a) Survey year	Control					Intervention					Remediation				
	N	Preceding year	Survey year	Difference	*P*-value	*N*	Preceding year	Survey year	Difference	*P*-value	*N*	Preceding year	Survey year	Difference	*P*-value
1989	103	9.9	11.8	−1.9	0.0001	2	32.5	20.0	12.5	0.0001	---	0.0	0.0	---	---
1990	78	10.2	8.9	1.3	0.0137	1	28.0	16.0	12.0	0.0091	54	15.3	10.7	4.6	0.0001
1991	134	9.1	6.4	2.6	0.0001	---	0.0	0.0	---	---	63	10.0	6.3	3.6	0.0001
1992	175	6.5	7.1	−0.6	0.0321	3	24.3	9.0	15.3	0.0001	22	9.7	10.4	−0.7	0.4032
1993	182	7.0	5.1	1.8	0.0001	10	19.0	13.3	5.7	0.0001	30	10.4	7.2	3.2	0.0001
1994	184	5.3	5.7	−0.4	0.0385	11	15.2	11.2	4.0	0.0001	19	6.4	8.1	−1.6	0.0072
1995	176	5.4	5.0	0.3	0.0511	14	14.6	11.4	3.1	0.0001	15	6.7	5.3	1.3	0.0286
1996	170	5.2	4.8	0.3	0.0992	16	14.3	10.7	3.7	0.0001	17	9.4	7.9	1.5	0.0151
1997	145	5.2	4.8	0.4	0.0289	9	14.3	10.4	3.9	0.0001	8	7.3	5.0	2.3	0.0017
1998	155	4.8	4.5	0.3	0.1398	7	13.4	9.3	4.1	0.0001	10	7.3	5.7	1.6	0.0207
Overall 1989–1998	Total	6.5	6.1	0.4	0.0001	Total	16.1	11.3	4.8	0.0001		10.5	7.9	2.5	0.0001

(b) Year	Remediation vs. Control		Intervention vs. Control		Remediation vs. Intervention	
	Estimate	*P*-value	Estimate	*P*-value	Estimate	*P*-value
1989	---	---	14.4	0.0001	---	---
1990	3.3	0.0001	10.7	0.0203	−7.4	0.1062
1991	1.0	0.0909	---	---	---	---
1992	−0.1	0.9456	16.0	0.0001	−16.0	0.0001
1993	1.3	0.0506	3.8	0.0013	−2.5	0.0569
1994	−1.2	0.0528	4.4	0.0001	−5.6	0.0001
1995	1.0	0.1190	2.8	0.0001	−1.8	0.0389
1996	1.2	0.0676	3.3	0.0001	−2.1	0.0197
1997	1.9	0.0102	3.5	0.0001	−1.6	0.0931
1998	1.3	0.0593	3.9	0.0001	−2.5	0.0183
Overall 1989–1998	2.1	0.0001	4.4	0.0001	−2.3	0.0001

---=data not available.

Table 6
Population percentile for the LHIP intervention level and effective intervention level by year 1992–1998

Year	Blood lead geomean (μg/dl)	GSD	Calculated percentile of intervention level	Actual percent of children above intervention level	Effective intervention level* (μg/dl)	Percentile of effective intervention level
1992	6.5	1.64	95%	7%**	20	99%
1993	4.4	2.10	86%	15%	15	95%
1994	5.1	1.84	86%	17%	14	94%
1995	5.0	1.87	86%	15%	13	93%
1996	4.7	1.85	88%	12%	10	89%
1997	4.5	1.84	90%	12%	11	93%
1998	4.0	1.86	93%	8%	11	93%

** Intervention level = 15 μg/dl in 1992, 10 μg/dl in subsequent years.
* The effective intervention level is that blood lead concentration above which the change in blood lead is significant at the $P<0.01$ level.

children exhibited extremely high blood lead levels. Also, the declining trigger level for intervention resulted in many more children receiving home visits. Prior to 1993, children receiving intervention at the 20 μg/dl to 25 μg/dl trigger levels represented the upper 5th percentile of the blood lead distribution. The change in the intervention trigger to 15 μg/dl in 1992 and to 10 μg/dl in 1993 increased the number of home visits by an order of magnitude and resulted in children as low as the 85th percentile receiving home visits. This protocol resulted in both a substantial reduction in INTPRE blood lead levels and the degree to which successful intervention can reduce absorption.

This procedure also complicates the group analysis because most of the children experiencing higher rates of absorption (i.e. $>85^{th}$ percentile) are removed from the CTL and REM groups and are counted in the INT group for these later years. This restricts the range of response for the latter groups in subsequent analysis. To compensate for this problem, several additional runs of the initial model were accomplished using progressively restrictive definitions of intervention for the years following 1993. Successive runs incrementally sub-divided the INT group by blood lead levels, and examined these sub-groups for significant differences in blood lead decreases between the intervention (INT) and control (CTL) populations. The results of this sub-analysis, summarized in Table 6, show that intervention had no detectable effect below the 93rd percentile of the blood lead distributions for all but one year. Based on these results, the effectiveness levels noted in the above definition were used in this analysis for inclusion in the intervention group. Children who received both intervention and remediation were classified REM group children in the following tables if their blood lead level was less the effective intervention level. Alternative classification schemes were also analyzed.

These results suggest that intervention, although demonstrably beneficial in reducing total absorption, may only be effective for children in the tail of the distribution, or approximately the 5–10% highest children. This may be because these children are particularly vulnerable to excess absorption as they engage in atypical behaviors, are exposed to extreme sources, or experience high absorption rates due to nutritional or physiological pre-disposition. These factors can be identified and corrected with an effective intervention protocol and blood lead levels can be reduced to below the effective intervention blood lead level. However, these techniques may not be permanently protective of children with blood lead levels below the 90–95th percentile. These children's behaviors and pre-disposition are more typical, less prone to modification and are responding to more common environmental source concentrations and loadings. Although intervention may be successful in reducing extreme responses, it remains a secondary measure requiring identification and investigation

Table 7
(a) Exposure model coefficients and treatment group differences, combined data 1988–1998, imputed dust and (b) Age-specific exposure model coefficients and treatment group differences, combined data 1988–1998, imputed dust

(a) All Years: 1988–1998 Effect	Estimate	Pr>|t|
CTLPRE	3.402	0.0001
CTLPOST	3.661	0.0001
INTPRE	12.089	0.0001
INTPOST	8.315	0.0001
AGE	−0.397	0.0001
SOILPOST	0.311	0.0001
LNDUSTIMP	0.296	0.0035
REMPRE	5.673	0.0001
REMPOST	4.980	0.0001
GCITSOMN	2.266	0.0001
NEIGH200	0.612	0.0001
MISSDUST	0.416	0.0003
Differences		
PRE–POST CONTROLS	−0.259	0.0102
PRE–POST INTERVENTION	3.773	0.0001
PRE–POST REMEDIATION	0.693	0.0082
REM vs. CTL	0.952	0.0006
CTL vs. INT	−4.032	0.0001
REM vs. INT	−3.080	0.0001

(b) All Years: 1988–1998 Effect	Estimate	Pr>|t|
CTLPRE	3.583	0.0001
CTLPOST	3.786	0.0001
INTPRE	12.348	0.0001
INTPOST	8.454	0.0001
AGE	−0.440	0.0001
SOILPOST*AGEGROUP0–1	0.204	0.2433
SOILPOST*AGEGROUP2–4	0.461	0.0001
SOILPOST*AGEGROUP5–6	0.177	0.0516
SOILPOST*AGEGROUP7–9	0.251	0.0034
AGEGROUP0–1*LNDUSTIMP	0.154	0.2591
AGEGROUP2–4*LNDUSTIMP	0.234	0.0285
AGEGROUP5–6*LNDUSTIMP	0.285	0.007
AGEGROUP7–9*LNDUSTIMP	0.416	0.0001
AGEGROUP0–1*GCITSOMN	2.112	0.0072
AGEGROUP2–4*GCITSOMN	3.013	0.0001
AGEGROUP5–6*GCITSOMN	2.493	0.0001
AGEGROUP7–9*GCITSOMN	1.328	0.0001
REMPRE	5.889	0.0001
REMPOST	5.134	0.0001
AGEGROUP0–1*NEIGH200	0.910	0.0381
AGEGROUP2–4*NEIGH200	0.375	0.0141
AGEGROUP5–6*NEIGH200	0.730	0.0006
AGEGROUP7–9*NEIGH200	0.828	0.0001
MISSDUST	0.415	0.0003
Differences		

Table 7 *(Continued)*

(a) All Years: 1988–1998 Effect	Estimate	Pr>|t|
PRE–POST CONTROLS	−0.203	0.0460
PRE–POST INTERVENTION	3.895	0.0001
PRE–POST REMEDIATION	0.755	0.0043
REM vs. CTL	0.958	0.0006
CTL vs. INT	−4.098	0.0001
REM vs. INT	−3.140	0.0001

AGE, child age; LNDUSTIMP, imputed log transformed dust concentration (mg/kg); MISSDUST, missing vacuum sample indicator (unitless); GCITSOMN, geometric mean city soil lead concentration; NEIGH200, geometric mean yard soil lead concentration within a 200 foot radius; SOILPOST, yard soil lead concentration (mg/kg); CTL, control blood lead level (μg/dl); INT, intervention blood lead level (μg/dl); REM, remediation blood lead level (μg/dl); PRE, preceding year; POST, survey year.

of children already experiencing excessive lead absorption. Preventing excessive blood lead levels for an exposed population requires source control.

3.5. Assessing remedial effectiveness through mixed model exposure analysis

The effects of the decreasing exposures (and other significant co-factors) on blood lead levels were examined by combining all the years' PRE and POST observations into a single data set and adding exposure and co-factor variables to the model. Several combinations were examined by individually adding and deleting specific variables to evaluate potential co-linear effects among the soil exposure measurements. Table 7a shows addition of the age, dust and soil exposure variables to the mixed model. Addition of the yard soil variable SOILPOST results in decreases to all the blood lead estimates and the difference for the REM group. This suggests that changes in all group blood lead levels are partially explained by changes in yard soil lead concentrations and that a substantial portion of the remedial effect is reflected in the reduced soil lead levels. Addition of either the community mean soil lead variable or the house dust lead variables substantially decreases both groups PRE and POST blood lead estimates but does not greatly affect the difference in REMPRE and REMPOST levels. This indicates a strong correlation between house dust and community mean soil lead levels and a strong influence of either (or both) on blood lead levels. Addition of the neighborhood soil variable NEIGH200 diminishes the effect of the community soil variable in both the model forms.

Inclusion of the transformed imputed house dust variable (LNDUSTIMP) also tends to reduce the no-action group's PRE and POST blood lead estimate to what could be considered background levels. Inclusion of the AGE variable decreased the difference between PRE and POST no-action CTL blood lead levels to non-significance. Age shows approximately a 0.4 μg/dl decrease in lead levels per year. Other significant variables that were included in the imputed dust model were the missing vacuum cleaner sample indicator (MISSDUST). Children from homes that could not supply a vacuum sample had blood lead levels approximately 0.4 μg/dl higher than those from homes with vacuums (all other factors being equal). For the imputed dust model, slope coefficients for dust were slightly decreased to 0.30. The slope for the yard soil variable increased to 0.31 and to 2.3 for community soil. The neighborhood soil coefficient decreased to 0.61. The difference between decreases in the REM and CTL groups (1.0 μg/dl) was significant at the $p = 0.0006$ level for the model with imputed dust, indicating an independent effect of remediation after accounting for changes in age, house dust, and yard, neighborhood and community soil lead levels.

Age-specific exposures were developed for the soil and dust variables by creating interaction variables for specific age-groups (i.e. 0–1 years, 2–4 years, 5–6 years and 7–9 years) in Table 7b. Both the yard soil and house dust variables were significant in the model for particular age groups. Non-significant age groups were deleted from the variable selection procedure. The neighborhood soil effect is strongest in the youngest and oldest age groups (0.9–0.8 μg/dl per 1000 mg/kg), whereas the community mean soil lead is strongest in the middle age groups (2.5–3.0 μg/dl per 1000 mg/kg). However, the co-linearity of these variables likely affects these coefficients. The coefficient for LNDUSTIM is non-significant with the youngest group and shows similar results for older age categories (0.4 μg/dl per 1000 mg/kg). MISSDUST shows a constant effect of 0.4 μg/dl. Yard soil SOILPOST shows peak effect at ages 2–4 years of 0.46 μg/dl per 1000 mg/kg, is not significant for ages 0–1 years, and shows lower and marginally significant values of half the peak for older children. The no-action CTL group shows marginally significant difference PRE and POST, suggesting that the age and exposure variable additions account for the difference seen in the original model form. PRE and POST intervention (INT) group blood lead levels continue to show a difference of 3.9 μg/dl as opposed to 4.8 μg /dl in the original group comparisons model. This suggests that some portion of the original estimated decrease is accounted for by age and environmental exposure changes accomplished through remediation, with 80% of the decrease independently attributable to intervention. For the remediation REM group, originally a 2.5 μg/dl difference between the REM group and no-action CTL group was noted. After accounting for decreases in exposure, the independent effect of remediation remains at approximately 1.0 μg/dl ($p = 0.0043$).

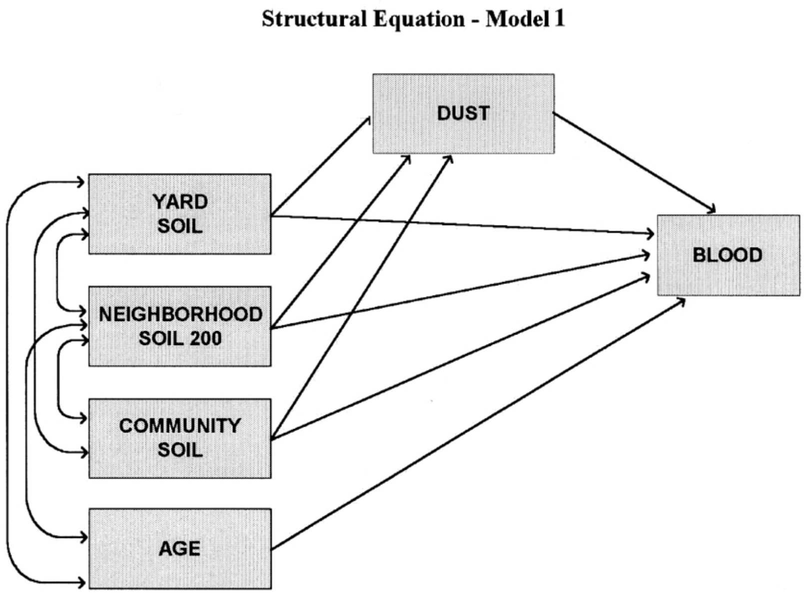
Although the results may be confounded by the co-linear aspects of the soil variables, the general effect of the remediation effort on children's blood lead can be assessed by substituting typical pre- and post-remediation values for the exposure and co-factor variables. Using the imputed dust model, this analysis suggests that the yard remediation has an independent effect of reducing absorption by 1.0 μg/dl over the entire effort. There was also the direct effect of reducing the individual yard soil exposure from a typical lead concentration of near 1700 mg/kg to 200 mg/kg. This home-specific effect also decreased blood lead absorption by approximately 0.7 μg/dl for a typical 2-year-old child. In addition, there are indirect effects of the remediation manifested in lower neighborhood and community soil and consequent house dust exposures. By the imputed dust model, these reductions were typically 0.6 μg/dl for neighborhood soil, 5.0 μg/dl for community soil, and 0.2 μg/dl for house dust, assuming a 900 mg/kg reduction in house dust concentrations. A 2-year-old child would have an additional 3.9 μg/dl reduction with the intervention effort. This suggests that the remediation effort (without intervention) has an overall effect of approximately 7.5 μg/dl in reducing a typical 2-year-old child's mean blood lead levels over the course of the last ten years. In this model form, approximately 1.7 μg/dl of the reduction is directly attributable to the individual yard remediation and approximately 5.6 μg/dl is achieved indirectly through community and neighborhood soil lead reduction. In turn, an additional 0.2 μg/dl is due directly to house dust lead reduction, aside from soil sources. These wider effects of the yard remediation program benefit all children in the community, regardless of their REM status, and account for the overall reductions in blood lead levels seen over the years in the no-action CTL group.

The mixed model form, however, fails to account for the pathways of lead to children and tends to diminish the effect of house dust lead on children's blood lead levels. Biokinetic model analysis and LHIP follow-up investigations continue to point out the importance of declining house dust levels to achieving acceptable blood lead levels. Studies at this and other sites have long-noted dust as a most significant source of lead to children (Yankel et al., 1977; Walter et al., 1980; Duggan, 1983; Duggan and Inskip, 1985; US Environmental Protection Agency, 1986; TerraGraphics, 1990; Fergusson and Kim, 1991; Stanek and Calabrese, 1992; Agency for Toxic Substances and Disease Registry Division of Health Studies, 1997; Lanphear and Roghmann, 1997; Stokes et al., 1998; Lanphear et al., 1998; Succop et al., 1998; Rao et al., 1999; Manton et al., 2000). Examination of historical dust lead data suggests that lead in dust at the BHSS is principally derived from the 3 soil sources (yard, neighborhood and community) and other sources including lead paint and residual lead in carpets and building structures (Panhandle Health District, 1986; TerraGraphics, 1987, 1990, 1997, 2000a). The mixed model analysis inherently ignores these pathways and attributes the blood lead reduction to the decreasing lead levels in the ultimate soil source. The soil sources are also correlated, requiring caution in interpreting the model coefficients. As a result, it is not possible in the mixed model form to distinguish between the effect of direct contact with these soils vs. that manifested through house dust.

3.6. Assessing source contributions through pathways analysis

The blood lead to soil and dust lead relationships can be further assessed through structural equations that can quantify the direct and indirect impacts of the remedial activities on house dust and subsequent blood lead levels. This is accomplished by constructing a series of simultaneous regression equations representing plausible pathways of lead in the child's environment. The model is not applied to the available data and examined as to whether it is a useful approximation of reality (Hatcher, 1994; Statsoft, 1999). The US Environmental Protection Agency (USEPA) and others have successfully used the technique to quantify lead pathways and abatement effects at other sites (US Environmental Protection Agency, 1996b; Succop et al., 1998). Two basic model forms were assessed as illustrated in Fig. 5. Each assumes that children access lead directly from the soils in their home yard and directly from other yards and soils in their community. Both of these sources combine through airborne and tracking routes to contribute to lead levels in dust within the home, that is another primary lead source for children. Two equations describe each of these models as shown in Table 8. Other variables or co-factors that moderate the degree of lead transfer along these pathways have been included. Not surprisingly, these are the same co-factors that showed significance in the linear regression and repeat measures mixed-model analysis.

However, there are some important differences to note in model construction for the structural equations application vs. the regression and mixed-model analysis. Structural equations modeling assumes that all variables are normally distributed as opposed to the typical regression analysis assumption of normally distributed residuals. As a result, the dependent variable blood lead and the independent variables representing neighborhood and community mean soil concentrations have been log-transformed, as were house dust and yard soils in the multiple regression analysis. For struc-



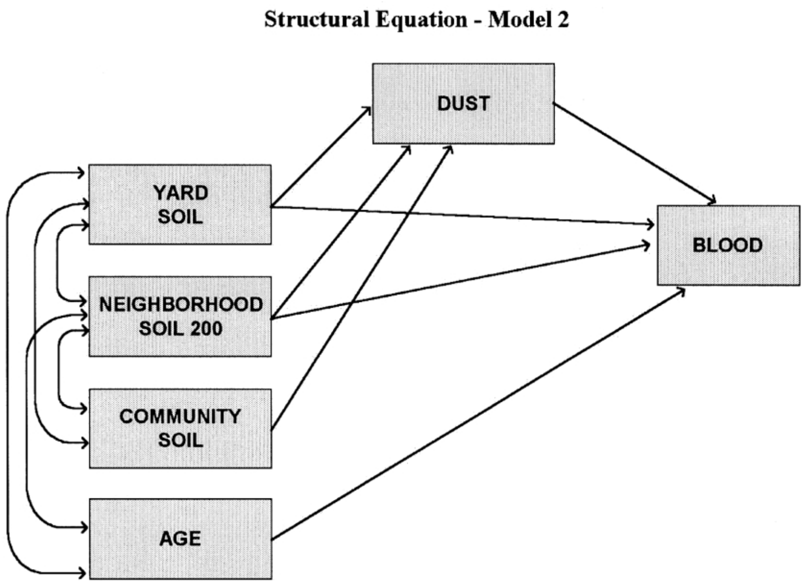


Fig. 5. Structural equation models 1 and 2.

Table 8
Structural equations models for blood lead and soil and dust pathways (Hatcher 1994)

Model 1					
Equation 1 dependent variable LNBLPOST					$R^2=0.892$, $n=1512$
Parameter	Estimate	Standard error (T-value)	Standardized estimate		Percent contributions
ERROR	1.000		0.329		
Intercept	−0.519	0.186 (−2.8)	−0.171		
AGE	−0.065	0.006 (−11.2)	−0.210		
LNDUST	0.159	0.019 (8.3)	0.597	42%	
LNSOPOST	0.051	0.011 (4.6)	0.171	12%	
LNSOIL200	0.067	0.024 (2.8)	0.267	19%	
LNCITSOMN	0.095	0.037 (2.6)	0.389	27%	
Equation 2 dependent variable LNDUST					$R^2=0.986$
Parameter	Estimate	Pr>t	Standardized estimate		Percent contributions
ERROR	1.000		0.117		
Intercept	3.237	0.233 (13.9)	0.487		
LNSOPOST	0.129	0.015 (8.7)	0.114	22%	
LNSOIL200	0.133	0.032 (4.1)	0.141	28%	
LNCITSOMN	0.235	0.049 (4.8)	0.256	50%	
Goodness of fit indices					
Largest standardized residual	Chi-square	P	CFI	NFI	NNFI
0.183	21.309	0.0001	0.9993	0.9993	0.9863
Model 2					
Equation 1 dependent variable LNBLPOST					$R^2=0.892$, $n=1512$
Parameter	Estimate	Pr>t	Standardized estimate		Percent contributions
ERROR	1.000		0.329		
Intercept	−0.206	0.143 (−1.4)	−0.116		
AGE	−0.064	0.006 (−11.1)	−0.208		
LNDUST	0.165	0.019 (8.6)	0.619		50%
LNSOPOST	0.051	0.011 (4.5)	0.171		14%
LNSOIL200	0.115	0.016 (7.3)	0.456		37%
Equation 2 dependent variable LNDUST					$R^2=0.986$
Parameter	Estimate	Pr>t	Standardized estimate		Percent contributions
ERROR	1.000		0.117		
Intercept	3.237	0.233 (13.9)	0.487		
LNSOPOST	0.129	0.015 (8.7)	0.114		22%
LNSOIL200	0.133	0.032 (4.1)	0.141		28%
LNCITSOMN	0.235	0.049 (4.8)	0.256		50%
Goodness of fit indices					
Largest standardized residual	Chi-square	P	CFI	NFI	NNFI
0.183	27.9899	0.0001	0.9992	0.9991	0.9913

CFI, comparative fit index; NFI, normed fit index; NNFI, non-normed fit index; LNBLPOST, log transformed blood lead levels (μg/dl); LNDUST, log transformed vacuum dust lead concentration (mg/kg); LNSOPOST, log transformed yard soil lead concentration (mg/kg); LNSOIL200, log transformed mean yard soil lead concentration with a 200 foot radius (mg/kg); LNCITSOMN, log transformed mean city soil lead concentration (mg/kg); AGE, child's age.

Table 9
Estimated mean soil and dust lead intake and effective bioavailability 1988–1998

Year	Geomean blood lead (arithmetic mean) (μg/dl)	Geomean estimated soil and dust lead intake[a] (arithmetic mean) (μg/day)	Aggregate soil and dust effective bioavailability geometric mean (arithmetic mean)
1988	8.5 (9.9)	205 (248)	14% (17%)
1989	9.9 (11.4)**	196 (255)	17% (23%)
1990	7.8 (8.9)**	116 (139)**	18% (23%)
1991	5.5 (6.3)**	96 (110)*	17% (22%)
1992	6.5 (7.4)**	87 (99)	21% (26%)
1993	4.4 (5.6)**	75 (83)**	14% (21%)
1994	5.1 (6.2)**	67 (76)*	18% (24%)
1995	5.0 (6.0)	62 (74)	17% (23%)
1996	4.7 (5.8)	57 (68)	21% (30%)
1997	4.5 (5.4)	48 (65)*	22% (32%)
1998	4.0 (4.8)*	45 (53)	21% (30%)

[a] Assumes dust/soil intake is 42% housedust, 27% community soil, 19% neighborhood soil, 12% yard soil
* $P \leq 0.05$ significant change from previous year.
** $P \leq 0.001$ significant change from previous year.

tural equation analysis, only the raw dust model format is examined to avoid the use of imputed values. Also, the arithmetic mean neighborhood and community soil exposure variables are employed as these better represent an integrated exposure profile. That is, all sub-units in a neighborhood are equally accessed by children. Because these models require a relatively large number of observations, age-specific effects are not included and the results are reflective of the 9-month to 9-year population.

Examining the results for Model 1 in Table 9 suggests that the variable most influencing outcome blood lead levels is house dust. The relative magnitude of the standardized coefficients indicate that house dust accounts for approximately 42% of the soil and dust contribution to blood lead. Soils directly represent 58% of the soil/dust contribution with the community mean variable accounting for an estimated 27% and neighborhood and yard soils contributing 19% and 12%, respectively. The dust lead equation suggests that the soil contribution to house dust is approximately 50% from the community, 28% neighborhood and 22% yard. Overall, the pathways model indicates approximately 50% of the soil contribution to blood lead originates from throughout the community, approximately 30% in the neighborhood and 20% from the home yard. These results are consistent with the partition of soils and dusts used in devising the cleanup criteria for the site; i.e. that 40% of absorbed lead from soils and dust were due to house dust, 30% from community soils and 30% from the home yard. (Panhandle Health District, 1986; Jacobs Engineering Group Inc. et al., 1989; TerraGraphics, 1987, 1990; CH2M-Hill, 1991). This structural equation model estimates that pre-remedial soils accounted for more than 80% of lead in house dust and, by 1998, approximately 60% of dust lead was from soil.

Table 8 also shows the results for the alternate Model 2 pathways that deletes the direct contact with community-wide soils pathway for blood lead. The result is that 50%, as opposed to 42%, of blood lead effect is due to dust, with neighborhood soil contributing 37% vs. 19%, and yard soil 14% vs. 12%. The dust lead equation maintains the same relative percentage contribution from soils and select variable substitutions show similar predictions for pre and post-remedial and background conditions. Both models suggest the majority of pre-remedial blood lead levels were due to soil, including community-wide, neighborhood and home yard soils sources. Children's primary exposure was either through direct contact with these soils, or manifested through house dust, the single largest component of exposure. Although these results may be confounded by the co-linear nature of the soil variables, it seems clear that house dust has been the dominant source of lead to children, and will likely remain so in the post-remedial environment. Mean post-remedial concentrations are predicted to be between 350 mg/kg and 500 mg/kg. Analysis of dusts from similarly situated homes in Northern Idaho outside the mining district suggests that approximately 200–400 mg/kg of house dust lead is associated with sources other than soil, such as lead paint or residual contamination in structures and carpets (TerraGraphics, 2000a; Spalinger, 2000). As a result, it is expected that BHSS house dust lead concentrations will remain higher than non-mining areas, with the residual component unrelated to the soil sources assuming the role of the largest contributor in post-remedial conditions.

3.7. Lead intake, bioavailability and biokinetic modeling analysis

In addition to residential soil cleanup and intervention activities, other factors and site conditions have affected decreased soil, dust and blood lead exposures on the site. Remedial actions have been undertaken to stabilize sources outside the residential areas, and commercial and residents' activities have effected positive contributions. Natural soil building and revegetation processes have accelerated in many areas since smelter closure. Nationwide, mean blood lead levels for pre-school children dropped from 3.6 to 2.0 μg/dl over this time period (Pirkle et al., 1994, 1998; Centers for Disease Control, 2000). All of these factors have likely contributed to lowered exposures and absorption rates. The relative influence of soil-borne and other lead sources can be examined through intake rates and bio-kinetic analysis.

Soil and dust lead intake were estimated by multiplying soil and dust ingestion rates by the respective lead concentrations. This was accomplished for each child for each year assuming a typical combined soil/dust consumption rate of 100 mg/day partitioned by the 42% house dust/27% community-wide/19% neighborhood/12% yard soil partition suggested by the structural equations analysis. These intake rates, shown in Table 9 and Fig. 6, estimate how much lead a typical child ingested each day from soil and house dust for the 1989–1998 period. Fig. 6 contrasts mean intake and blood lead levels for 1989–1998 and helps to explain how blood lead levels have changed in response to soil cleanup activities. Lead intake and, consequently, blood lead levels decreased markedly in the first 3 years (1989–1991) of cleanup as most children's home yards were remediated in the high risk cleanup program. Significant site-wide reductions in estimated lead intake from soil and dust were achieved in 1989–1991 from near 200 μg/day to 96 μg/day with a corresponding 45% (4.4 μg/dl) drop in blood lead. In 1991–92, no significant decrease in intake was achieved and mean blood lead increased by 1.1 μg/dl. In 1992–1993 mean lead intake decreased to 75 μg/day and blood lead decreased significantly by 2.1 μg/dl. No significant change in intake was evident from 1994–1996, as children moved to contaminated homes on the site. Correspondingly, there was little change in mean blood lead levels during those same years. This stalemate was broken after 1996 as area-wide yard removals diminished the number of contaminated home yards and neighborhoods that families could move into. Intakes and blood lead levels have both gradually decreased to historically low levels since 1997.

The intake:blood lead relationship illustrated in Fig. 6 was used to estimate the aggregate bioavailability of soils and house dust. This was accomplished by estimating blood lead uptake by dividing observed blood lead levels by the Harley–Kneip age-specific coefficient for lead absorption after accounting for uptake from the other dietary, air and drinking water routes (Harley and Kneip, 1985). This analysis is similar to the methodology used to develop the soil cleanup criteria for the site in 1990. In that analysis, the reciprocal clearance coefficient for lead was used to estimate a site-specific bioavailability for soil and dust lead that was approximately half the USEPA recommended 30% default value (Jacobs Engineering Group Inc. et al., 1989; US Environmental Protection Agency, 1990; CH2M-Hill, 1991). In this

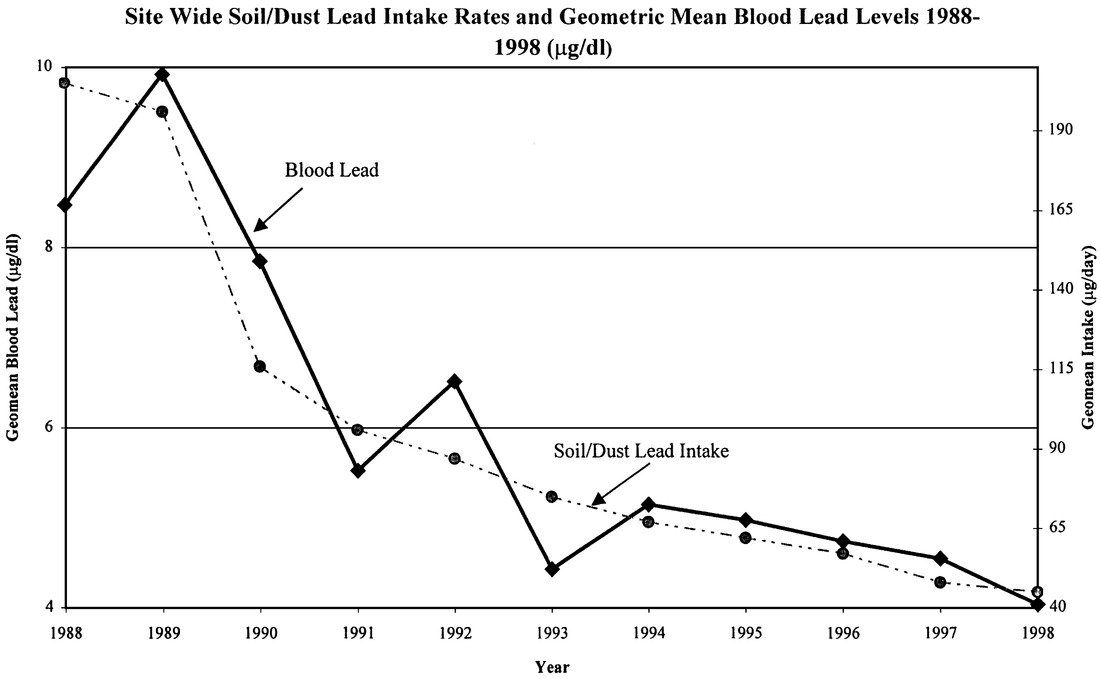


Fig. 6. Site wide soil/dust lead intake rates and geometric mean blood lead levels 1988–1998 (mg/dl).

case, age-specific soil and dust intake rates are estimated using default ingestion rates from the Integrated Exposure Uptake Biokinetic (IEUBK) model for lead and the soil/dust partition suggested by the structural equations analysis (US Environmental Protection Agency, 1994a,b). Table 9 summarizes estimated mean bioavailability for the years 1988–1998.

The geometric mean bioavailability was near 14% in 1988, ranged near 18% in the 1989–95 time period and has been approximately 21% since 1996. The initial value corresponds to the reduced bioavailability used in developing the cleanup criteria in 1990 and has since been noted for some mining-related wastes at other sites (Jacobs Engineering Group Inc. et al., 1989; Steele et al., 1990; TerraGraphics, 1990; CH2M-Hill, 1991; Mushak, 1991; Ruby et al., 1996; US Environmental Protection Agency, 1996a; Casteel et al., 1997; Henningsen et al., 1998; US Environmental Protection Agency, 1999a). The arithmetic mean value ranged from 18% to 22% from the beginning of the cleanup through 1995. Since 1996, arithmetic mean bioavailability has been near the default level of 30%. These results suggest that the slope of the relationship between blood lead and soil and dust lead may have increased as the cleanup progressed. In assessing the apparent change, it is important to remember that this analysis assumes the ingestion rates and underlying biokinetic relationships in the IEUBK model and attributes the change to increasing bioavailability. It should be emphasized that any change in the absorption rate could be due either to bioavailability or ingestion rate differences, or some combination of both. Three primary hypotheses for why the response rate may have increased as the cleanup proceeded are: (i) demographic changes in the population (i.e. increased soil and dust ingestion rates reflective of demographic and behavioral changes), (ii) changing biokinetic relationships at lower blood lead levels (i.e. lead biokinetics are not linear and ingested lead is more efficiently absorbed at lower concentrations) and (iii) changes in source characteristics (i.e., as the cleanup proceeds, the dominant sources change and differing chemical or physical characteristics affect ingestion or uptake rates).

The structural equations analysis adds support to the third hypothesis. These model results suggest that as the cleanup progressed, direct intake of soil lead decreased and the main pathway to children became increasingly dominated by the house dust route, and sources other than soil become greater relative contributors. These other sources may be paint or residual smelter contaminants that are more available, increasing aggregate bioavailability. There is little reason to suspect that there are significant differences in chemical or matrix effects between soils and house dust lead derived from those soils. However, there are reasons as to why house dusts would be more bioavailable to children than yard soils. House dust particles are smaller and more accessible to young children than soils. These dusts are available to children throughout the year, more readily adhere to hands, toys and personal items, and are more prone to absorption by the gut, all other factors being equal. As a result, increased bioavailability, increased dermal adherence, and increased ingestion rates are all possible explanations for the enhanced response rate. It is also possible that dust ingestion rates have increased as newcomers moved to the site and the effectiveness of the health intervention effort has diminished over the years. The marked difference in arithmetic and geometric mean bioavailability estimates suggests that some smaller number of children are responding at much higher rates. These higher response rates could be due to any number of physiological, nutritional, socioeconomic, or behavioral causes; or possibly, are artifactual due to unaccounted sources not included in the analysis.

3.8. Applying the IEUBK model for lead

The Integrated Exposure Uptake Biokinetic Model for lead (IEUBK) has been developed by the USEPA to predict blood lead concentrations and the probability that a child will exceed critical blood lead levels. The IEUBK is a four-component model linking exposure, uptake, biokinetic and probability distribution modules. Inputs include lead concentration and bioavailability for various media and age-weighted parameters for intake of food, water, soil and dust. The model simulates uptake, distribution and elimination of lead in the body and estimates mean blood lead levels. The probability distribution function estimates the likelihood of exceeding critical blood lead levels. The USEPA currently requires the use of this model in performing lead risk assessments and recommends default parameters that should be used in the absence of compelling site-specific information (US Environmental Protection Agency, 1994a,b,c, 1996a, 1998a,b, 1999a,b). Several applications were run using the existing blood lead environmental exposure database pairing children's observed blood, soil and house dust lead concentrations. Both the USEPA default and a site-specific version of the model were developed. In the default version, USEPA recommended parameters were used except for soil and dust lead concentrations. Observed house dust and yard soil lead values were used when available. For missing house dust values, the geometric mean house dust lead concentration for that community and year were substituted. Missing yard soil values were replaced with the geometric mean pre-remediation community-wide soil lead concentration. If both house dust and yard soil were missing, the observation was not included. Observations for 8- and 9-year-old children were assigned an age of 84 months to include the same population as the preceding analyses.

The site-specific application was developed using the 42% house dust, 27% community soil, 19% neighborhood soil, 12% yard soil partition and 18% bioavailability parameters suggested in the pathways and intake–absorption analysis. Missing dust lead observations were estimated using the dust lead structural equations model. All other parameters were the same as the default version. Table 10a summarizes site-wide predicted and observed blood lead levels, geometric standard deviations, and percent to exceed 10 μg/dl for the period 1988–1998 for all ages in the batch mode applications. The USEPA default model significantly over-predicted observed blood lead levels. However, as the residential soil cleanup progressed, the degree of over-prediction decreased consistent with the apparent change in dose–

Table 10
(a) Observed and predicted blood lead levels for the USEPA default and site-specific IEUBK model (geometric mean) and (b) Observed and predicted percent of children ≥10 μg/dl

Year	Observed	EPA default prediction	Site-specific prediction
(a) Mean blood lead levels 0–9-year-old children (μg/dl)			
1988	8.5	14.7	10.2
1989	9.9	14.6	10.2
1990	7.9	9.8	6.6
1991	5.5	8.2	5.9
1992	6.5	7.6	5.8
1993	4.4	7.0	5.5
1994	5.1	6.3	5.1
1995	5.0	6.8	4.9
1996	4.7	5.7	4.4
1997	4.5	5.3	4.1
1998	4.0	5.2	3.7
(b) Percent of Children with blood lead ≥10 μg/dl			
1988	46%	74%	51%
1989	59%	72%	51%
1990	37%	49%	27%
1991	16%	37%	20%
1992	27%	34%	19%
1993	15%	30%	16%
1994	17%	24%	13%
1995	15%	30%	12%
1996	13%	22%	10%
1997	11%	16%	7%
1998	8%	15%	5%

response rate. In 1988–1989, when estimated intake rates from soil and dust were near 200 μg/day, the effect was nearly 2-fold (i.e., 60–90% over-prediction). From 1990 to 1993, intake rates were in transition to 70–80 μg/day and there was 25–55% over-prediction. From 1994 through 1998, over-prediction ranged from 57% in 1995 to 7% in 1997. In other years, over-predictions were near 20%.

For the site-specific model, both predicted and observed levels decreased consistently with estimated soil and dust lead intake rates. The site-specific model inherently corrects for the apparent change in response rate by assuming a constant bioavailability approximately 1/3 lower than the default, and a partition rate more reflective of site-specific pathways than the default 55:45 dust:yard soil ingestion ratio. The site-specific dust:soil partition includes both neighborhood and community soil components in estimating intake rates, as opposed to the default reliance on the home yard as the soil exposure unit as recommended by the USEPA guidance (US Environmental Protection Agency, 1998b). It also reflects the progress in reducing concentrations in each of the three soil sources simultaneously as the cleanup progressed. As a result, the site-specific model reasonably predicts geometric mean blood levels across the site and for the entire cleanup period.

Table 10b shows predicted and observed percent of children to exceed 10 μg/dl. Because the USEPA default version significantly over-predicts mean blood lead levels, it also over-predicts the incidence of high blood lead levels. For the site-specific model, percent to exceed values are well predicted for all areas and all years prior to 1994. Since 1994, percent to exceed values have been slightly under-predicted. This result is not unexpected, as follow-up investigations of the highest blood levels observed in the later years of the cleanup, show that many are due to exposures unaccounted for in the model (e.g., recreational exposures from outside the site). Those children whose apparent greater response rates confound this analysis are, not coincidentally, those intensively evaluated by the LHIP follow-up program. Review of these children's histories since 1996, when suggested increases in effective bioavailability were noted, provides some insight regarding the potential sources of this variation. These histories show that the LHIP found the majority of these children are socio-economically disadvantaged, highly mobile, with care often provided in multiple locations among extended family or cooperative situations. These children tend to exhibit frequent hand-to-mouth activity and poor to fair personal and home hygiene. Most were also exposed to high concentration soil and dust sources in play areas or away from their home. These included relatives' and daycare yards in unremediated portions of Kellogg, hillsides, common areas surrounding particular housing complexes and debris from the 1996 flood. Extended recreational activities at contaminated locations and moving from contaminated homes outside of the BHSS has also been noted more frequently in recent years. Several children were noted to be in homes with relatively high dust concentrations. Some were indicated to be in homes with poor interior paint condition.

These observations suggest that individual high response rates are due to a number of factors. Frequent hand-to-mouth activities, poor personal and home hygiene, high house dust concentrations and any paint lead reflected in those dusts are all factors accounted for in the model analysis. Those factors related to sources outside the home environment, i.e., flood debris, hillsides, campgrounds, unremediated areas in Kellogg, and contaminated soils in the greater Coeur d'Alene Basin are conditions not accounted for in the model predictions.

4. Summary and conclusions

Efforts to reduce children's blood lead levels in the BHSS have been ongoing since the epidemic poisonings of the 1970s. A comprehensive cleanup and risk-reduction program was instituted in 1985 and residential area soil cleanup commenced in 1989. The Remedial Action Objectives (RAOs) for the BHSS included achieving post-remedial blood lead goals of 95% of children <10 μg/dl and <1% exceeding 15 μg/dl. This was to be accomplished by reducing individual home yard soil lead concentrations to <1000 mg/kg, reaching a community mean soil lead concentration $<$ 350 mg/kg, that would effect mean house dust lead concentrations <500 mg/kg. The strategy and cleanup criteria established in 1991 were based on site-specific analysis of years of blood lead survey and environmental contamination data using the IEUBK model.

Assessing compliance with soil and dust RAOs is relatively straight-forward. All properties in the BHSS are tracked and representative surveys are periodically conducted using appropriate sampling methods. By 2001, approximately 80% of homes exceeding the 1000 mg/kg criteria had been remediated. Geometric mean soil lead levels for the various communities range from -100 to 500 mg/kg and mean house dust concentrations range from 236 to 532 mg/kg. All soil and dust criteria will be met at the completion of remediation. Evaluating compliance with the 5% blood lead RAO is more problematic. The 2001 survey indicated that 3% of children exceed 10 μg/dl. However, blood lead samples are solicited in a volunteer program designed to identify individual high blood lead levels that could bias the results through self-selection. Examination of school records suggest that more than half the total population is tested each year and that approximately half of these are new to the LHIP. The majority of parents that refuse are cognizant of the LHIP and believe their children have low levels due to past testing or limited exposures. As a result, any participation bias may be toward higher blood lead levels and comparison of survey results to the RAO is, likely, appropriate and the criteria will be met.

In evaluating remedial effectiveness and the prognosis for long-term risk reduction, however, it may be more meaningful to examine the blood lead to soil/dust lead relationship that was the basis of the cleanup strategy. Although the database accumulated as part of the continuing health response program and was not collected as a designed experiment, it is sufficiently large and representative enough to support analysis of the blood lead to soil/dust lead relationship and remedial effectiveness. A variety of analyses were conducted by collaborative effort in the USEPA mandated 5-year review of the BHSS ROD. The overall analysis should be viewed as a forensic exercise to learn as much as possible from this decade-long health response effort. Caution should be exercised in considering individual results, as these were not designed experiments. Ethical and practical considerations precluded expending scarce resources randomly, or on those not requiring the services. Characterizing the effort as a study or experiment would have negatively affected participation rates. Despite these shortcomings, these analyses provide a comprehensive picture of childhood lead poisoning and allowed development of site-specific factors that have effectively been used to reduce exposures to acceptable levels.

Blood:soil/dust lead slope factors derived from linear regression techniques are age-dependent and similar to the lower range of literature reported values. Blood lead levels tend to increase approximately 0.9 μg/dl per 1000 mg/kg house dust lead across all age groups at typical concentrations. Not having a vacuum cleaner tends to add approximately 0.6 μg/dl to average blood lead levels. The blood to soil slope is highest for community-wide soils, approximately 1.5–2.5 μg/dl per 1000 mg/kg and most pronounced for 5–6-year-old children. Neighborhood and home yard soils show slopes of approximately 0.6–1.0, and are highest for younger children. These results are additive and suggest an overall ratio of near 4.0 μg/dl per 1000 mg/kg lead in soil.

Repeat measures analysis was conducted to assess the year to year relationships between blood lead levels and changing exposures due to remedial and intervention activities. The results suggest that intervention efforts can be successfully applied to reduce blood lead levels for children in the tail of the distribution or approximately the 5–10% of children with the highest blood lead levels. Below the 90^{th} percentile, intervention had no detectable effect. The remediation effort (without intervention) had approximately a 7.5 μg/dl effect in reducing a typical 2-year-old child's mean blood lead level over the course of 10 years of cleanup. The mixed models analysis suggests that most of the effect is achieved indirectly through community and neighborhood soil lead reduction and consequent house dust lead decreases, with a lesser but significant portion of the reduction directly attributable to the individual yard remediation.

Pathways models indicate that from 40% to 50% of the blood lead absorbed from soils and dusts is through house dust with approximately 30% from community-wide soils and 30% from the home yard and immediate neighborhood. These relative contributions agree with findings of studies conducted in the early 1980s and the IEUBK dust:soil partitions used to develop the cleanup criteria for the site. The same structural equation models suggest that the community-wide soil component accounts for 50% and 60% of the soil contribution to house dust with the neighborhood and home yard contributing approximately 20% each. This results in soils ultimately accounting for approximately 80% of lead to house dust in the pre-remedial environment and an estimated 50–60% post-remedial with the remainder likely due to lead paint, residual dust in structures and soft surface reservoirs and non-mining-related sources.

The pathways results allowed estimation of daily lead intake rates from the various soil and dust exposure routes. This is a key measure in remedial effectiveness, as it integrates the effects of cleanup activities through the various media to the child and corresponds directly with blood lead levels. Geometric mean pre-remediation (before cleanup) intake rates were near 200 μg/day site-wide and have been reduced to near 40 μg/day. During the first year of remediation in 1989–1990, mean intake decreased by 40–50% and another 20–30% reduction was achieved in 1990–1991. In those two years, home yards of all identified 0–9-year-old children and pregnant women were remediated. Corresponding mean blood lead levels dropped by 40% in the same time period. In 1991–1992, no significant decrease was accomplished and blood lead increased as an influx of families moved into contaminated properties. From 1992–1997 little net progress was made in reducing intake or blood lead levels. During these years, children moving to contaminated properties offset the effect of those whose yards were remediated. Significant reductions were achieved again after 1998, when area-wide remediation provided clean yards for relocating families. As a result, mean blood lead levels and percent of children to exceed toxicity levels have paralleled the percent of children living on contaminated yards and intake rate estimates. Analysis of these data indicates that the decreasing blood lead levels are consistent with the estimated intake of lead from soils and dusts. However, the ratio of blood lead per unit of soil and dust lead intake seems to be increasing, indicating that either ingestion rates are increasing, the lead is becoming more bioavailable, the dose–response curve is changing, and/or the baseline sources of lead (other than soils and dusts) are becoming relatively larger contributors as soil sources are eliminated.

IEUBK results suggest that, although the absorption rate may be increasing, it remains approximately 60% of default values expected at a typical site. The USEPA default IEUBK model continues to over-predict observed blood lead levels by approximately 20 to 25% (i.e., the observed value was approximately 75% of the predicted value). This result is similar to the assumptions used in developing the cleanup strategy and establishing the RAOs for the site. Application of the model using the soil and dust partitions suggested in the pathways model, default ingestion parameters, and a reduced bioavailability of 18%; accurately predicts mean blood lead levels and the percent of children to exceed 10 μg/dl throughout the eleven year cleanup period. This suggests that when complete, the cleanup strategy for residential soils and dust will be successful in reducing blood lead levels and risk to acceptable criteria for the vast majority of the population.

It should be noted that the reduced response rate application assumed lower bioavailability. Similar results could be obtained by reducing ingestion rates by 40%, or various combinations of bioavailability and ingestion. If reduced absorption reflects temporary conditions associated with ongoing cleanup efforts or behavioral changes associated with the health intervention program, it would be inappropriate to apply reduced factors to evaluations of the long-term risk reduction strategy. Based on default absorption rate parameters suggested by the USEPA, the soil cleanup may not be adequate to achieve the blood lead goals. However, the reduced response rate has been evident for two decades and mean blood lead levels are now less than 4 μg/dl indicating reliance on the site-specific parameters is warranted. In either case, some number of high blood lead levels can be expected due to sources of lead in the environment that remain unaddressed by both the models and remedial activities. There are significant questions as to whether the highest blood lead concentrations observed in recent years are due to sources accounted for in the IEUBK analyses, or represent peculiar exposure situations. Some of these sources will be addressed in upcoming remedial activities. Those problems identified outside the scope of the remediation strategy will need to be resolved on a case-by-case basis.

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