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GUIDANCE MANUAL FOR THE INTEGRATED EXPOSURE UPTAKE BIOKINETIC MODEL FOR LEAD IN CHILDREN

Prepared by

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for

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PREFACE

The Guidance Manual has been developed to assist the user in providing appropriate input to the Integrated Exposure Uptake Biokinetic (IEUBK) Model for Lead. The IEUBK Model is designed to model exposure from lead in air, water, soil, dust, diet, and paint and other sources with pharmacokinetic modeling to predict blood lead levels in children 6 months to 7 years old. This manual emphasizes the use of the IEUBK Model for estimating risks from childhood lead exposure to soil and household dust that might be encountered at CERCLA/RCRA sites, although other applications of the model are possible. The manual provides background information on environmental exposure parameters and recommends some useful approaches that allow flexibility for site-specific risk assessments, where possible. Default parameters are recommended unless there is sufficient data to characterize site-specific conditions. A separate Appendix on sampling is being developed and will be issued later. A Technical Support Document details the basis for the biokinetic parameters and equations in the IEUBK Model. In addition, EPA is continuing to compare the results of field studies with model predictions and will release these findings in a later document.

One of the proposed uses of this model will be support for the implementation of an Interim Directive of the Office of Solid Waste and Emergency Response (OSWER). This Interim Directive explains how the IEUBK Model results can be a tool for the determination of site-specific cleanup levels. In this context, the model is viewed as a predictive tool for estimating changes in blood concentrations as exposures are modified. The model is also viewed as a useful tool that should aid the Agency in making more informed choices about the concentrations of lead that might be expected to impact human health.

The development of the model has included the cooperative efforts of several EPA programs over nearly a decade. For the last three years, these efforts have been coordinated by the Technical Review Workgroup for Lead. During its development, the model has undergone review by outside scientists, and its usefulness has been evaluated by EPA staff, contractors, and other reviewers assessing site-specific risk. The current version of the IEUBK model and the Guidance Manual incorporates many of their recommendations.

The use of mathematical and statistical models for environmental risk assessment has become increasingly widespread because of the many practical difficulties encountered in controlling human exposure to toxicants with subtle and long-lasting effects. Exposure to lead during infancy and childhood increases the risk of irreversible neurobehavioral deficits

at levels of internal exposure as low as 10 to 15 μg Pb per 100 mL of blood (10 to 15 μg/dL). Lead has many known sources, and many pathways from its environmental sources into the child's body (U.S. Environmental Protection Agency, 1986). The Environmental Protection Agency has long been interested in methods for relating environmental lead concentrations to blood lead concentrations in children. Earlier approaches based on statistical correlations provided essential information on the existence and magnitude of childhood lead uptake from persistent exposure to different environmental sources, including lead in air, diet, drinking water, soil, dust, and lead-based paint. Unfortunately, these statistical relationships are limited in their ability to estimate the effects of alternative lead abatement methods that change pathways as well as sources.

In 1985 the EPA Office of Air Quality Planning and Standards began to develop an alternative approach for estimating the effectiveness of alternative National Ambient Air Quality Standards for lead, particularly around point sources of air lead emissions such as smelters. This was a computer simulation model with two components: (1) a model of the biokinetics of lead distribution and elimination whose parameters vary with the child's age, and (2) a multi-source and multi-media lead exposure model in which air lead concentrations change over time. The biokinetic model was based on studies at New York University by Naomi Harley, Theodore Kneip, and Peter Mallon. The U.S. Environmental Protection Agency Clean Air Science Advisory Committee (CASAC) reviewed and found acceptable the OAQPS staff report documenting the model in 1989. A subsequent OAQPS staff paper reviewing the National Ambient Air Quality Standard for Lead, which included results of applying the model to point sources of air lead such as smelters and battery plants, was also evaluated by CASAC in 1990 (U.S. Environmental Protection Agency, 1990B).

Those who had been involved in developing the lead model then received a large and growing number of requests on applications of the model in a wide variety of other contexts not originally intended for model use. The largest number of these requests involved the use of the model to estimate the effects of soil lead abatement at Superfund sites.

The air model was further developed to include enhancements in absorption and biokinetics. In November, 1991, the Indoor Air Quality and Total Human Exposure Committee (IAQTHEC) of EPA's Science Advisory Board (SAB) reviewed the Uptake Biokinetic Model for Lead (version 0.4) and evaluated its use in assessing total lead exposures and in aiding in developing soil cleanup levels at residential CERCLA/RCRA sites. The Committee's Report was transmitted to EPA Administrator William K. Reilly in March, 1992. The Committee concluded that while refinements in the detailed specifications

of the model would be needed, the approach followed in developing the model is sound. The Committee stated that the model can effectively be applied for many current needs even as it continues to undergo refinement for other applications, based upon experience gained in its use.

The Committee was concerned that the reliability of the results obtained using the model is very much dependent on the selection of the various coefficients and default values that were used. In particular, the Committee identified the need for guidance on the "proper" geometric standard deviation (GSD) and the use of default values for other parameters. In addition to these general comments, specific comments were included in the Report. The comments of the SAB and other reviewers have been considered in this revision of the Guidance Manual.

Since the SAB review, EPA has further refined the model. The four main components of the current IEUBK model are: (1) an exposure model that relates environmental lead concentrations to age-dependent intake of lead into the gastrointestinal tract; (2) an absorption model that relates lead intake into the gastrointestinal tract and lead uptake into the blood; (3) a biokinetic model that relates lead uptake in the blood to the concentrations of lead in several organ and tissue compartments; and (4) a model for uncertainty in exposure and for population variability in absorption and biokinetics. A Technical Support Document that details the selection of parameters and equations in the model is available.

As with any multicompartmental model, pools in the compartmental analysis can be identified with specific organs or organ systems only if biological concentrations of the compartments are known. For some compartments, the biological concentrations have been measured at a number of time points so that the movement of lead from one compartment to another can be estimated. The biokinetic and absorption components of the model, however, are not observed directly but are inferred from accessible data.

In developing the IEUBK Model, EPA has learned much from "real world" comparisons of blood lead and predicted values—not only that the model works, but also that it can be made to work better. Guidance on the appropriate use of the model is based on our experiences, where possible, and on the experiences of many users and reviewers of the model. Many of the most useful parts of the Guidance Manual have been suggested by these reviewers.

While the model has been used to support the NAAQS for Lead, the Clean Water Act national regulations, and several other regulatory and enforcement issues, EPA is continuing its validation of the IEUBK Model with detailed evaluation of additional data collected from different types of sites. Comparison of predicted and empirical blood lead concentrations will be described in the Field Study Data Set Comparisons Document described in Section 1.2.2.

Although EPA is releasing version 0.99d of the IEUBK Model to ensure consistent application among users, the Agency will continue to evaluate the results of validation exercises and different applications of the model. The Environmental Protection Agency will determine periodically whether refinements to the model are warranted, considering scientific advancements and the development of alternative approaches.

The Environmental Protection Agency welcomes the suggestions of those using the IEUBK model. Questions regarding the site-specific application of the IEUBK Model should be raised with the appropriate Regional Toxics Integration Coordinator. Comments on the technical content of the manual or suggestions for its improvement may be brought to the attention of the Technical Review Workgroup for Lead, whose current addresses are listed on page xxi.

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GLOSSARY OF MODEL TERMS

Absorbed dose - The amount of a substance penetrating an absorption barrier (the exchange boundaries) of an organism, via either physical or biological processes.

Absorption barrier - Any of the exchange barriers of the body that allow differential transport of various substances across a boundary. Examples of absorption barriers are the skin, lung tissue, and gastrointestinal tract wall.

Accuracy - The measure of the correctness of data, as given by the difference between the measured value and the true or standard value.

Ambient - Surrounding conditions.

Ambient measurement - The measurement (usually of the concentration of a chemical or pollutant) taken in an ambient medium, normally with the intent of relating the measured value to the exposure of an organism that contacts that medium.

Ambient medium - One of the basic categories of material surrounding or contacting an organism (e.g., outdoor air, indoor air, water, or soil) through which chemicals or pollutants can move and reach the organism. (See biological medium, environmental medium.)

Arithmetic mean - The sum of all the measurements in a data set divided by the number of measurements in the data set.

Background level (environmental) - The concentration of substance in a defined control area during a fixed period of time before, during or after a data gathering operation.

Bias - A systematic error inherent in a method or caused by some feature of the measurement system.

Bioavailability - The fraction of intake at a portal of entry into the body (lung, gut, skin) that enters the blood. Bioavailability is typically a function of chemical properties, physical state of the material that an organism ingests or inhales, and the ability of the individual organism to physiologically absorb the chemical. The absorption rate varies widely by type of substance and can greatly influence the toxicity of lead over that acute timeframe.

Biokinetics - processes affecting the movement of molecules from one internal body compartment to another, including elimination from the body.

Biological measurement - A measurement taken in a biological medium. For the purpose of exposure assessment via reconstruction of dose, the measurement is usually of the concentration of a chemical/metabolite or the status of a biomarker, normally with the intent of relating the measured value to the internal dose of a chemical at some time in the past.

(Biological measurements are also taken for purposes of monitoring health status and predicting effects of exposure). (See ambient measurement.)

Biological medium - One of the major categories of material within an organism (e.g., blood, adipose tissue, or breath) through which chemicals can move, be stored, or be biologically, physically, or chemically transformed. (See ambient medium, environmental medium.)

Body burden - The amount of a particular chemical stored in the body at a particular time, especially a potentially toxic chemical in the body as a result of exposure. Body burdens can be the result of long term or short term storage, for example, the amount of a metal in bone, the amount of a lipophilic substance such as PCB in adipose tissue, or the amount of carbon monoxide (as carboxyhemoglobin) in the blood.

Comparability - The ability to describe likenesses and differences in the quality and relevance of two or more data sets.

Compartment - A distinct anatomical organ, tissue, fluid pool, or group of tissues within the body that are regarded as "kinetically homogeneous."

Dose - The amount of a substance available for interaction with metabolic processes or biologically significant receptors after crossing the outer boundary of an organism. The potential dose is the amount ingested, inhaled, or applied to the skin. The applied dose is the amount of a substance presented to an absorption barrier and available for absorption (although not necessarily having yet crossed the outer boundary of the organism). The absorbed dose is the amount crossing a specific absorption barrier (e.g., the exchange boundaries of skin, lung, and digestive tract) through uptake processes; internal dose is a more general term denoting the amount absorbed, without respect to specific absorption barriers or exchange boundaries. The amount of the chemical available for interaction by any particular organ or cell is termed the delivered dose for that organ or cell.

Environmental medium - One of the major categories of material found in the physical environment that surrounds or contacts organisms (e.g., surface water, ground water, soil, or air) and through which chemicals or pollutants can move and reach the organisms. (See ambient medium, biological medium.)

Exposure - Contact of a chemical, physical, or biological agent with the outer boundary of an organism. Exposure is quantified as the concentration of the agent in the medium in contact integrated over the time duration of that contact.

Exposure pathway - The physical course a chemical or pollutant takes from the source to the organism exposed.

Exposure route - The way a chemical or pollutant enters an organism after contact (e.g., by ingestion, inhalation, or dermal absorption).

Exposure scenario - A set of facts, assumptions, and inferences about how exposure takes place that aids the exposure assessor in evaluating, estimating, or quantifying exposures.

Geometric mean - The nth root of the product of n values. Also, the exponential function of the mean or expected value of the natural logarithm of a variable.

Geometric standard deviation (GSD) - The exponential function of the standard deviation of the natural logarithm of a variable.

Guidelines - Principles and procedures to set basic requirements for general limits of acceptability for assessments.

Intake - The process by which a substance crosses the outer boundary of an organism without passing an absorption barrier (e.g., through ingestion or inhalation). (See also "potential dose").

Internal dose - The amount of a substance penetrating across the absorption barriers (the exchange boundaries) or an organism, via either physical or biological processes.

Matrix - A specific type of medium (e.g., surface water, drinking water) in which the analyte of interest may be contained.

Median value - The value in a measurement data set such that half the measured values are greater and half are less.

Monte Carlo technique - A repeated random sampling from the distribution of values for each of the parameters in a generic (exposure or dose) equation to derive an estimate of the distribution of (exposures or doses in) the population.

Pathway - The physical course a chemical or pollutant takes from the source to the organism exposed.

Pharmacokinetics - The study of the time course of absorption, distribution, metabolism, and excretion of a foreign substance (e.g., a drug or pollutant) in an organism's body.

Potential dose - The amount of a chemical contained in material ingested, air breathed, or bulk material applied to the skin.

Precision - A measure of the reproducibility of a measured value under a given set of conditions.

Probability samples - Samples selected from a statistical population such that each sample has a known probability of being selected.

Random samples - Samples selected from a statistical population such that each sample has an equal probability of being selected.

Range - The difference between the largest and smallest values in a measurement data set.

Reasonable worst case exposure or risk range - The lower portion of the "high end" of the exposure, dose or risk distribution. The reasonable worst case conceptually should be targeted at above the 90th percentile in the distribution, but below about the 98th percentile ("maximum exposure or risk range").

Representativeness - The degree to which a sample is, or samples are, characteristic of the whole medium, exposure, or dose for which the samples are being used to make inferences.

Risk - The probability of deleterious health or environmental effects.

Route - The way a chemical or pollutant enters an organism after contact (e.g., by ingestion, inhalation, or dermal absorption).

Sample - A small part of something designed to show the nature or quality of the whole. Exposure-related measurements are usually samples of environmental or ambient media, exposures of a small subset of a population for a short time, or biological samples, all for the purpose of inferring the nature and quality of parameters important to evaluating exposure.

Scenario evaluation - An approach to quantifying exposure by measurement or estimation of both the amount of a substance contracted, and the frequency/duration of contact, and subsequently linking these together to estimate exposure or dose.

Structural Equations Model - A statistical model of a process in which several regression equations are solved simultaneously, and outputs or responses from one equation may be used as inputs or predictors in another equation. Useful in pathway modeling.

Surrogate data - Substitute data or measurements on one substance used to estimate analogous or corresponding values of another substance.

Uptake - The process by which a substance crosses an absorption barrier and is absorbed into the body.

1. BEFORE YOU START

1.1 BACKGROUND: PURPOSE AND DEVELOPMENT OF THE MODEL

The Integrated Exposure Uptake Biokinetic (IEUBK) Model for Lead in Children is a stand alone, PC compatible software package. It allows the user to estimate, for a hypothetical child or population of children, a plausible distribution of blood lead concentrations centered on the geometric mean blood lead concentration predicted by the model from available information about children's exposure to lead. From this distribution, the model calculates the probability that children's blood lead concentrations will exceed the user selected level of concern (default 10 μg/dL). The user can then explore an array of possible changes in exposure media that would reduce the probability that blood lead concentrations would be above this level of concern.

The model should be viewed as a tool for making rapid calculations and recalculations of an extremely complex set of equations that includes scores of exposure, uptake, and biokinetic parameters. This Guidance Manual concisely describes key features of the conceptual underpinnings of the IEUBK model, its evolution and development, its capabilities, and its limitations. The Manual then goes on to offer guidance on the use of the model as a risk assessment tool while cautioning against a number of possible misapplications of the model. A detailed description of the equations and parameters used in the model is provided in the Technical Support Document: Parameters and Equations Used in the Integrated Exposure Uptake Biokinetic Model for Lead in Children (a companion document to this Guidance Manual).

1.1.1 Description of the Model

The IEUBK Model is a simulation model. As a risk assessment tool, it can be a useful component of remediation strategies for lead in the human environment. The simulation of childhood lead exposure and retention is only one part of the risk assessment process. It is important to note that the model alone does not determine the level of cleanup required for a specific site. Rather, it predicts the likely blood lead distribution for children given the exposure to lead at that site, and the probability that children exposed to lead in that environment will have blood lead concentrations exceeding a health-based level of concern.

Blood lead concentrations are not only indicators of recent exposure, but also are the most widely used index of internal lead body burdens associated with potential health effects. Health effects of concern have been determined to be associated with childhood blood lead concentrations at or below 10 μg/dL (U.S. Environmental Protection Agency, 1986, 1990; CDC, 1991). The probability that children will have blood lead levels exceeding this level of concern is an important consideration for a risk assessor in compiling and evaluating all information applicable to a site to enable remediation decisions.

The IEUBK model can be applied at several different scales of application, but the interpretation of the model output and the form of the model or subsequent risk estimates is different for each application. In most uses of the model, a site is a spatial domain that is appropriate for remediation decisions, typically a residential yard with a single housing unit, or an equivalent area for multi-unit buildings or for undeveloped lots. The home and its surrounding yard is the basic unit for risk analysis because lead exposure for pre-school children commonly occurs within this domain. In Sections 1.4.4.2 and 4.2 we will describe an array of applications of the IEUBK model based on aggregating clusters of sites. The array is:

A: One location
- A1: one living unit, one child;
- A2: one living unit, more than one child;
- A3: more than one living unit, more than one child, homogeneous media concentrations;

B: Multiple locations, one neighborhood, homogeneous media concentrations

C: Multiple locations, one neighborhood, heterogeneous media concentrations;

D: Multiple locations, more than one neighborhood, heterogeneous media concentrations;

In category A, risk is calculated as the probability that, in a single child at a single site with the specified exposure scenario, the child's blood lead concentration will exceed the level of concern. The probability distribution describes the likely variability in blood lead for a child with a given exposure scenario. The best single-number prediction of blood lead concentration is the geometric mean of the distribution of blood lead concentrations that may occur for a child with the specified exposure scenario. This single-child assessment is used to evaluate remediation options on a house-by-house or yard-by-yard basis.

In categories B, C, and D, a frequency distribution of the individual risk of exceeding a blood lead level of concern is obtained. The percentage of children in multiple sites that are likely to have a blood lead concentration exceeding the level of concern can then be calculated. For category B, where all children of the same age have the same exposure scenario, this can be done with a single run of the IEUBK model. For categories C and D, where distinct subgroups have different exposure scenarios, risk must be calculated by aggregating the results from a number of model runs. Risk estimation for more than one neighborhood, for category D, has the added complication that a variety of model parameters may differ between neighborhoods, and within each neighborhood. Therefore, environmental lead concentrations may differ between neighborhood subgroups.

1.1.2 Simulation of Childhood Lead Exposure and Retention

Lead is a naturally occurring nonnutrient metal that follows environmental pathways similar to those of nutrient metals such as calcium. In the human environment, these pathways or routes of exposure transfer lead from sources such as food, drinking water, air, soil, and dust, to the human body by means of ingestion or inhalation. There are important analogies to be made between lead and calcium that contribute to our understanding of the biological behavior of lead. These analogies have aided in the formulation of the lead model. In particular, the nature of gut absorption of lead and calcium may be similar. Childhood growth and development of bone and soft tissue which require calcium influence the uptake of environmental lead from the gut. In addition to similarities in absorption, both lead and calcium are stored in quantity and subsequently released from bone tissue.

Shown conceptually on Figure 1-1, inhaled or ingested lead is absorbed through the lungs or gut into the blood stream where it is transferred to body tissues, including bone tissues. After a period of time, this lead returns to the blood stream where it is transferred to other tissues or eliminated with urine. Lead may also be eliminated from the body with sweat, hair or sloughed epidermal tissue, or it may be transferred through the liver and bile duct back to the gut where it passes out of the body with feces.

In Figure 1-1, the oval shapes show environmental lead media, and some of the pathways between them. The large rectangle shows the compartment that is central to lead distribution in the child, the blood plasma pool and associated extra-cellular fluid. Each lower rectangle shows a compartment in the child's body where lead may be retained. The excretion of lead from the body is shown by the circles.

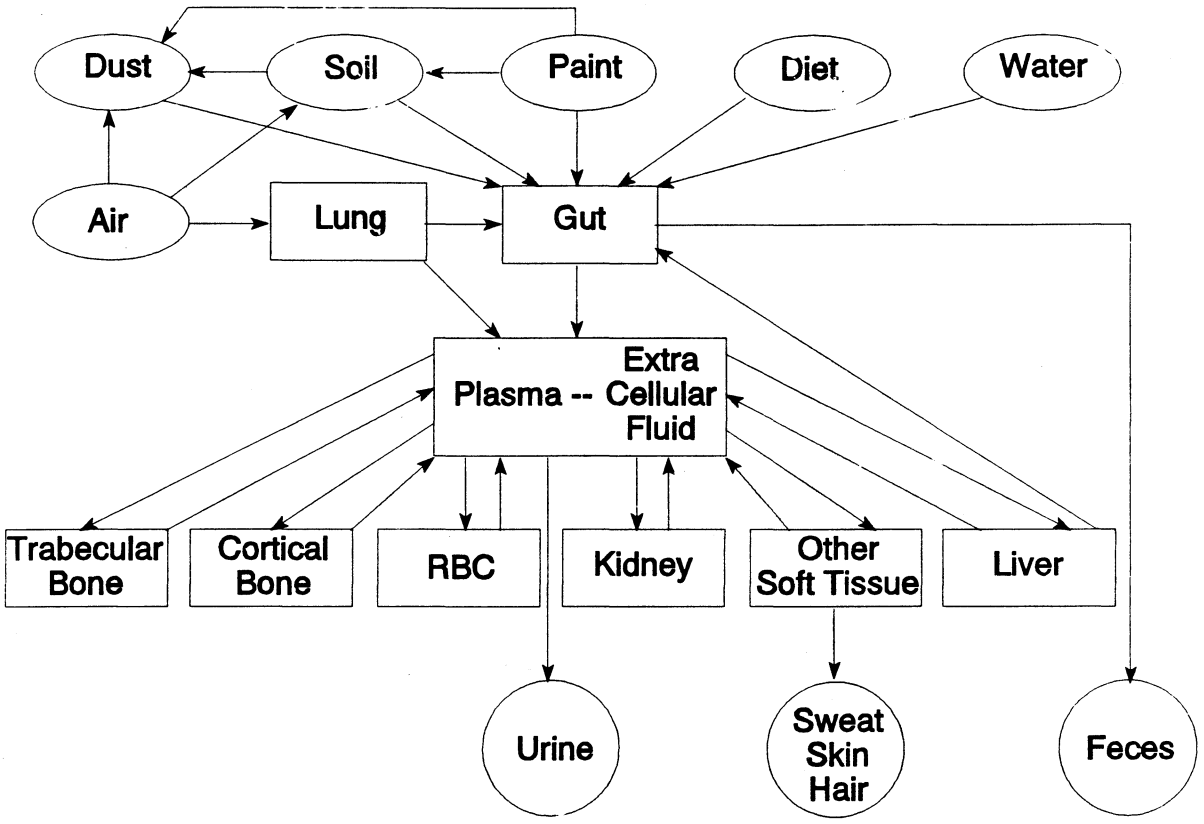


Figure 1-1. Conceptual diagram of the movement of environmental lead into and through the human body. The oval shapes show environmental media and the pathways of uptake. The large rectangle is the blood plasma compartment central to the distribution of lead in the body.

The foundation of the present IEUBK model is the construction of a detailed and thorough exposure scenario for children aged 0 to 84 months that can be adjusted to match the exposure of any child. The user starts with exposure information specific to these children and accepts generalized assumptions about any additional information required to complete the exposure scenario. The site-specific information usually consists of environmental media concentrations such as soil lead concentrations.

The model inserts default values whenever site-specific information is not used. The default values (e.g., dietary lead concentrations and consumption values) are typical of a child's environment in the sense that they are broad-based estimates of the expected

environment of a child. These default values are not necessarily appropriate for every site and should be reviewed by the user for every site-specific application.

This model uses standard age-weighted exposure parameters for consumption of food, drinking water, soil, and dust, and inhalation of air, matched with site-specific concentrations of lead in these media, to estimate exposure for the child. The model simulations represent chronic exposure and do not incorporate the variability in consumption patterns and media concentrations on a daily or seasonal basis. The model includes continuous growth of the child and simulates the changing environment of the child on a yearly basis. In theory, the exposure component of the model would apply to a single child or to any number of children with the same lead exposure scenario. With the proper substitution for media concentrations, the exposure component (but not the biokinetic component) would also apply to any other substance with sources and pathways of exposure similar to lead.

The model simulates lead uptake, distribution within the body, and elimination of lead from the body. The uptake portion of the model takes into consideration two mechanisms of absorption of lead in the digestive tract: saturable and non-saturable. Elimination of lead is modeled through several routes: urine, gastro-intestinal excretion, and sloughing of epidermal tissue, including hair and nails.

1.1.3 Historical Evolution from Slope Factor Models to the IEUBK Model

An explicit mathematical method for estimating the likely risk of elevated blood lead concentrations in young children has previously been used by the Environmental Protection Agency as one of its tools for developing the National Ambient Air Quality Standard for Lead and the National Primary Drinking Water Regulation for Lead. The method has historically been based mainly on an estimation of relationships between lead concentrations in children's blood and lead concentrations in specific individual environmental media such as air, water, soil and dust, based on empirical observations derived from experimentally controlled human exposure, animal toxicological studies, and epidemiological analyses. Such relationships also provide a basis for estimating the probability that elevated blood lead concentrations exceed a level of concern due to exposure to environmental lead in these media.

A mathematical approach of this type was used to evaluate potential alternative air lead standards based on health effects criteria (U.S. Environmental Protection Agency, 1977,

1978, 1989a). The relationship between blood lead and lead in environmental media was estimated statistically, both for adults and children (U.S. Environmental Protection Agency, 1986, 1989a). While the relationship was somewhat non-linear at blood lead concentrations above about 40 μg/dL in adults and 30 μg/dL in children, it was nearly linear at lower blood lead concentrations of interest. The relationship between blood lead and environmental lead concentrations in different media (air, water, soil, dust, food) was estimated using a model linear in lead concentrations. The linear regression coefficients between blood lead and lead in each of the environmental media have since become known as the slope factors for the media.

As more evidence has become available, it has become clear that these slope factors can not be regarded as universal constants that are the same everywhere, for all children at all sites. Some of the problems involved in the use of slope factors have been discussed by the U.S. Environmental Protection Agency (1989a) and by Brunekreef et al. (1984). In the development of improved lead models (U.S. Environmental Protection Agency 1986, 1989a), the following points were discussed:

(1) Slope factors are a function of many factors: media ingestion rates; bioavailability and absorption of lead from the medium; and biological kinetics of lead retention and elimination in the child. Biological and physical differences between sites and study populations cannot be incorporated explicitly and quantitatively into regression slope factors from different studies.

(2) Slope factors for a single medium, such as lead in air or lead in soil, may provide only a very incomplete picture of total lead exposure from a particular source, even if the source is identified with the medium. A single medium such as household dust may contain lead from many sources, and lead from a single source such as exterior lead-based paint may contribute to several exposure media pathways to the child.

Therefore, in 1985, the EPA Office of Air Quality Planning and Standards (OAQPS) initiated a project that would allow the calculation of blood lead concentrations in children exposed to differing arrays of concentrations of lead in air, soil, and dust. This model, called the Uptake/Biokinetic (or UBK) model for lead, was a computer simulation model based on the biokinetic model for lead in children developed by N. Harley and T. Kneip (1985). The biokinetic parameters for the UBK model were extrapolated from long-term feeding studies on infant and juvenile baboons (Mallon, 1983), autopsy data on human children, human infant feeding studies, and other sources. The exposure model that was

coupled to the biokinetic model was developed by OAQPS. Model calibration and validation was done using data from the 1983 EPA/CDC/Montana study on children in East Helena, Montana, who lived in the vicinity of a large primary lead smelter. The modeling approach was reviewed and approved by EPA's Clean Air Science Advisory Committee (CASAC) in 1990.

The overall framework of both the UBK and IEUBK models is shown in Figure 1-2. The oval shapes show environmental lead concentrations and the funnel-shaped symbols show lead intake from the environment at the portals of entry, the lung and the gut. These are the exposure/intake components of the IEUBK model. The next large rectangle shows the gut not only as the main portal of entry for lead from most exposure media, but also as the site for key absorption/uptake components of the IEUBK model for the evaluation of lead from soil, dust, diet, and drinking water. The very large rectangle shows the child's blood lead, partitioned into plasma-extracellular fluid and red blood cells. The two boxes to the right of the blood lead pool sketch the bone and soft tissue pools, and the elimination pathways are shown as circles. The right-hand box shows the blood lead concentration in the child, and the subdivisions show the estimated contribution of each medium to the child's blood lead concentration. In the example in Figure 1-2, we have assumed that all external lead media have been used in the IEUBK model, as have all internal lead sources. There is no unattributable component called "background". The attribution of specific fractions of blood lead to uptake from specific media is not as subject to statistical artifacts, since pathways from soil lead and air lead to dust lead are also included in the IEUBK model.

In all particulars, the present version of the model, the IEUBK model, may be considered an enhancement and extension of the UBK model. Theoretically, in situations where the child has constant long-term or chronic lead exposure, both the slope factor approach and the UBK model (now the IEUBK model) should produce similar results when sufficient data exist to correctly characterize lead exposure, absorption, and biokinetics.

The IEUBK Model addresses three emerging paradigms of environmental risk assessment.

(1) Assessments that recognize the multimedia nature of exposures to environmental toxicants are a significant improvement in assessing health risks. Assessments restricted to single pathways of exposure can overlook situations where integrated multimedia exposures are high enough to trigger health concerns. The lead model is structured to integrate exposures occurring through air, water, food, soil, and dust in estimating the blood lead levels in children in realistic environmental settings.

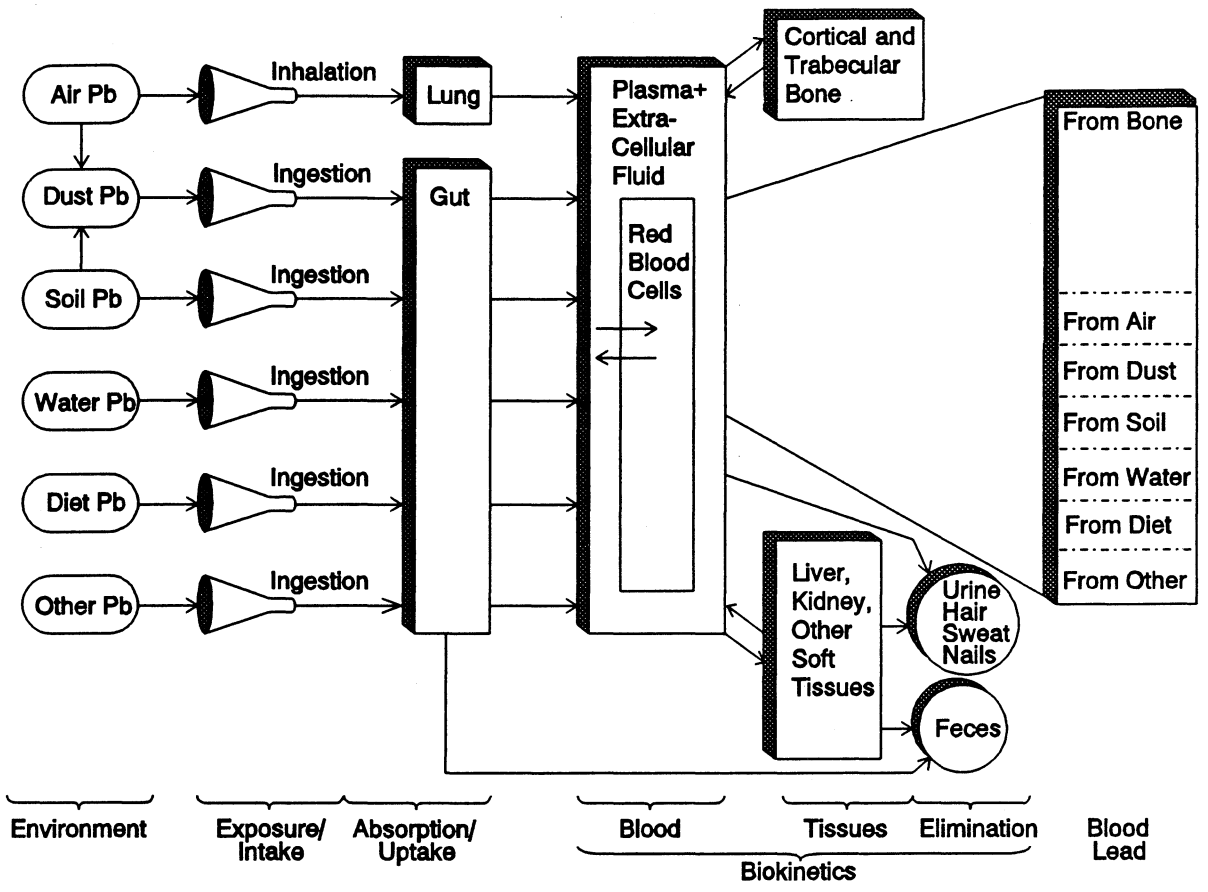


Figure 1-2. Components of the IEUBK Model, showing environmental exposure sources and pathways, absorption compartments, critical body tissue compartments, and elimination pathways.

(2) Pharmacokinetic information can strengthen the validity of environmental health assessments in comparison with more traditional methods that address only external dose or intake of a compound. Internal measures of dose that are pertinent to the biological effects exerted by a compound form an improved metric for risk assessment. The IEUBK estimates of blood lead concentrations as an internal indicator of potential health risk are based on pharmacokinetic modeling of lead absorption, transport, redistribution, and elimination.

(3) Environmental assessments need to address the substantial variability in exposure and risk resulting from these factors. Single point estimates of exposure or risk are of limited utility. Individuals differ in their surroundings, behavior, and physiological status. The Lead Model addresses variability through the estimation of probability distributions of blood lead levels for children exposed to similar environmental

concentrations of lead. Through systematic application of the model, data on the variability of levels of environmental lead contamination can be translated into estimates of the distribution of blood lead levels within populations of children.

1.1.4 Using the IEUBK Model for Risk Estimation

The IEUBK Model for lead is designed to facilitate: (a) rapid delineation of the relationship between environmental lead and blood lead in children; and (b) calculation of the risk of elevated blood lead (i.e., the probability of a given child or a group of children having blood lead concentrations exceeding a specified level of concern). As such, the IEUBK Model provides a tool for site-specific risk assessment for young children exposed to lead from different media and through different pathways in their environment, with particular emphasis on lead in air, water, soil, and household dust. Many other applications are possible. The intended applications of the IEUBK model are to:

(1) Provide a summary of children's long-term, primarily residential, exposure to lead;

(2) Provide a best estimate of the geometric mean blood lead concentration for a typical child aged 6 to 84 months, assumed to reside at a given residence;

(3) Provide a basis for estimating the risk of elevated blood lead (i.e., for exceeding a designated blood lead concentration of concern) for a hypothetical child of specified age with given site-specific residential lead exposure;

(4) Provide a basis for estimating the risk of elevated blood lead concentrations among early pediatric populations in a given neighborhood by aggregating the individual residential risk estimates;

(5) Predict likely changes in risk of elevated blood lead concentrations from exposure to soil, dust, water, or air lead following abatement actions designed to reduce exposure levels from one or more environmental media;

(6) Provide assistance in determining appropriate soil or dust lead target cleanup levels at specific residential sites;

(7) Provide assistance in estimating blood lead concentrations associated with soil or dust lead concentrations at undeveloped residential sites that may be developed in the future.

Each of these applications is discussed in more detail in Chapters 2, 4, and 5. The IEUBK model has been used for many purposes in addition to those for which it was originally intended. We are sure that the IEUBK model will continue to be used in many unintended and unexpected applications, just like any other new tool that has multiple uses. Some of these new applications are valid, others are demonstrably invalid, and the validity of many applications is simply unknown.

The risk estimates are calculated for a hypothetical child or a hypothetical population of children who could be occupying the specific household at the time of the measurements or at some future time. The IEUBK model can therefore be used to estimate the risk of elevated blood lead even when there are no children currently living at a house, or if there exist only environmental lead data for the dwelling unit. The model does not require that a neighborhood or community blood lead study be carried out. The user should be aware that a site-specific risk assessment requires site-specific soil and dust concentrations, and some of the absorption parameters may depend on specific characteristics of the soil and dust at the site. The IEUBK model accepts user inputs for site-specific differences in bioavailability of lead in different media, and site-specific differences in environmental lead pathways for different lead sources.

1.1.5 Validation of the IEUBK Model

What does it mean to say that a computer simulation model is "valid"? In general, we interpret this to mean that:

- the model is biologically and physically plausible and incorporates the best available empirical data on parameters;
- the model uses numerically accurate algorithms and the accuracy of the computer codes for these algorithms has been verified;
- the model provides some satisfactory empirical comparisons of model output with real-world data.

We believe that the scientific basis and computational correctness of the IEUBK Model is sound, and that the IEUBK model provides valid prediction of observed blood lead

concentrations from representive populations of children with typical exposure. The empirical comparisons in which there are differences between observed and predicted blood lead concentrations underscore the importance of valid exposure scenarios as input. They also show the importance of valid blood lead data from truly representative population sampling methods when interpreting these empirical comparisons.

1.1.5.1 The Model Is Biologically and Physically Plausible

The parameters and equations used in the model are documented in the Technical Support Document: Parameters and Equations Used in the Integrated Exposure Uptake Biokinetic Model for Lead in Children. The exposure model component is based on data for human children in most instances, with lead exposures that are characteristic of children in the U.S. since about 1980. The ingestion parameters are based on surveys for drinking water and tap water (Ershow and Cantor, 1989), market basket estimates of dietary intake (Pennington, 1983; Gartrell, 1986), and on observational studies of soil and dust ingestion for children in the U.S. (Binder et al., 1986; Calabrese et al., 1989, 1992a,b, 1993; Davis et al., 1990). While these studies have not resolved all of the uncertainty in childhood lead exposure, especially from sources such as lead-based paint, they have provided a much more realistic basis for quantitative modeling. The exposure component of the IEUBK model extends the UBK model assumptions (U.S. Environmental Protection Agency, 1989a) that have been reviewed by CASAC (1990).

An absorption component was developed for the IEUBK model based on evidence discussed in Section 4.1. This evidence includes in vivo data in infant and juvenile baboons and human infants whose intake of lead is observed and known (Mallon, 1983; Sherlock and Quinn, 1986). The model has two modes for absorption, saturable and non-saturable. In the non-saturable mode, absorption of lead is a constant fraction of the total lead ingested for a specific medium. The saturable mode follows the Michaelis-Menten kinetics for saturable absorption as proposed by Aungst and Fung (1981). Development of the algorithm is also based on data from lead balance and feeding studies in human infants and children (Alexander, 1974a,b; Ryu et al., 1983, 1985; Ziegler et al., 1978).

The compartmental structure of the earlier biokinetic model is based on compartmental models for lead in adults as discussed in detail in the Air Quality Criteria Document for Lead (U.S. Environmental Protection Agency, 1986). The model was verified and extended based on studies in infant and juvenile baboons (Mallon, 1983) whose age (5 to 26 months) and size (2.5 to 6 kg) are only slightly smaller than those of human children. The biokinetic distribution and elimination parameters use ratios of lead concentrations in tissues and blood

following chronic exposure. The ratios of lead concentrations in tissues of human children from autopsy data (Barry, 1975, 1981) were used to adjust the baboon's biokinetic distribution parameters to human infants and children (Harley and Kneip, 1985). The biokinetic parameters for baboons were re-estimated using the compartmental structure of the current IEUBK model (Marcus, 1992). The tissue-to-blood concentration ratios from the human child autopsy data were incorporated in the IEUBK model, assuring complete consistency with the best available data.

1.1.5.2 The Model Is Computationally Accurate

The IEUBK model uses a fast and accurate one-step numerical integration method known as 'backward Euler', with user-adjustable time steps to verify numerical accuracy of the solution. Coding of the model equations was verified by a separate recoding of the model in another programming language. Independent code verification will be described in forthcoming Technical Memoranda (see Section 1.2.2).

1.1.5.3 Empirical Comparisons of the Model

Comparison of the IEUBK model output with empirical human blood lead data has two requirements. The first requirement is that the child's total lead exposure is completely and accurately characterized by the empirical data, including site-specific data on environmental lead concentration, media ingestion, and bioavailability. The second requirement is that the blood lead data from the field study are accurate and typical for that exposure scenario. A typical child may not have the exposure described by the measured and default parameters of the model, or a child may also respond atypically to the measured and default parameters. The solution is to find the correct set of parameters (measured or site-specific alternatives to default) that describes the child's site-specific exposure or response to exposure.

Environmental lead concentrations and blood lead measurements are subject to measurement errors such as repeat sampling variability and analytical error. Without careful attention to quality assurance/quality control (QA/QC) procedures, there may be systematic biases in blood lead measurements. The results of the blood lead field study may also differ from the model predictions for typical children if the blood lead sample is not representative of the population being sampled.

Validation by empirical comparisons with paired data sets of good quality is an ongoing process. In earlier versions of the model, empirical comparisons indicated satisfactory agreement between observed and predicted blood lead concentrations. Several data sets have been identificed that are of adequate data quality for evaluating the validity of the IEUBK

Model, and more data sets are expected to become available in the future. The Field Study Data Set Comparisons document referred to in Section 1.2.2 will discuss the results of these analyses. Comparisons of empirical data with the IEUBK model require appropriate site-specific exposure scenarios, valid assumptions about bioavailability, and demonstrated representativeness of the sample of children recruited into the study in relation to the target population from which they were drawn.

Our preliminary analyses of several data sets so far indicate that the model satisfactorily predicts blood lead concentrations for the overall sample populations in specific neighborhoods. Further analyses will be needed to determine if empirical comparisons are as strong for subpopulations defined by factors such as differences in age, differences in contact or behavior that affected the amount of soil ingested, suspected or possible differences in bioavailability, differences in contribution of soil to household dust, and identifiable biases in recruitment of children. More extensive evaluation of these data sets will be described in the Field Study Data Set Comparisons document described in Section 1.2.2.

Careful determinations should be made by users with regard to how well default values specified by this manual for key exposure and demographic parameters apply to the particular sample of children (or subpopulations) being evaluated. Appropriate adjustments made in pertinent default values may notably improve the fit of the model to empirical data. We caution the user not to arbitrarily select alternate values for the default parameters, but rather to obtain site specific or population specific data on important parameters.

1.2 ORGANIZATION OF THE MANUAL

1.2.1 Increasing Levels of Guidance and Technical Assistance

This manual is designed to provide you with the information you need at several levels of detail. The further you read into manual the more specific guidance you will find for using the model. By the time you have finished reading Chapter 1, you should have a general understanding of how the model works and what it can do. You may want to install the model and then work your way through Chapter 2 as you become more familiar with each feature of the model. Instructions for installing the model are found in Section 2.4.

As you explore the various features of the model, you will become familiar with the menus and their options. An overview of the menu system is in Section 2.1, and a detailed

description of these menus can be found in Section 2.2. This is the section that the novice user will want to follow closely. In a guided tour through the menu system, you will find that each menu option becomes a part of the process of constructing a model "run," and that these runs may be as simple as determining the blood lead concentration using only default exposure conditions, or as complicated as neighborhood risk estimation calculated as the sum of individual risks. Many of these options were suggested by comments received during the extensive review of drafts of this Guidance Manual.

As you begin to apply the model to a specific risk assessment situation, you will find that Section 2.3 contains detailed recommendations for building an exposure scenario. This section also contains a helpful worksheet for planning model runs. Follow this section closely, as it contains many helpful suggestions on the appropriate use of the model, as well as warnings of improper applications. In Chapter 4, you will find a detailed discussion on assessing the relationship between soil/dust lead and blood lead. This chapter also describes the biokinetics of the model and specific issues in the use of the model for the ingestion of paint chips. If you need more help, turn to Chapter 5, where several specific examples are available to guide you through some of the more complicated procedures. As you become more experienced, you will find Chapter 3 a quick and ready reference to the various menu options. This chapter also contains a comprehensive review of default parameters.

1.2.2 Additional Documentation

Additional technical documents are or soon will be available to supplement the IEUBK Model and this Guidance Manual. These are:

- Technical Support Document: Parameters and Equations Used in the Integrated Exposure Uptake Biokinetic Model for Lead in Children—a description and documentation of all equations and parameters in the model;

- Field Study Data Set Comparisons—a description of several validation exercises that have been or will shortly be carried out;

- Sampling Manual—approaches and protocols for environmental and biological sampling for collection of data compatible with the IEUBK Model;

- Technical Memoranda—occasional technical updates that will be released to explain some features in greater detail or to alert the user to possible misapplications of the model.

1.3 GETTING READY TO USE THE MODEL

1.3.1 Preparing a Site-Specific Exposure Scenario

The use of the IEUBK model requires input data that are appropriate to the site(s) and subject(s). The most convenient way to do this is to construct a multi-media, site-specific exposure scenario using the exposure scenario worksheet (Figure 2-11; see Section 1.4.3).

For most assessments of lead-contaminated soils, the minimal site-specific data are the soil lead and indoor dust lead concentrations for the residential exposure unit. Additionally, it would be helpful to include estimates of specific exposures from diet, drinking water, air, maternal exposure, or other sources that could replace the default exposure parameters believed to be of concern at the particular site.

There may be potentially important differences among sites, and predictions of blood lead values are expected to become more accurate as more site-specific data are added. Children at highest risk are those with the highest exposures to some lead-containing medium. Data should be collected at a site so as to identify locations in the residence or community where young children may be exposed to elevated levels of lead in soil, dust, water, or air. Household-level data are useful because proposed soil, dust, and paint abatements are usually based on the house and yard as the most likely sources of lead exposure in preschool children. High exposures from lead in the household water distribution system are also possible, and this source has been identified in some childhood lead poisoning cases (Cosgrove et al., 1989). The preferred level of environmental input data for the model can be derived from a comprehensive multimedia household environmental lead study.

The households studied should be representative of housing or sites where young children currently reside, as well as the places where young children may live in the future. In many applications, you will also need to include existing homes not occupied by children. These can usually be addressed in the same manner as housing currently occupied by children, using specific measurements of various environmental media lead concentrations. Risk assessments addressing as yet unbuilt housing should use existing residential site soil concentration data.

Predictions of blood lead concentrations may improve with better information on lead concentrations where the child spends time during the day, or on child-specific behavior.

Activity pattern analysis, based on data taken from questionnaires and family interviews, can be useful in identifying children currently at risk, and in determining site-specific differences in behavior or access to lead sources that may differ in bioavailability. Public education and parental awareness of lead hazards may reduce the amount of lead in soil and dust ingested by the child, and quantitative studies of the effects of such actions are currently in progress.

Exposure of children in day care centers, playgrounds or open areas may substantially affect total exposure to lead when potential lead exposures in such areas are high. These cases need to be considered in site risk assessment. The IEUBK Model allows dust and drinking water ingestion components to be separated into household and non-household sources by allocating a percentage of dust and water intake outside the home to sources with other concentrations. Time-weighted average air lead exposures are believed to be adequate indices of lead intake by inhalation in home and non-home settings under most circumstances and are used in the model. However, there is presently little information on the use of time-weighted averages for ingestion of soil, dust, or water away from the home. Soil and dust ingestion depends on children's activities, on hand-to-mouth behavior, and on intensity of soil contact related to sources and pathways away from home.

In addition to exposure, the IEUBK Model also allows site-specific information on the bioavailability of lead from various sources to be taken into account. Bioavailability describes the relationship between the potentially available lead intake from environmental media and the amount of lead entering the body through the lungs or the gut and then into systemic circulation.

You should be alert to the possibility that there may be site-specific differences in bioavailability of lead at different sites, particularly with respect to soil and paint. Some factors that may affect bioavailability include chemical speciation of lead in soil or paint, size of particles, mineral matrix of the particles, and whether the particles are likely to be ingested by the child along with meals or on an empty stomach. These are discussed in Section 4.1. Many of the issues are subtle and should be referred to the EPA Technical Review Workgroup for Lead.

In some cases, relatively non-available environmental lead in soil or paint can be converted into readily available lead particles in household dust by physical and chemical processes in the environment. A housing unit with lead in paint or soil will continue to generate household dust lead exposure as long as paint deteriorates or is disturbed by

remodeling, and as long as outside soil and surface dust are moved into the house by pets and by human activities like gardening and remodeling.

The model default value for the Geometric Standard Deviation (GSD) (reflecting variability among individuals who have contact with a fixed lead concentration) is based on analyses of data from neighborhoods having paired sets of environmental concentration and blood lead data. The recommended default GSD of 1.60 is believed to be very widely applicable. Only when reliable site-specific paired data from a sufficiently large study are available, should the substitution of a site-specific GSD be made using guidance given in Section 4.2.

1.3.2 Understanding How the Biokinetic Component of the Model Works

The general term "biokinetic" is used to describe the movement of lead through various parts of the human body as a kinetic process. Current blood lead concentrations depend on prior exposure history as well as present exposure. With constant lead exposure, a near steady-state blood lead concentration level is achieved because there is a dynamic near-equilibrium between lead moving out (from blood plasma to peripheral tissues and through excretory routes), and lead moving in (to plasma from gastrointestinal uptake and remobilization into plasma from peripheral tissues and long-term bone storage).

The IEUBK Model assumes that skeletal lead turnover occurs relatively more rapidly in children than in adults. The lead in a child's blood is thus a mixture of lead taken up from recent environmental exposure and lead released from skeletal stores that reflect historical exposures. However, the faster turnover time assumed for children compared to adults implies that the lead burden in the skeleton is a smaller fraction of total body burden in children than in adults. The skeletal contribution to blood lead thus increases as the skeletal fraction of total body burden of lead increases.

The blood lead concentrations in children achieve nearly a steady state relationship with exposure within a period of months after changes in exposure. The situation in children is more complicated than in adults because the kinetic parameters also change with the child's growth and with changes in behavior that affect lead intake, absorption, distribution, and elimination. The model is adequate to estimate childhood blood lead concentrations in near-equilibrium or in slowly changing exposure settings, as may be attained some time (months) after abatement occurs. The gradual phase down of lead in gasoline would be an example of

changes that occurred slowly enough in most urban areas to permit accurate modeling of blood lead concentration changes accompanying the air lead concentration changes.

1.3.3 Understanding Limitations of the Model

The IEUBK Model is designed to evaluate relatively stable exposure situations, rather than rapidly varying exposures. The model does not report each iterative calculation; rather, it reports one-year average blood lead concentrations. Because the IEUBK Model allows changes in exposure to environmental lead concentrations only at one year intervals, and provides output at only one year age intervals, changes in exposure are smoothed over one year. The model cannot be used to predict the effects of short term exposure episodes, such as exposure over a few days or weeks to lead dust and airborne particles that may be generated during lead paint abatement. The IEUBK Model should provide reasonable accuracy for blood lead concentration prediction as long as the changes in these environmental lead concentrations can be approximated by annual average values.

The model is intended to describe a single residential-level exposure setting. The dwelling unit could be a detached single-family home, a separate home in a multiple-unit building such as a row house or duplex, or an apartment in a multiple-unit building. There is an implicit assumption that the input parameters characterize long-term residential exposure scenarios in such settings. While exposure changes daily in response to changes in the child's diet and activity, there is presumably a true mean exposure level that can, in principle, be estimated from real-life samples. For this reason, the IEUBK model allows changes in air, food, dust, and soil lead exposure input parameters only at 1-year intervals. Although water lead exposure could, in principle, be handled in similar detail, the IEUBK model does not allow annual changes in drinking water lead during the model run. The IEUBK model includes some capabilities for dealing with lead exposures outside the home, such as by use of separate dust ingestion parameters and concentrations at day care centers, schools, and secondary residences.

We recommend using a simple average or arithmetic mean of soil lead concentrations from a representative area in the child's yard, and an average of dust lead concentrations from representative areas frequented by children inside the house. This rationale is appropriate for areas that are sufficiently small so that any part of the area may be accessible to a typical child living at a random residence located within the area.

The IEUBK model calculates blood lead and tissue lead burdens for all ages from 0 to 84 months. However, the blood lead concentrations in children less than 6 months of age will still be affected by pre-natal lead exposure and are likely to show little influence from exposure to soil, dust, and paint, which are the media currently of greatest interest. The results of the model simulation are therefore not reported for children younger than 6 months.

There are many reasons why individual blood lead concentrations may differ from the predicted geometric mean blood even though the predicted mean accurately describes the population. Some of the components of individual differences are discussed in Section 4.2. The GSD is the only parameter in the model that characterizes the combined variability in blood lead attributable to inter-individual differences and "random" temporal variability in absorption and biokinetics, "random" behavioral changes and inter-individual differences affecting ingestion rate, and measurement errors in environmental lead concentration. The strength of this approach is that GSD estimates are based on empirical data on the variability of blood lead levels in children exposed to similar concentrations of lead. Other approaches to evaluating the effects of variability, such as Monte Carlo simulation, were deferred for the present version of the IEUBK Model, because they demanded excessive computation and require much greater amounts of model input data. Monte Carlo methods, however, are still being evaluated as a possible enhancement of the IEUBK model, as discussed in Section 1.5.

1.4 RUNNING THE MODEL

1.4.1 Your Responsibilities

The IEUBK model provides a great deal of flexibility in describing site-specific or age-dependent exposure scenarios. The price for this level of flexibility is that no exposure scenario is appropriate for every application of the IEUBK model, and this is particularly true of the "default" parameters. The responsible use of the IEUBK model requires input data that are appropriate to the site(s) and subject(s). The most convenient way to do this is to use the exposure scenario worksheet (Figure 2-11; see Section 1.4.3).

The most sensitive parameters for most applications involving soil lead exposure are the soil-to-indoor dust transfer coefficient, the soil and dust ingestion parameters, the soil lead absorption fraction, and the Geometric Standard Deviation. You should always review these parameters.

Factors affecting transport of soil lead into household dust should be noted when appropriate. For example, houses with very small grass-covered yards are likely to have a smaller contribution of the yard's soil lead concentration to household dust lead concentration than houses with large yards, no grass cover, and fine uncompacted surface soils that are easily blown or carried into the house by humans and outdoor pets. While the concentration of lead in exterior dust derived from the soil may be a useful measure of exposure, these data are not usually available because exterior surface dust samples are not usually collected. You are always responsible for the decision to use default values in place of either measured dust lead concentrations or dust lead concentrations estimated from soil lead concentrations.

The proportion of intake in the form of soil vs. dust should be considered carefully, as there may be differences in the bioavailability of lead in soil vs. lead in house dust even when much of the dust is derived from soil. In spite of considerable efforts to determine the ingestion intake of soil and dust by children, these values are still subject to uncertainty. Site-specific data on soil ingestion by children are rarely available, but would be valuable in modeling site-specific exposure to lead. Only limited information is available about the effects of the child's micro-environment on soil and dust ingestion, with evidence suggesting much larger intakes of soil for children in intrinsically dirty environments such as campgrounds, and lower soil intake for children who spend much of their time in cleaner environments such as day care centers.

You are responsible for the choice of non-default bioavailability parameters. Bioavailability parameters may differ among sites. Non-default bioavailability parameters may be justified by experimental studies with the actual site materials, assessments of other sites with similar materials, or site specific information on properties of particles that may affect bioavailability.

The Geometric Standard Deviation is not considered a highly site-specific parameter, and should normally be kept at its default value of 1.60. If you use some other value, you should document the reasons for this modification, since risk estimates are typically very sensitive to the GSD value used.

1.4.2 Exploring Model Options

The IEUBK model has a large number of options. You are encouraged to explore these options before doing any substantive analyses, because there are often several alternative methods that can be used to obtain model outputs. These options are identified in Chapter 2.

They include alternative source menus for soil and dust lead, dietary lead, and lead in drinking water. The soil/dust lead menu includes options for air-to-dust and soil-to-dust transfer coefficients, as well as for non-household sources.

There are options beyond single runs of the model. These include multiple runs for overlay plotting of probability curves, for plotting blood lead vs. environmental media lead concentration, and for multiple runs (batch mode input) for each of a group of individual children of different ages using child-specific data.

The multi-media bioavailability menu includes options for changing the passive vs. facilitated absorption of lead from all media. The half-saturation uptake, a parameter that determines the extent of non-linear or saturable absorption, may also be changed from the normal default value of 100 μg Pb/day.

Run options include the choice of an iteration time step. With low exposure and no year-to-year change in concentration, as used in the "Default" option, there should be no differences in output using other iteration time steps. Differences in blood lead of a few percent may occur with higher and rapidly changing exposures. For a single run, almost any PC (XT or later) will produce a solution within 60 seconds, even without a math coprocessor, with the default iteration time of 4 hours. However, with a batch mode input file of several hundred records, the simulation run may take many hours. In this case, you may select a longer iteration time and speed up the run for a preliminary analysis. If you use a longer time step, you should verify accuracy using records with high exposure or large changes in exposure.

1.4.3 Documentation of Input Parameter and Data Files

By reviewing every adjustable parameter in the model and noting which ones have been modified in a particular run, you have a permanent record of the input. An electronic copy of the exposure input parameters can be made using the parameter SAVE option. Distinctive names for parameter files ([name].SV3), input data files ([name].DAT), simulation run files (RESULTS.TXT), batch mode output files ([name].TXT and [name].ASC), probability plot overlay files ([name].LAY) and blood lead vs. media concentration files ([name].MED) may be used to document input specifications as well as output.

The worksheet provides a convenient format for noting reasons for use of non-default parameters, or justification for use of default parameters. For example, soil lead

concentrations and dust lead concentrations could be measured values at each house. Repeated values of household data would be used to weight the statistical results from batch mode files. Missing value imputation methods should be identified, for example, "KID ID = 17,22,35, missing dust lead concentration estimated by PbD = 180 + 0.28 * PbS." This is critical information in allowing other users to reproduce your results (including yourself, since it is unlikely that most users will be able to recall over one hundred model parameters after the passage of some months or years).

1.4.4 Documentation of Model Output

1.4.4.1 Selecting Output Alternatives

Results of IEUBK model simulations may be saved in several forms. You should select in advance the most useful of these forms, since the results of some interactive simulations cannot be recovered once you have bypassed the opportunity to save the results. Choices are:

(1) A sequence of single simulation runs. Sequential runs can be interactively appended to the file named RESULTS.TXT. The average of the geometric mean blood lead concentrations for children in sequential one-year age intervals, the input concentrations for several media, and the media-specific daily lead uptake for each year are saved. You must use the "Save" option at the end of each run to be saved, but this allows you to drop results from non-informative runs rather than save them.

(2) A sequence of graphics overlay simulation runs. The multiple plot option saves input data for blood lead probability plots for a range of evenly spaced media lead concentrations. For example, you may generate plot data for soil lead concentrations of 250, 500, 750, and 1000 ug/g, for children of ages 12 to 24 months. The data in the [name].LAY overlay file includes the geometric mean blood lead for children in the age range, the lead concentration in soil and in other media. The actual plots of probability density or cumulative distribution functions depend on the GSD value selected, and these plots include the probability of exceeding the user-specified LOC for use in risk estimation. Probability plots may be printed on standard laser printers.

(3) A sequence of blood lead vs. media lead simulation runs. The media range option saves input data for blood lead vs. media lead plots for a range of evenly spaced media lead concentrations. For example, you may generate plots of blood lead vs. soil lead concentrations smoothly interpolated from calculated values at 250, 500, 750, and 1000 ug/g, for children of ages 12 to 24 months. The data in the [name].MED overlay

file includes the geometric mean blood lead for children in the age range at the selected media lead concentrations, the lead concentration in soil and in other media. Plots may be printed on standard laser printers.

(4) Batch mode simulation runs. The batch mode option requires an input data file, as described in Chapter 2. Output consists of user-named files [name].ASC and [name].TXT that contain predicted blood lead concentrations for each case or record (child) in the input data file. The output files also document the missing value imputations when some of the input data on residential lead concentrations in air, water, soil, or dust are missing. The files may be used as input for the statistical analysis programs in the companion PBSTAT program, which produce statistical and graphical comparisons of the observed and predicted blood lead concentrations.

1.4.4.2 Understanding the Output

You should carefully review the output options described in Section 1.4.4.1. Each option allows you to examine a different aspect of the IEUBK simulation. The numerical simulation component of the IEUBK model produces an estimate of a geometric mean blood lead concentration for children of a given yearly age. This is the average of the estimates for children during that one-year interval. The IEUBK model arrives at these estimates by calculating at each time step an updated estimate of all compartment lead masses, or equivalent tissue lead concentrations. The update algorithm combines uptake of lead from the environment with all of the movements of lead into each compartment from another compartment, or out of each compartment, either into another compartment or by elimination from the child's body. In this version of the IEUBK model, the output consists of the daily uptake rate (intake rate times fraction absorbed) for each medium, and the blood lead concentration, as annual averages.

The output from a single simulation run may be displayed in several forms. Most users wish to see the variability associated with a predicted blood lead concentration. This range can be demonstrated graphically by selecting the intrinsic variability GSD and then plotting a cumulative probability distribution. The range of plausible blood lead values may be determined graphically as defined by upper and lower percentiles of the distribution. For example, the 5th and 95th percentiles of the distribution will include 90 percent of the children with the given site-specific or household-specific exposure scenario. Since "plausible range" requires a subjective choice of percentiles, you are free to choose any appropriate values. Since the predicted geometric mean blood lead concentration is based on

an a priori mathematical simulation and not on a data-driven statistical estimate, this plausible range should never be considered as equivalent to a confidence interval.

The other output characteristic that many users wish to see is the estimated probability of exceeding the specified blood lead level of concern, corresponding to the given exposure scenario or scenarios (for multiple runs in a given medium). This also requires a GSD value. This probability may be interpreted as the percentage of children with the given household-specific exposure scenario who are expected to exceed the level of concern. If applied to a single site or residence, it may also be interpreted as the probability of exceeding the level of concern for any single child who may reside at that site in the future.

1.4.4.3 Interpreting the Output and Communicating the Results

The model calculates the probability that a blood lead concentration derived from the model's specified parameters will exceed a level of concern specified by the user. There are two valid interpretations for the output:

(1) The output of the model may be considered to be the best estimate of a plausible range of blood lead concentrations for a hypothetical child with a specific lead exposure scenario. The range of values is centered on the geometric mean blood lead concentration expected for a typical child with this exposure scenario. The upper tail of the probability distribution provides an estimate of the risk of exceeding some blood lead level of concern for a typical child of that age residing in the same household and with the same exposure history.

(2) The output of the model may also be considered to be the predicted geometric mean blood lead of a *population* of children with the same lead exposure scenario, and the upper tail of the probability distribution to be the fraction of children exceeding the chosen blood lead level of concern when all of these children have the same exposure history.

The array of applications for which the IEUBK model can be validly used is:

A: One location
- A1: one living unit, one child;
- A2: one living unit, more than one child;
- A3: more than one living unit, more than one child, homogeneous media concentrations;

B: Multiple locations, one neighborhood, homogeneous media concentrations

C: Multiple locations, one neighborhood, heterogeneous media concentrations;

D: Multiple locations, more than one neighborhood, heterogeneous media concentrations;

A single run of the IEUBK model is sufficient for categories A and B. A classification or disaggregation of the neighborhood into distinct exposure subgroups is required in categories C and D, with the possibility of different ingestion or absorption parameters for different neighborhoods in category D. Neighborhood-scale and community-scale risk estimation requires aggregating the risk estimates for individuals or subgroups.

The differences between these levels is sketched in Figure 1-3. Category A requires calculating only a single blood distribution. Category B requires calculating a blood lead distribution for each child, but since each child of the same age has the same exposure scenario in category B, a single run of the model is sufficient to characterize risk for this subgroup. In category C, there are different exposure scenarios for each subgroup. Risk estimates must be calculated for each such subgroup, then added up across sites and children.

The model output in category A: Single child, single site of exposure, includes a blood lead concentration, a distribution of blood lead concentrations, and a probability of exceeding the blood lead level of concern. Since children in environments with the same lead exposure may have a range of blood lead concentrations, we describe the likely variability in blood lead for a child with a given exposure scenario by a probability distribution. The predicted blood lead concentration is the geometric mean of the distribution of blood lead concentrations that may occur for a typical child with the specified exposure scenario. Risk is calculated from this distribution as the probability that a hypothetical child living at this site, with the specified exposure scenario, will have a blood lead concentration exceeding the blood lead level of concern. This single-child assessment is necessary in order to use the model to evaluate remediation options on a house-by-house or yard-by-yard basis. The single-child assessment also provides a criterion for model testing and validation using epidemiology data.

The model output in category B: Multiple children, single site or equivalent sites of exposure, is the predicted blood lead concentration for each child as the geometric mean of the distribution of blood lead concentrations that may occur for each child with the specified exposure scenario. Risk is calculated by aggregating the calculated risk for each child as the percentage of hypothetical children living at this site or at these sites, with the specified exposure scenario, that will have a blood lead concentration exceeding the blood lead level of

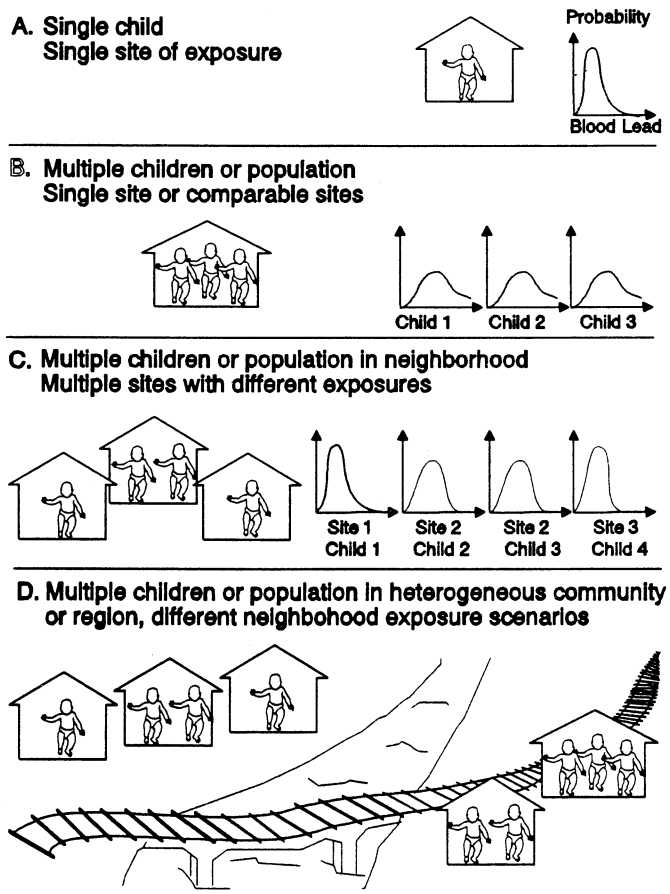


Figure 1-3. Categories of application of the IEUBK Model.

concern. The calculation is exactly the same as the single-child assessment, but there is an important shift in interpretation of the output.

There are situations in which a single site really can have multiple children of the same age with the same exposure scenario. A single housing unit may be occupied by several households with pre-school children of the same age. Rental properties may be occupied in succeeding years by different families, each of which may have a pre-school child of the same age with virtually the same exposure as occupants in other years. In general, the multiple-child or population exposure scenarios would be applied to a hypothetical population of occupants.

Neighborhood-scale risk estimation is discussed in Section 4.2, with examples. The model output in C: Multiple children, multiple sites with different exposure, cannot be

obtained by a single run of the IEUBK model. It is necessary to construct an exposure scenario for each distinct exposure subgroup in the population. For each child or exposure subgroup, risk is calculated in a single run of the IEUBK model with the specified exposure scenario. The risks for each exposure subgroup are aggregated across all subgroups, weighted by the number of children with that exposure scenario or by the percentage or likelihood of the exposure scenario.

There is no one-step method by which neighborhood-scale risk estimation can be done using this version of the IEUBK model. The problem of risk estimation for children in a large community or a region is even more difficult when different subgroups of children may have very different exposure scenarios, including differences in behavior that affect ingestion, and differences in lead absorption due to behavioral or nutritional differences.

A common misinterpretation of the IEUBK Model is that it predicts *community* geometric mean blood lead and the fraction of children at risk when the input is the mean or geometric mean of household-specific environmental lead concentrations. That mis-step can be misleading, particularly when the environmental variables have a wide distribution among the neighborhoods of the community. This misinterpretation is especially dangerous for post-abatement settings intended to eliminate the higher exposures when there are multiple exposure media. A correct approach requires applying the model to each individual home or site using the lead concentrations seen at that site and combining these results as an aggregate of sites in several neighborhoods to form an estimate of community risk. A second useful approach is based on subdividing a community into neighborhoods and clusters of residence units with similar media lead concentrations. Specific information on building appropriate neighborhood exposure scenarios is given in Section 2.3, *Building an Exposure Scenario*. Examples are provided in Section 4.2.

We should emphasize that the IEUBK model is intended to provide a best estimate of geometric mean blood lead. The IEUBK model is not intended to be used in a worst-case scenario, as the model does not apply any uncertainty factors or modifying factors in making risk estimates. If, as usual, there is some uncertainty about model parameters, these can be evaluated using sensitivity analyses. Remember that you are responsible for documenting plausible non-default values.

Uncertainty about parameters is not the same as the intrinsic variability in environmental data and blood lead responses. The components of variability are discussed in

Section 4.2 on the blood lead Geometric Standard Deviation (GSD), which plays a critical role in risk estimates.

1.5 REFINEMENTS AND ENHANCEMENTS

The biokinetic component of the IEUBK model is based on an age-dependent compartmental model with identifiable physiological compartments: red blood cells, plasma and extracellular fluids, kidney, liver, other soft tissues, trabecular and cortical bone (Figure 1-1). There are many compartmental models in the literature; some with fewer compartments (Rabinowitz et al., 1976), others with many more compartments (Leggett, 1993). The Technical Review Workgroup for Lead was aware of important research in the development of physiologically-based pharmacokinetic (PB-PK) models for lead in humans, primates and rats that took into account the slow diffusion of lead through the bone matrix (O'Flaherty, 1992a,b,c, 1993a,b). However, the Workgroup chose to develop a compartmental model that uses transfer times or transfer rates between compartments instead of physiologically based compartmental coefficients. The transfer rates can be estimated from data in non-human primates, especially the studies on infant and juvenile baboons that were done at New York University (Mallon et al., 1983; Harley and Kneip, 1985).

The IEUBK biokinetic model was based on:

(1) empirical kinetic data on blood lead in baboons of similar weight and developmental stage to human infants and young children;

(2) kidney, liver, tibia and femur lead concentrations in baboons after the end of the lead exposure study;

(3) autopsy data for lead levels in young children who died from causes not related to lead exposure;

(4) extrapolations from studies in human adults;

(5) lead feeding and lead balance studies in human infants.

There is, in principle, a degree of similarity between these approaches, since the compartments in the IEUBK model are defined by real anatomical and physiological properties. The transfer times from the PB-PK model can be calculated from blood flow rates to organs and tissue groups, volumes of these organs, partition coefficients across

membranes, and solid state diffusion coefficients for the bone matrix. The principal difference between the biokinetic components of the IEUBK and PB-PK models is that, in the absence of suitable physiological data, empirical data were used in estimating transfer times in the IEUBK model. Future development of the IEUBK Model is expected to continue in the direction of physiologically based biokinetic components similar to PB-PK models.

Many users have expressed interest in tools that allow a more detailed investigation of the effects of non-environmental variability on the distribution of blood lead concentration. The Monte Carlo approach would allow every parameter in the model to be assigned a random variation at every iteration of the computation. For example, each parameter could be multiplied by a random factor (mean value 1) at every iteration. This would require that adequate data would be available to support the input distributions. An extremely large amount of computing would be necessary. A substantial amount of additional study is needed before Monte Carlo methods can be added to the IEUBK model.

The IEUBK model currently evaluates children from birth to age 84 months. Many users have requested extension of the model to other populations, including older children and adults, with emphasis on populations at special risk. Both the physiological and biokinetic parameters of adults are at least as well known as those of children, with the possible exception of lead distribution within the human maternal-fetal unit. Transfer of lead from the mother to the neonate during lactation would also be of interest.

1.6 GETTING MORE HELP

As scientific knowledge advances, this Guidance Manual will be updated and revised. If you have questions regarding the site-specific application of the IEUBK Model, you may direct your inquiries to the appropriate EPA Regional Toxics Integration Coordinator. Comments on the technical content of the manual or suggestions for its improvement may be brought to the attention of members of the EPA Technical Review Workgroup for Lead listed in the front of this document.

2. A GUIDED TOUR THROUGH THE LEAD MODEL

2.1 THE LEAD MODEL IS DRIVEN BY MENUS

Environmental Protection Agency's Integrated Exposure, Uptake, and Biokinetic Model for Lead in Children (IEUBK Model) is a microcomputer program that performs many different functions related to estimating blood lead levels in children. The overall model functions are sketched in Figure 2-1.

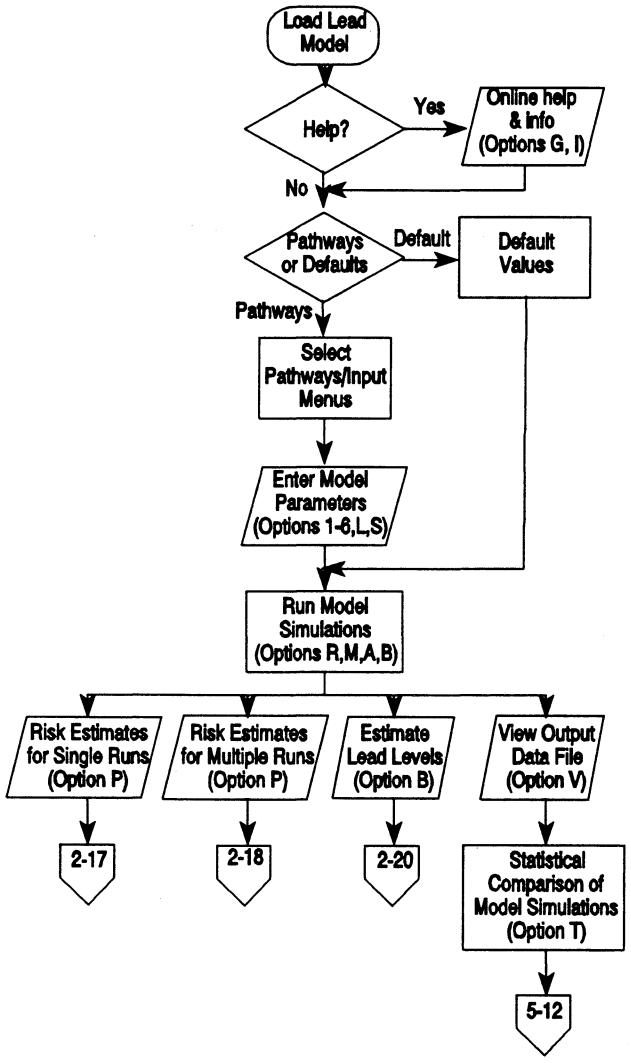


Figure 2-1. Schematic diagram of the overall functions of the lead model. Numbers in pentagons indicate sections in this document containing more detailed information.

The oval shapes are terminal steps (i.e., the beginning or end of a function or option). Rectangles show internal processes and rhomboids show user data entry operations or functions. Diamond-shaped figures are decision points where the user must choose one of the model options on a list. The "NO" branch usually follows the model's baseline or "default" parameters and functions. Horizontal and vertical arrows refer the user to another figure or page.

The IEUBK model is menu-driven, with on-line help available in almost any menu. The main menu, where any use of the IEUBK model begins, is shown in Screen 2-1. There are five numbered options:

1. Parameter Input Menu
   - 1: Air lead menu
   - 2: Dietary lead menu
   - 3: Drinking water lead menu
   - 4: Soil/Dust lead menu
   - 5: Alternative lead source menu
   - 6: Maternal lead menu
   - L: Load pre-saved parameter input menu
   - R: Return to Main Menu

2. Computation Menu
   - 1: Run a single model simulation
   - 2: Multiple simulation runs with a range of values
   - 3: Blood lead versus media with a range of values
   - 4: Multiple simulation runs with batch input (input data file for each child or household)
   - R: Return to Main Menu

3. Output Processing Menu
   - 1: Save program parameters to file
   - 2: Plot graphs of blood lead distributions
   - R: Return to Main Menu

4. Help Menu
   - 1: General information
   - 2: Information about menus plus help in other menus
   - R: Return to Main Menu

5. Quit
   - Q: Return to DOS prompt.

Screen 2-1. The main menu.

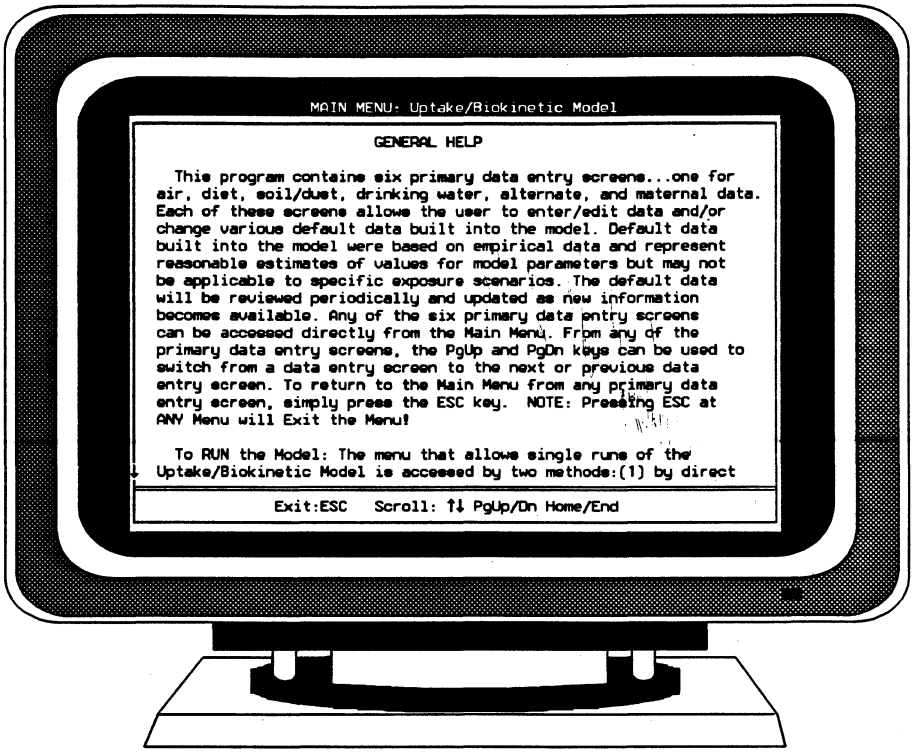
We will briefly discuss the options in each of the input menus. Scientific justifications for the options and guidance values are provided in Section 2.3.

2.2 DETAILED DESCRIPTION OF MENUS

2.2.1 Help Menu (4)

2.2.1.1 General Help (1)

The General Help menu provides on-line information on the data or parameter entry menus, menu selections for running single or multiple model simulations, and use of keyboard keys. This information is shown in Screen 2-2.



Screen 2-2. The general help menu.

2.2.1.2 Information Menu (2)

The Information Menu provides on-line information on the parameter save and load file options, on multiple-run and output processing menus. The information is presented here in Screen 2-3.

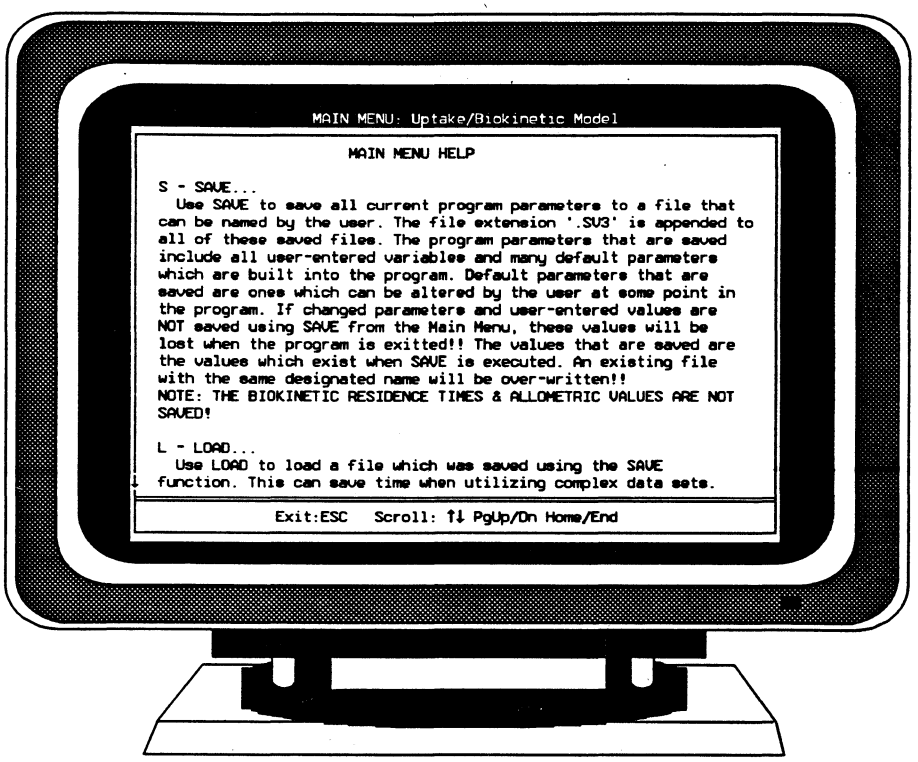
2.2.1.3 Other On-Line Help Menus

Most menu screens contain additional information on the lower part of the screen. Additional information screens are available on specific menu options.

2.2.2 Parameter Input Menus

2.2.2.1 Air Lead (1)

The Air Lead input parameter menu is shown in Screen 2-4 and schematically in Figure 2-2. The air lead concentration is set initially to a typical 1993 urban value of 0.1 $\mu g/m^3$ (U.S. Environmental Protection Agency, 1991c). It is assumed that the indoor air



Screen 2-3. The information menu.

Screen 2-4. The air lead menu.

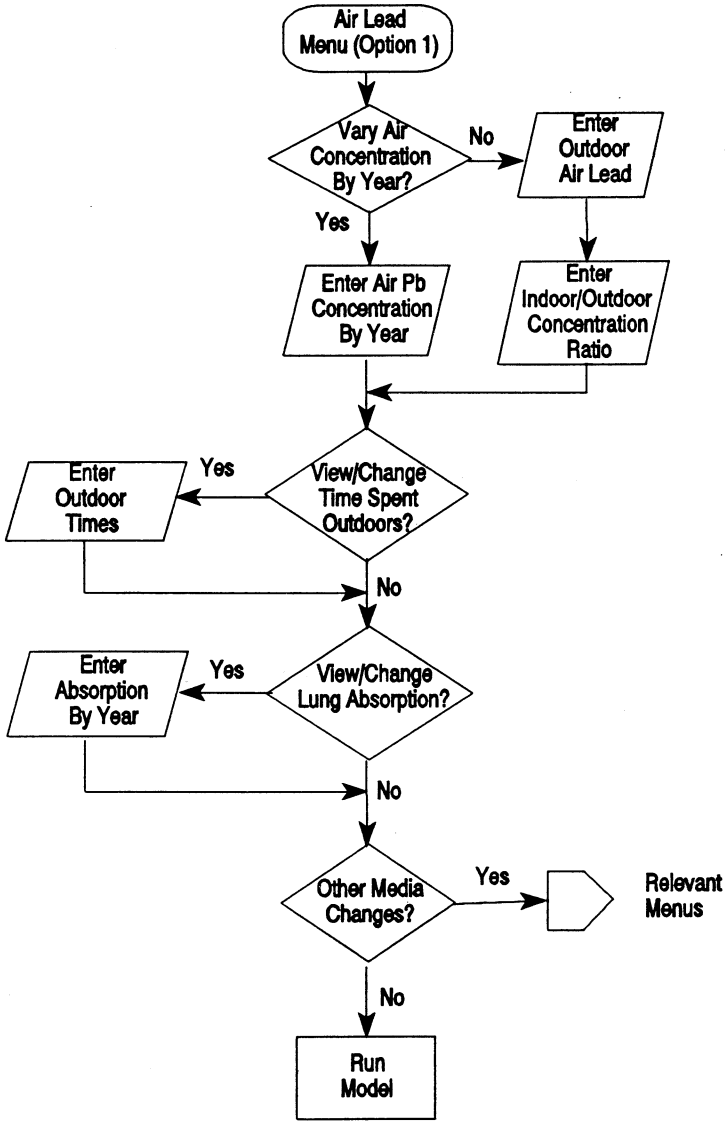
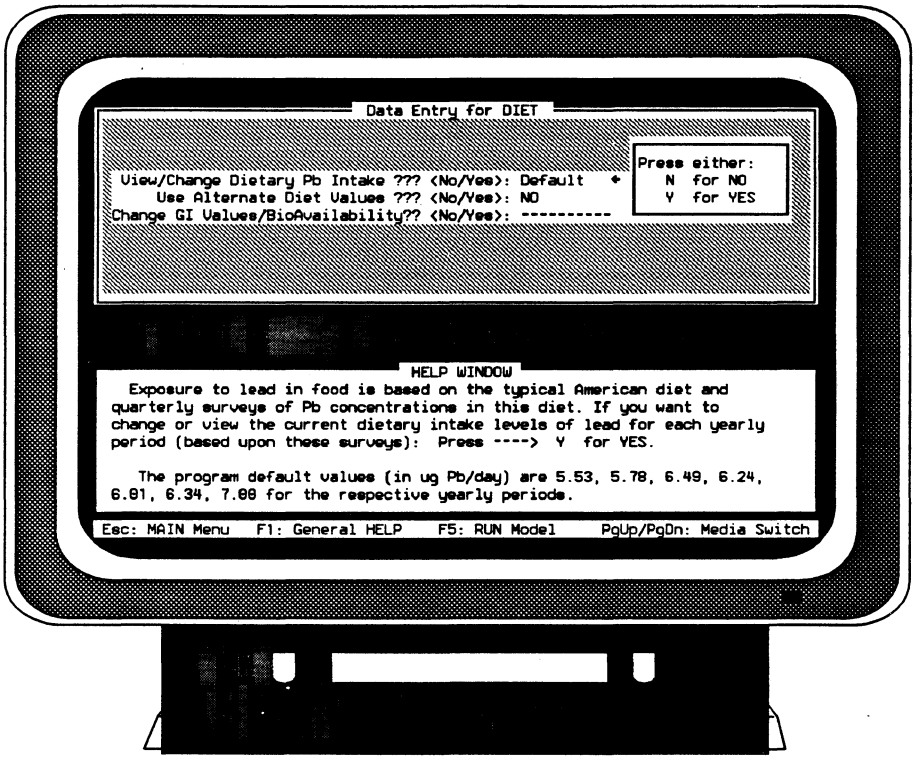


Figure 2-2. Decision diagram for the air lead menu options.

lead concentration is 30% of the outdoor concentration (i.e., 0.03 $\mu g/m^3$) initially. The time spent outdoors and ventilation rate are assumed to depend on the child's age. These parameters allow a time-weighted air lead intake to be calculated; 32% of that intake is absorbed through the lungs into the child's blood. All parameters except the indoor/outdoor air lead concentration ratio may be changed by entering YES in the first line. Some are age-specific values.

2.2.2.2 Dietary Lead (2)

The Dietary Lead input parameter menu is shown in Screen 2-5 and schematically in Figure 2-3. The daily dietary lead intake values for each age apply to a typical U.S. child in a typical setting in the United States after 1990. These dietary lead values may be altered by entering YES to the query "View/Change Dietary Pb Intake?" During the period 1982-1989 there was a distinct reduction in food lead generally attributed to the replacement of lead-soldered cans and the removal of lead from gasoline. Since 1990, food lead in U.S. supermarket food has remained relatively constant. Dietary lead ingestion for years prior to 1990 are given in Section 2.3.2.



Screen 2-5. The dietary lead main menu.

If the dietary lead sources are non-standard, usually because of suspected contamination of fruits, vegetables, fish and meat raised locally or otherwise lead-contaminated, the user can enter specific values by responding YES to the query, "Use Alternate Diet values?" This invokes the alternative menu shown in Screen 2-6.

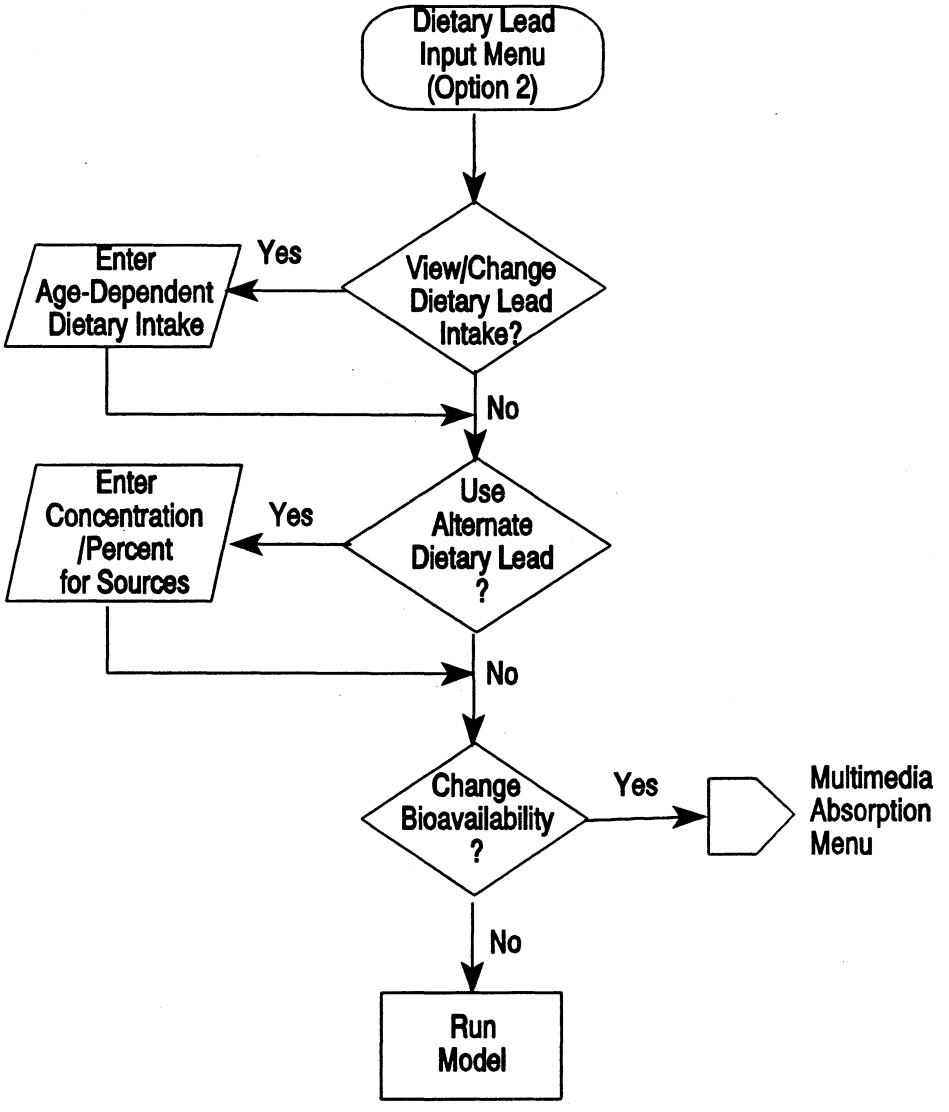
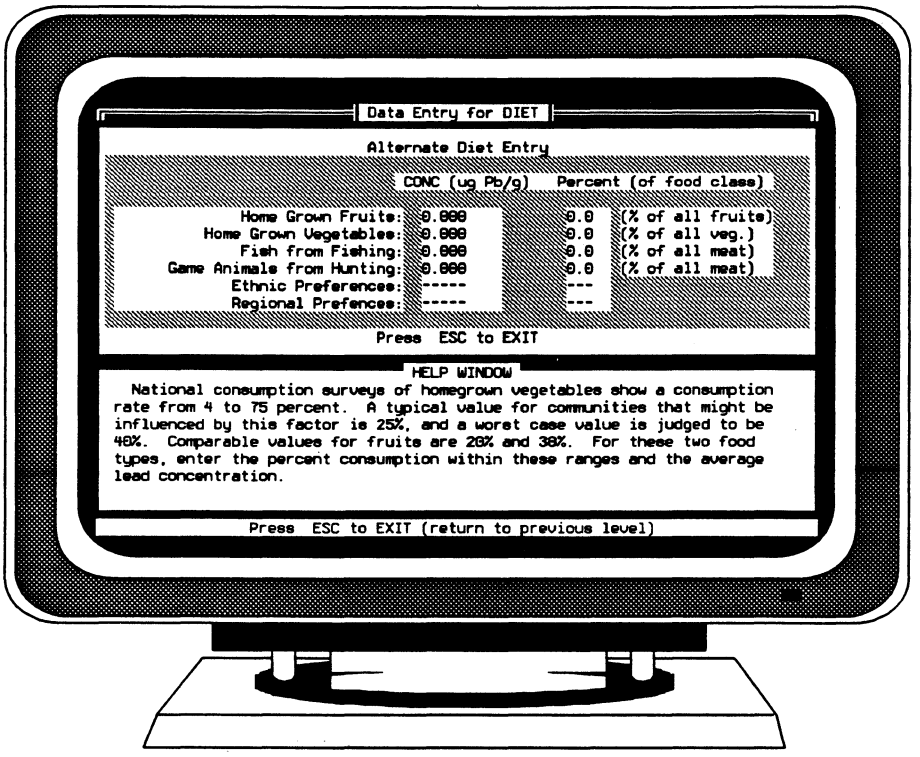


Figure 2-3. Decision diagram for the dietary lead menu options.

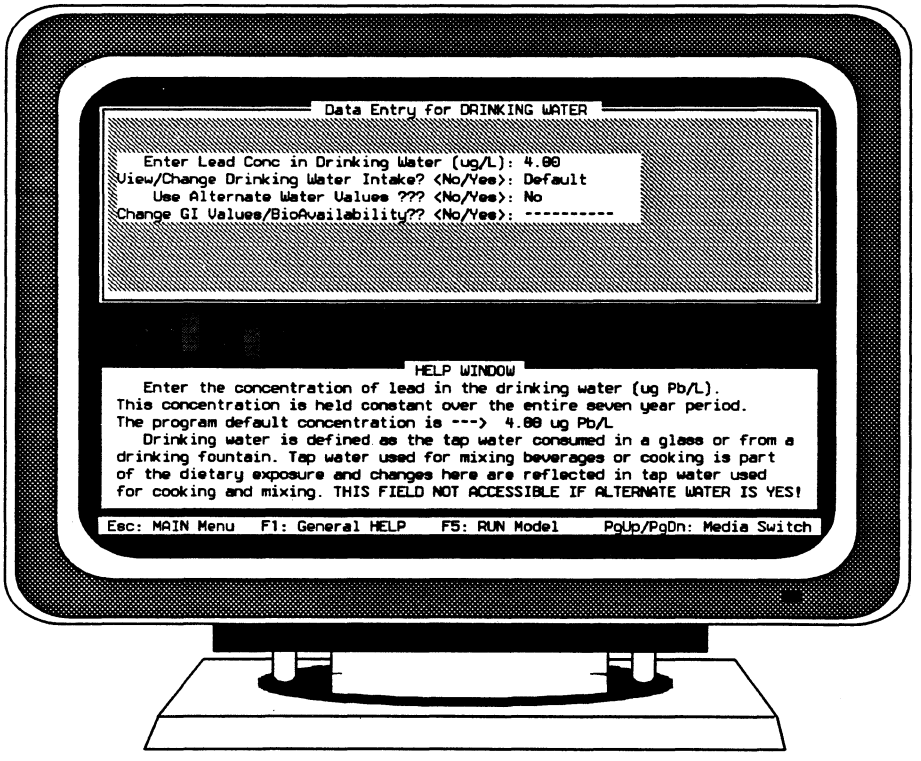
2.2.2.3 Drinking Water Lead (3)

The Water Lead input parameter menu is shown in Screen 2-7 and schematically in Figure 2-4. The water lead concentration is set initially to a typical 1990 urban value of 4 μg/L (Marcus and Holtzman, 1990). The age-specific ingestion of tap water is described in Section 2.3.3.2. Consumption may be modified by responding YES to "View/Change Drinking Water Intake?" and entering new values, as shown on Screen 2-8.

Alternative information may be available in the form of measured lead concentration and percentage of tap water intake from water fountains or other outside sources, and water



Screen 2-6. The alternative dietary source menu.



Screen 2-7. The drinking water lead main menu.

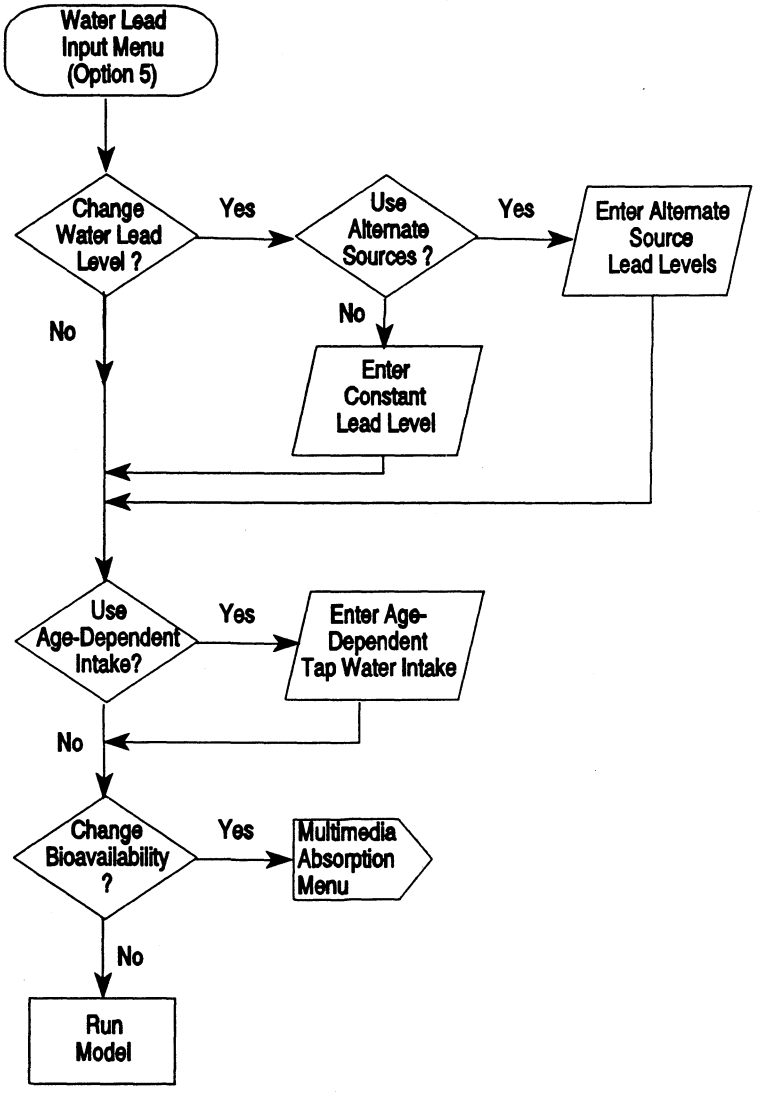
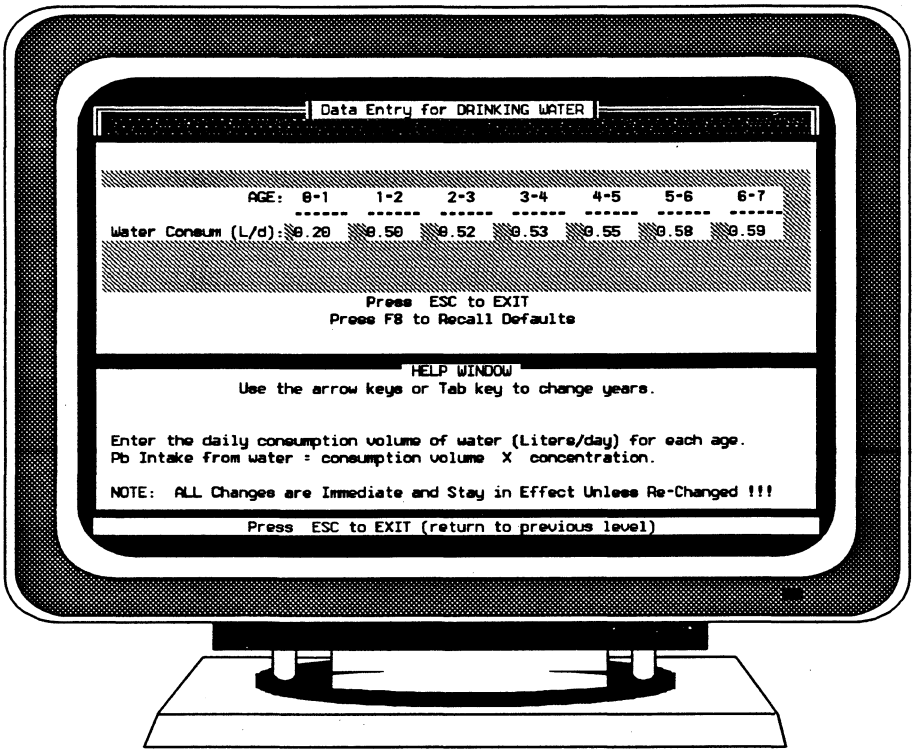


Figure 2-4. Decision diagram for the drinking water lead menu options.

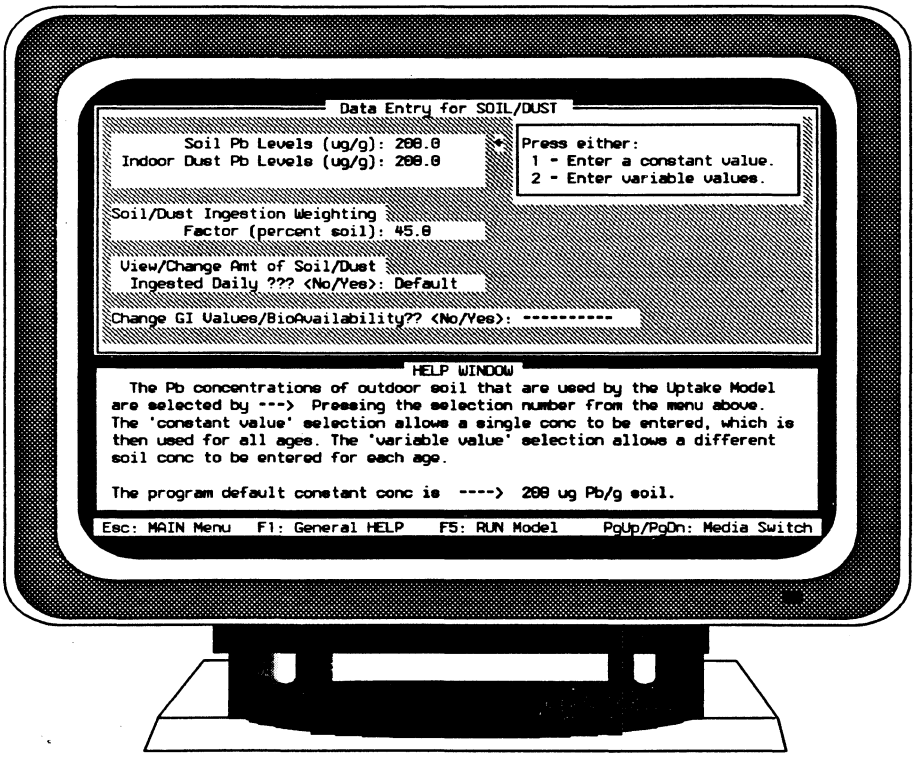
consumed at home in first-draw or flushed modes. This may be entered by responding YES to "Use Alternate Water Values?"

2.2.2.4 Soil and Dust Lead (4)

The Soil and Dust Lead input parameter menu is shown in Screen 2-9 and schematically in Figure 2-5. The soil and dust lead concentrations are set initially to a value of 200 μg/g. The age-specific ingestion intake of soil and dust combined was estimated from the EPA/OAQPS staff paper on Exposure Assessment Methodology and Validation for the first



Screen 2-8. The age-specific drinking water consumption menu.



Screen 2-9. The soil and dust main menu.

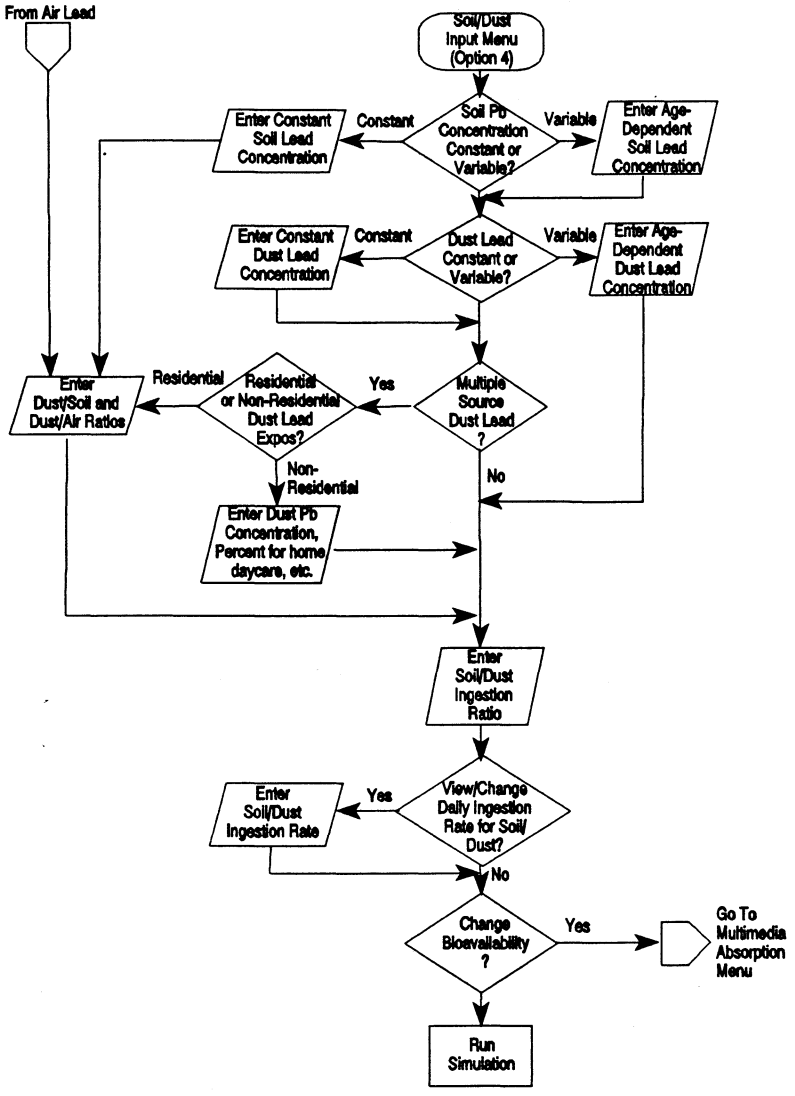


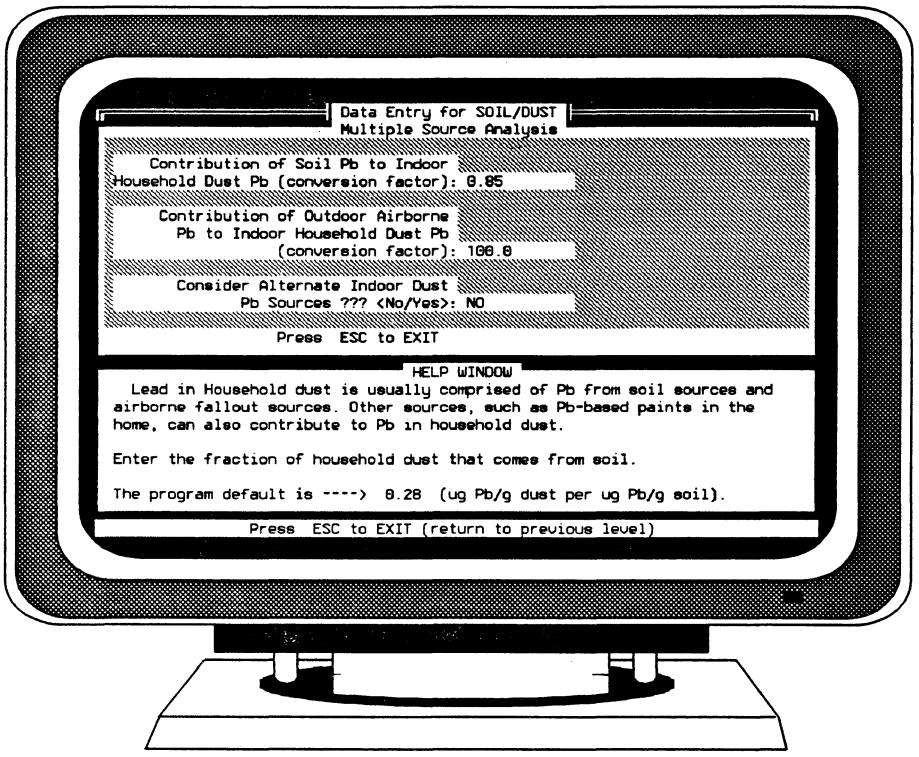
Figure 2-5. Decision diagram for the soil/dust lead menu options.

version of the UBK model (U.S. Environmental Protection Agency, 1989a). Both concentration and intake may be modified by the user.

As shown in Screen 2-9, both soil lead and dust lead concentrations may be changed on a yearly basis by user selection "2", allowing the user to construct reasonable site-specific scenarios.

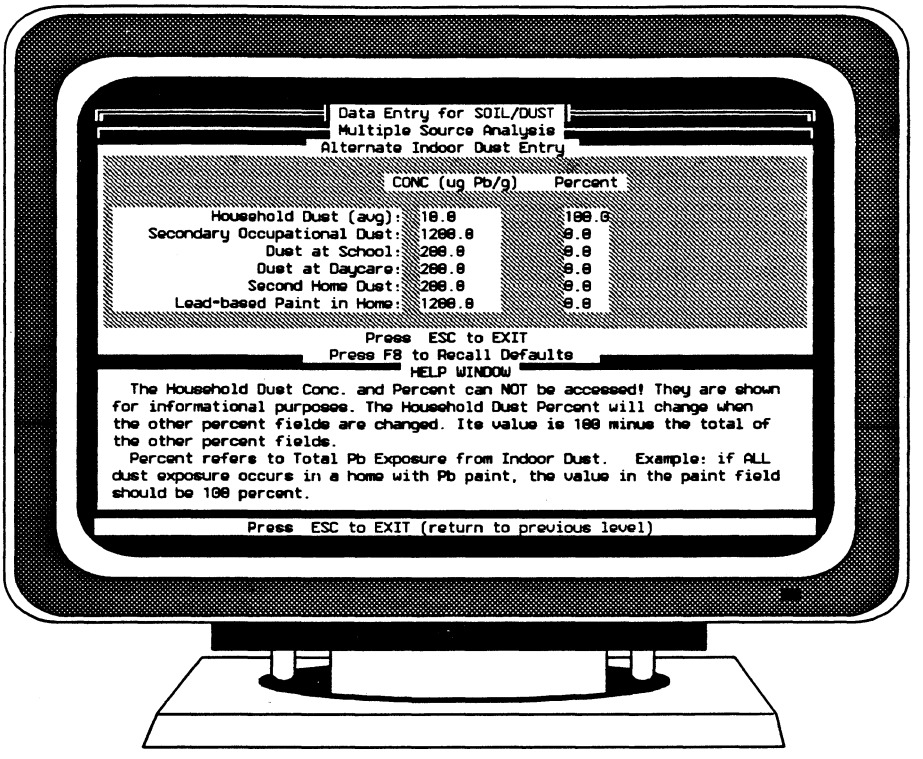
The multiple-source option ("3") on the dust entry line allows the user to use information about the contribution of soil lead, air lead, and other sources to household dust

lead. The Data Entry Screen for the Multiple Source Analysis (Screen 2-10) has three data entry lines. The first line is the *fraction of the soil lead concentration* that contributes to the *concentration of lead in household dust*. If there were no other sources, this would be the ratio of the dust lead concentration to the soil lead concentration. The current default value of 0.70 is appropriate to neighborhoods or residences in which loose particles of surface soil are readily transported into the house. The second data entry line is the contribution to household dust from the deposition of airborne lead, over and above the soil lead contribution. The current default value is an additive increment of 100 μg/g lead in house dust for each μg Pb/m^3 air.



Screen 2-10. The multiple dust source menu.

The third line asks whether the user wants to add other sources. If "Yes", then the Multiple Source Analysis Screen is replaced by the Alternative Indoor Dust Entry screen (Screen 2-11). The user may assign both the concentration and percentage of dust intake to baseline household dust, secondary occupational dust, dust at school, daycare, or second home, and the exposure to lead in dust from household paint measured as a percentage of total dust ingestion and its concentration. The default dust lead concentration in the



Screen 2-11. The alternative indoor dust menu.

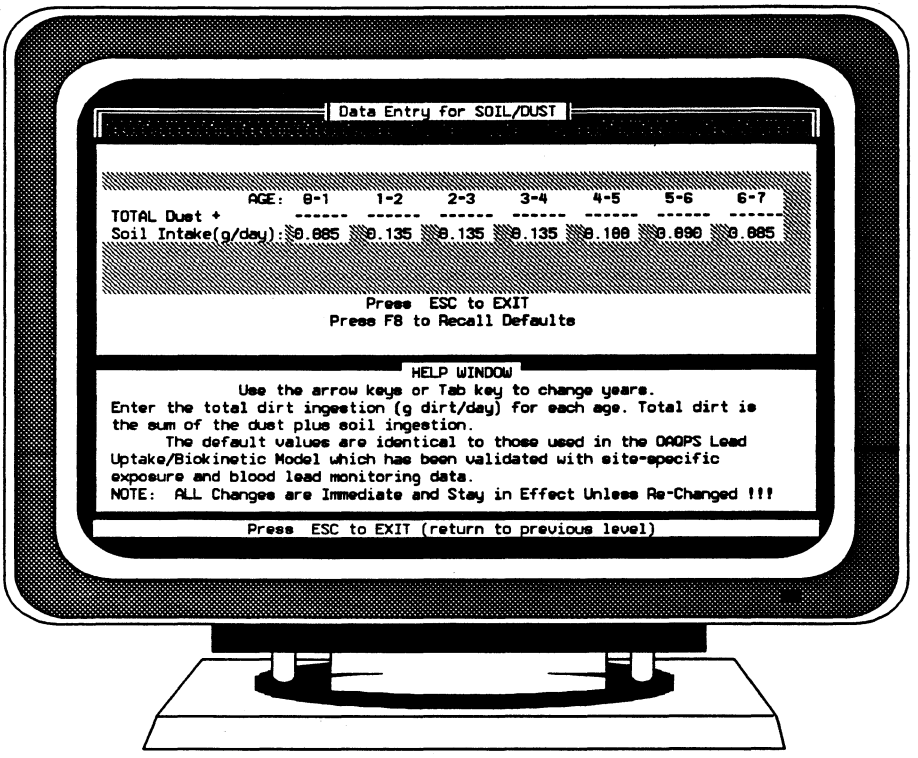
Alternative Indoor Dust Entry screen is 100% of household dust at 150 μg/g. If the Alternative Source Analysis is not used, then the default dust contribution consists of 70% of the soil concentration plus 100 times the air lead concentration. For default conditions, the total dust lead concentration equals 150 μg/g.

If non-residential exposures to soil/dust are important, the user may access the multiple non-residential source menu.

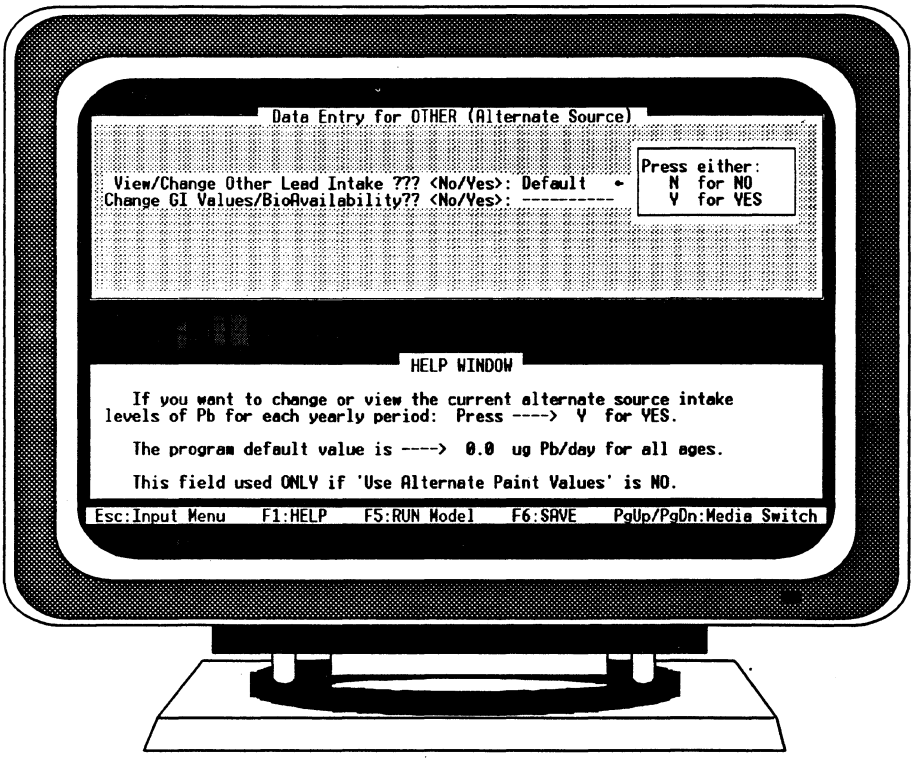
The combined soil/dust ingestion rate (grams total soil + dust per day) can be changed from the current default values in Screen 2-12.

2.2.2.5 Alternate Source (5)

The alternate exposure source menu is shown in Screen 2-13 and schematically in Figure 2-6. The default daily lead intake value for each age is set to 0 μg Pb/day. The user has the option to input any source not otherwise covered by other menus. Examples might be the direct ingestion of lead-based paint, cosmetics or home remedies. In this case, the amount of lead per day needs to be calculated from the information available. If the



Screen 2-12. The soil/dust ingestion rate menu.



Screen 2-13. The alternate lead source menu.

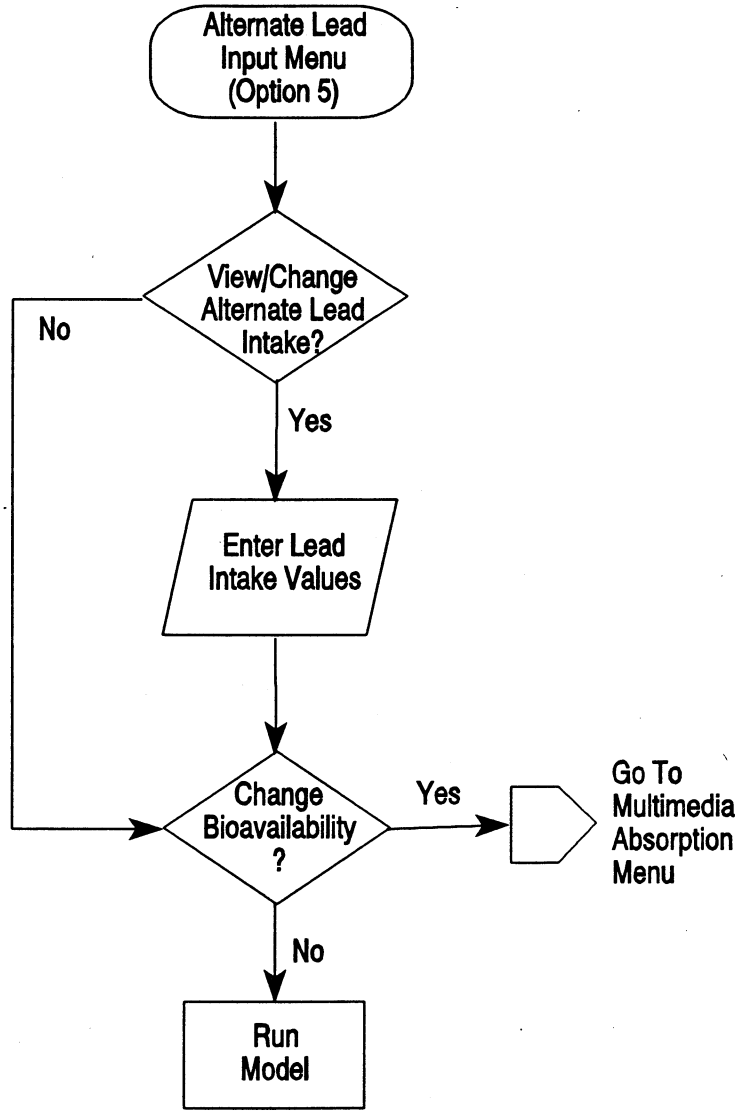


Figure 2-6. Decision diagram for the alternate lead source menu options.

alternative source is lead-based paint (LBP), this exposure would be in addition to exposure to lead-based paint in house dust, which is Option 4 in the multiple source menu of soil and dust. See Section 4.7.1 for a discussion on issues in the use of the model for paint chips.

Building an exposure scenario using this option should be done with care. The model assumes all entries represent chronic exposure. In the example above, the child would require immediate medical attention. Remember that the model output represents only those children defined by the exposure scenario.

2.2.2.6 Bioavailability of Lead in Food, Drinking Water, Soil, and Dust

Bioavailability or absorption of intake from the gut or lung into the blood is a key element in relating external exposure to body burden. Lead intake from media with low bioavailability poses much less of a hazard than does the same intake from media with high bioavailability. The bioavailability of lead from normal infant diet is known to be very high (Alexander et al., 1974a,b; Ziegler et al., 1978; Ryu et al., 1983), with at least 40 to 50% of the dietary lead intake passing into the child's blood. See Section 4.1 for a discussion of bioavailability.

The main functions of the bioavailability menu are shown in Figure 2-7. The model calculates lead absorption from the gut as a function of two components. The *passive* component does not depend on lead concentration in the gut and is not saturable. The *facilitated or active* component may become saturated when the total concentration of lead in the gut from total gut intake by all media is sufficiently large, which is a kinetically *non-linear* absorption mechanism. The data entry Screen 2-14 allows the user to specify the parameters for intake from soil, dust, drinking water, diet, and alternate sources. The total absorption percentage is the sum of the passive and facilitated absorption components. The default value of absorption for alternate sources is 0%, which requires that the user must enter the bioavailibilty of any specific alternative source, such as lead-based paint.

The total absorption from any medium is then divided into two components, and the user specifies a small fraction of the total absorption percent for the passive or non-saturable (i.e., high-dose) component. The default is 20% of the total available for absorption. The percentage absorption in the larger saturable component is the remainder of the total available for absorption. For example, with a dietary lead intake of 50%, the absorption fraction for the passive component is 20% of 50%, or 10% of dietary lead intake, and the saturable component is 80% of 50%, or 40% of dietary lead intake.

2.2.2.7 Maternal-Fetal Lead Exposure (6)

The maternal lead exposure input parameter menu is shown in Screen 2-15. The lead is transferred from the mother to the fetus *in utero*. The lead that is stored in the tissues of the newborn child is calculated by entering the maternal blood lead value at birth (default = 2.5 μg/dL). The IEUBK model assumes that the infant's blood lead at birth is a fraction of the maternal blood lead level, and the amounts of lead in the blood and other tissues in the newborn infant are calculated so as to be consistent with concentration ratios observed in autopsies of newborn infants (Barry, 1981).

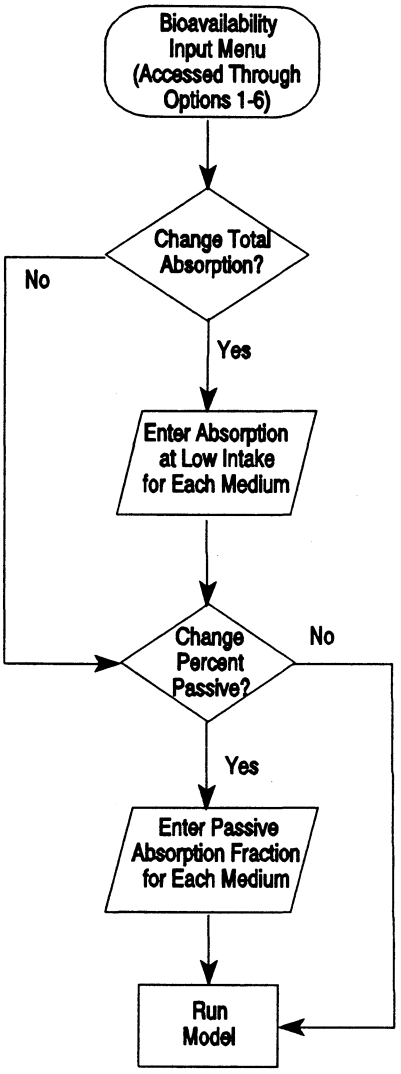
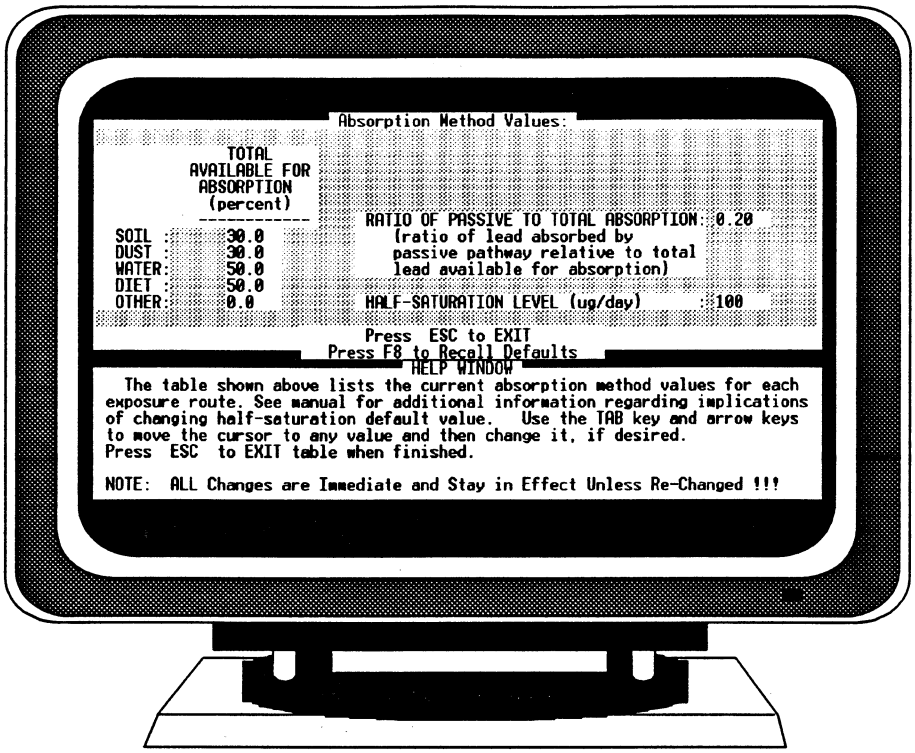


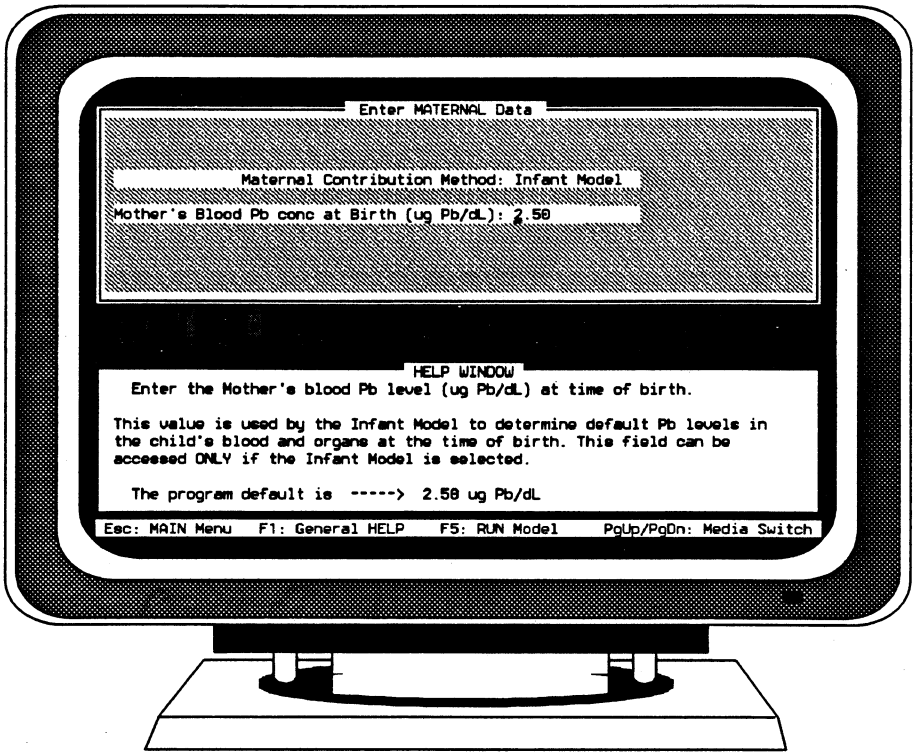
Figure 2-7. Decision diagram for the absorption/bioavailability menu options.

2.2.2.8 Save and Load Options

If the user wishes to use a certain set of model parameters as the starting point for another analysis, the parameter set created from use of Options 1 through 6 should be *saved* using the "S" option on the output menu accessed from the main menu, or the F6 option on any of the parameter input menus. The user may create an 8-character or shorter name for the file, which will be stored in the form [NAME].SV3. If a saved parameter set is needed later, it may be loaded from the "L" option on the Parameter Input Menu.



Screen 2-14. The absorption/bioavailability menu.



Screen 2-15. The maternal/fetal lead exposure menu.

2.2.3 Computation Menu

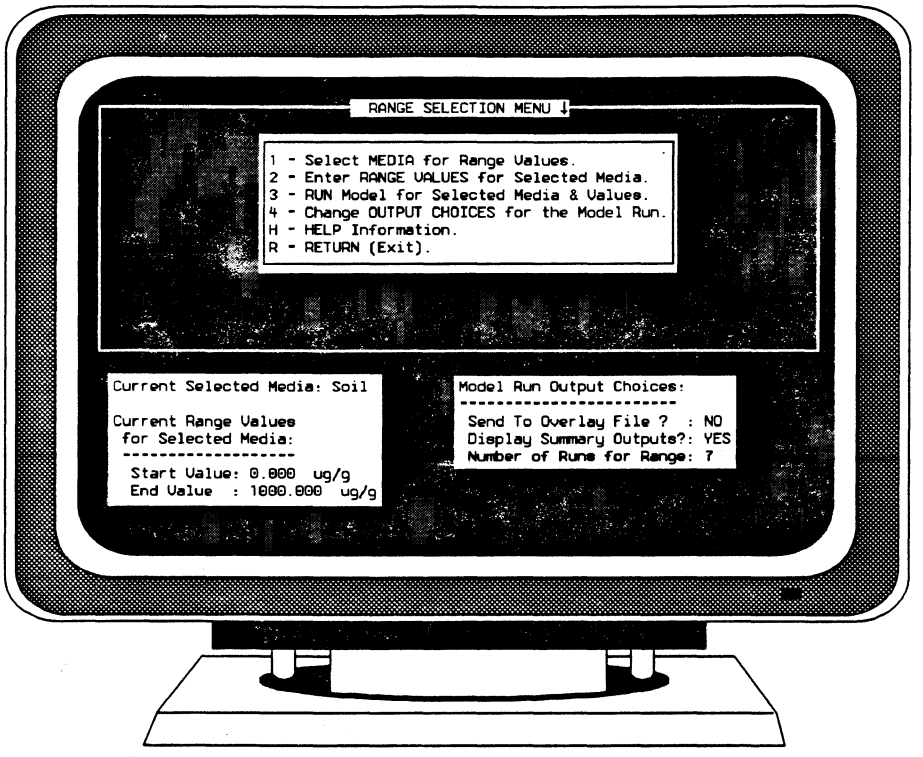
2.2.3.1 Run a Single Simulation of the Model (1)

The menus for the Run command are shown in Screen 2-16. This option uses only the currently loaded parameter set. The user may view or change the time step for the numerical iteration. The default is four hours. We recommend setting the iteration time to the lowest convenient selection, and verifying all "important" solutions by rerunning the model with the shortest possible time step (currently 15 min). An output option (Option 2) allows plotting of results and calculation of probability of elevated blood lead.

Screen 2-16. Single simulation using the program processing menu.

2.2.3.2 Run Multiple Simulations of the Model for a Range of Media Lead (2)

The menus for the Multiple Run command are shown in Screen 2-17 and schematically in Figure 2-8. More detailed menus for range selection and output are shown in Screens 2-18 and 2-19. This option uses only the currently loaded parameter set, except that it repeats the run for each new value of a medium concentration (e.g., soil lead concentration) or intake (dietary lead as μg Pb per day). The user may view or change the



Screen 2-17. Multiple simulation using the program processing menu.

time step for the numerical iteration during the run step. We recommend verifying all of the "important" solutions by rerunning the model with the shortest possible time step (currently 15 min). Since only one medium can be changed in each use of the "2" option, the user who wants to look at a range of soil lead values should use the Multiple Source Dust option "3" and a user-specified dust lead to soil lead concentration ratio. Output data for plotting, with overlays of results at each concentration in the range, may be saved when the user creates RANGE#.LAY files.

2.2.3.3 Multiple Simulation Runs of a Medium To Find Concentration of Lead in the Medium That Produces a Specified Blood Lead (3)

This option is similar to Option 2. The menus for the Multiple Run command are shown in Screen 2-20 and schematically in Figure 2-8. This option uses only the currently loaded parameter set, except that it repeats the run for each new value of a medium concentration (e.g., soil lead concentration) or intake (dietary lead as μg Pb per day) until the specified age-dependent geometric mean blood lead level is achieved *exactly* by that concentration.

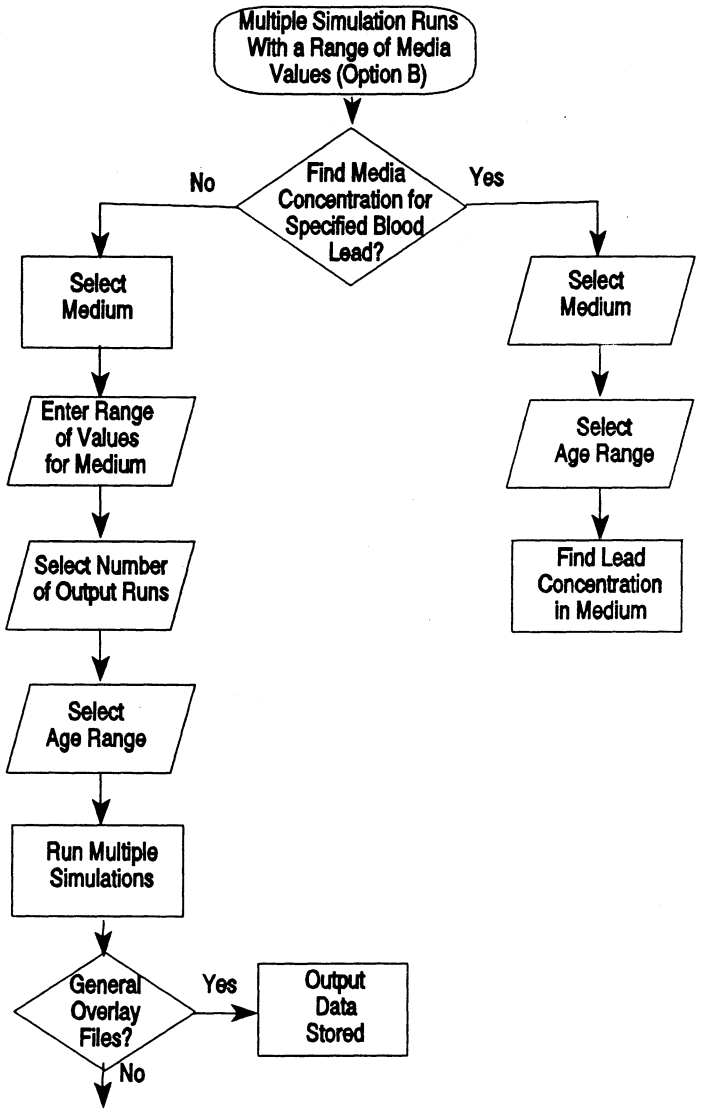
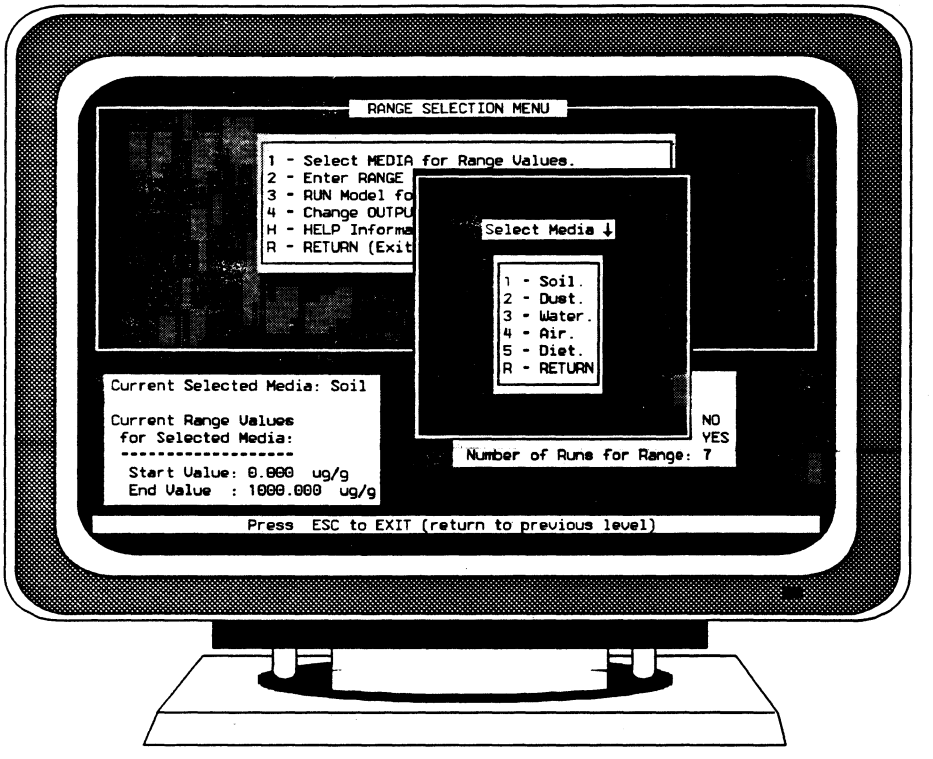


Figure 2-8. Decision diagram for the multiple simulation menu options.

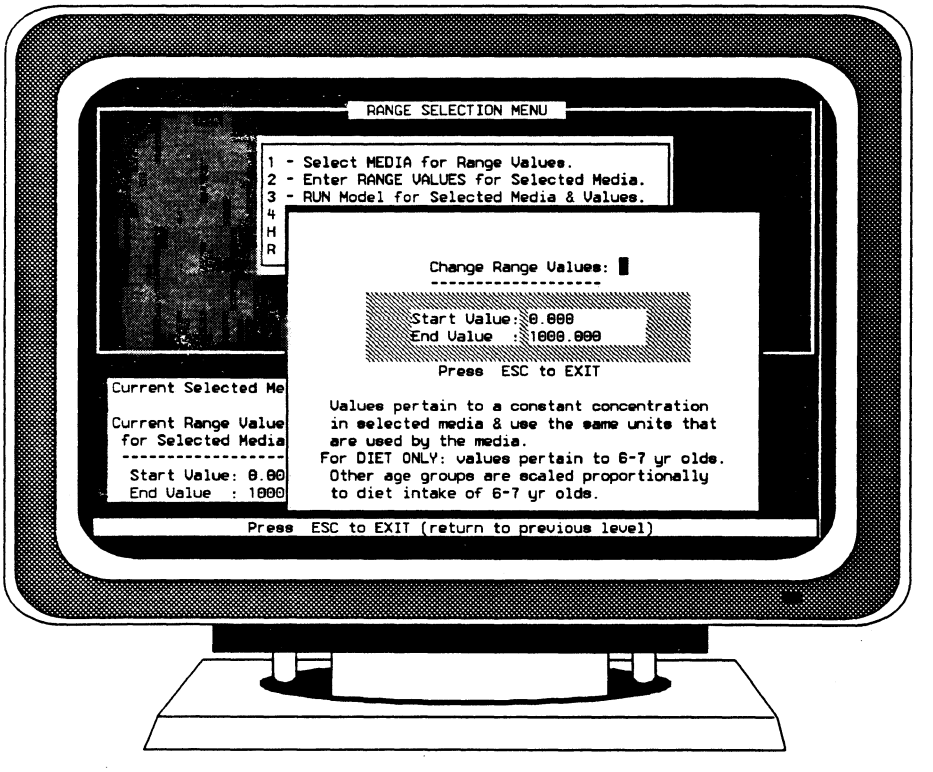
Since only one medium can be changed in each use of the Multiple Simulation Run "3" option, the user who wants to look at a range of soil lead values should use the Multiple Source Dust option "3" and a user-specified dust lead to soil lead concentration ratio. Output data for plotting may be saved when the user creates *.PBM files.

2.2.3.4 Batch Mode Multiple Simulation Runs Using Input Data Files (4)

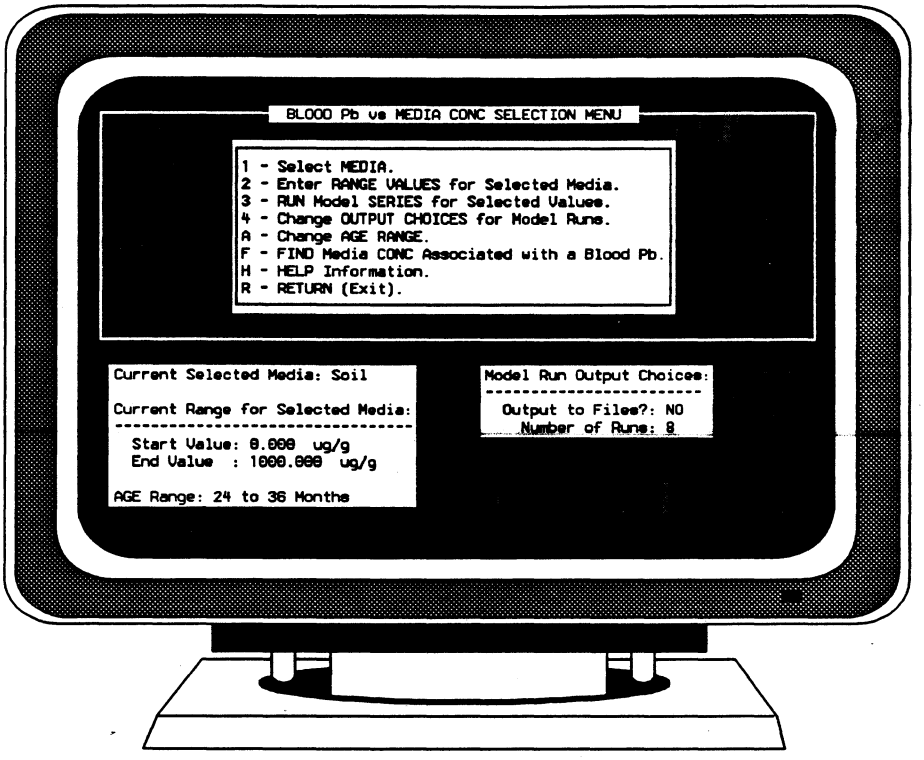
This option is similar to Option 2. The menus for the Batch Mode Run command are shown in Screen 2-21 and schematically in Figure 2-9. This option uses the currently loaded default parameter set, but repeats the run for using the new values for the five exposure



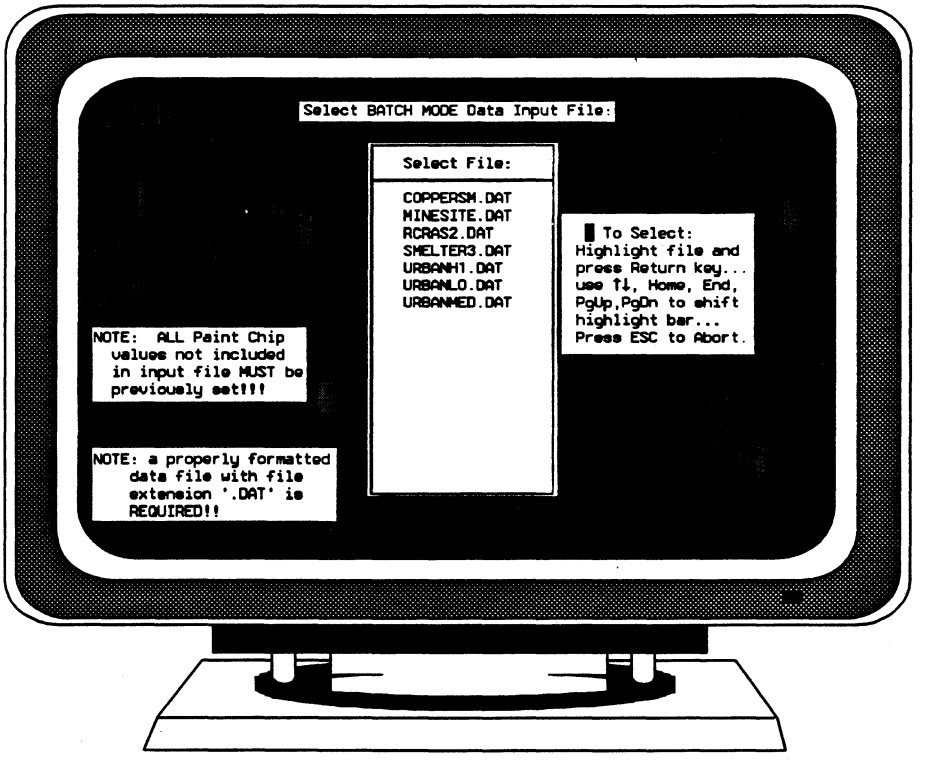
Screen 2-18. Selection of media for multiple range run.



Screen 2-19. Range selection during multiple processing.



Screen 2-20. Using multiple simulation to find acceptable media concentrations for a predetermined blood lead concentration.



Screen 2-21. Running the model in batch mode.

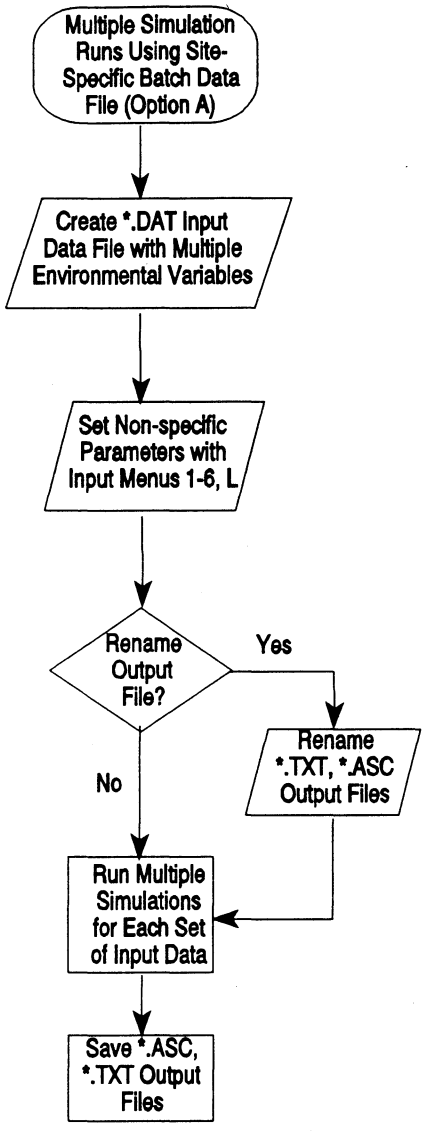


Figure 2-9. Decision diagram for the batch mode menu options.

parameters (soil concentration, dust concentration, drinking water concentration, air concentration and alternate source consumption) for each child in the data set. The input data are entered one line at a time from a data set with a specified list of input variables. These must be created by the user in a special *.DAT file in the Lead Model directory.

Each line of data *may* include:

The child code or case;

The "family" identifier for individuals at the same living unit;

An area, block, or neighborhood identifier;

Each line of data *must* include:

The child's age, in months, as of the end of the data collection period;

The soil lead concentration, in $\mu g/g$;

The house dust lead concentration, in $\mu g/g$;

The drinking water lead concentration, in $\mu g/L$;

The air lead concentration, in $\mu g/m^3$;

The alternate source intake rate, in $\mu g/day$;

The child's blood lead level at specified age, in $\mu g/dL$.

The child's age must be entered. Either a soil lead or a dust lead value is needed for the simulation, along with a stand-in value (imputation rule) if one of them is missing (for example, if the user does not fill in missing dust lead values, the current default is to replace a missing dust lead concentration by the soil lead concentration). The user may prefer to create an input data file with missing dust lead concentrations replaced by some fraction of the soil lead concentration. Missing values of air, water, and alternate lead are replaced by default values. If there is no actual child blood lead data, then Option 1 produces output data sets with *.ASC and *.TXT extensions that contain all of the input data, including imputed values, and predicted blood lead levels for each line of data.

The batch mode option can be used to perform statistical analyses of simulated community blood lead distributions, even without observed blood lead levels (for example, if an investigator has carried out a multimedia environmental lead study at a site, without blood lead data being collected). However, this option will be even more useful if blood lead data from a well-conducted study are available for model comparisons using statistical tests in Option 5. Output data files may be reviewed using Option 2, as demonstrated in later sections.

2.2.3.5 Statistical Analyses of Batch Mode Data Sets (4)

A set of statistical procedures for analyzing batch mode data sets exists as a separate module in the IEUBK Lead Model. Although the Option 1 data sets can be edited and used

in any other statistical programs the user may have available, we have included in Option 5 some of the most commonly used statistics, statistical hypothesis tests, and graphical data displays for comparing observed and modelled blood lead levels. We recommend using a variety of graphical and statistical techniques in evaluating the output of Batch Mode model runs. This will also be demonstrated in Section 5.

2.3 BUILDING AN EXPOSURE SCENARIO

2.3.1 Air Lead Menu

2.3.1.1 Default Air Lead Exposure Parameters

The default air lead concentration is 0.1 $\mu g/m^3$, which is approximately the average 1990 urban air lead concentration (U.S. Environmental Protection Agency, 1991b). During the period 1970-90, ambient air lead concentrations dropped drastically in the United States due to the phasedown of lead in gasoline (Figure 2-10). When adequate monitoring data exist to define concentrations higher or lower than the default outdoor lead concentrations, these should be used. Current air lead levels are low in most places in the United States, and do not require year-to-year specification. Elevated air lead levels have been reported around some point sources in the United States and Europe (Davis and Jamall, 1991) and lead modeling for changes in these sources requires year-by-year input data.

A constant air lead value larger than 0.1 $\mu g/m^3$ may be appropriate for assessment at locations in the vicinity of active point sources of lead emissions such as lead smelters or battery plants. In such cases, an appropriate estimate of annual average air lead concentration must be available.

An example of a striking increase over time was the air lead levels in Kellogg/Silver Valley, Idaho, following a September 1973 baghouse fire. These levels remained elevated for a sufficiently long time such that the use of these values in predicting blood lead concentrations for 1974-1975 from the Lead Model was justified (Agency for Toxic Substances and Disease Registry, 1988).

2.3.1.2 Ventilation Rate

The intake of air increases from infancy to adulthood. The range of values for child ventilation rates was established by EPA (U.S. Environmental Protection Agency, 1989a) as

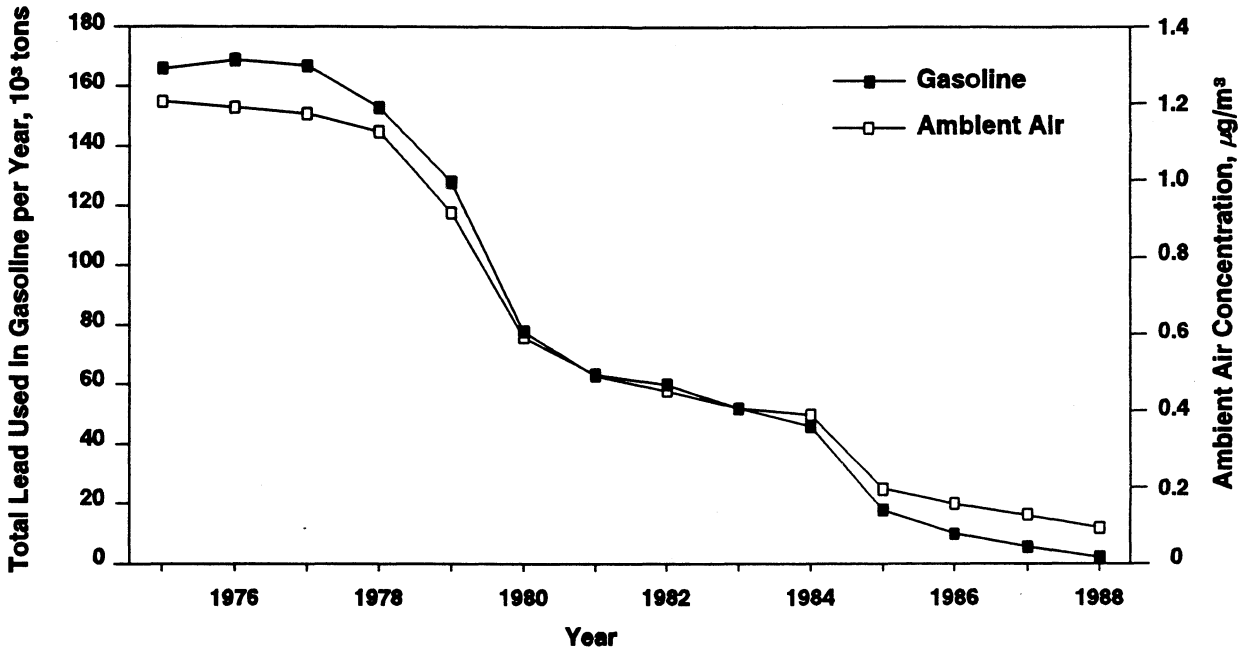


Figure 2-10. Historical relationship between lead in gasoline and lead in air in the United States.

Source: U.S. Environmental Protection Agency (1986), with updating.

2 to 3 m^3/day at age 0 to 1 years, 3 to 5 m^3/day at age 1, 4 to 5 m^3/day at ages 2 and 3, 5 to 7 m^3/day at ages 4 and 5, and 6 to 8 m^3/day at age 6. The Lead Model uses midrange values of 2, 3, 5, and 7 m^3/day at ages 0+, 1, 2 to 4, and 5 to 7 respectively. Children who exercise more than average will have a correspondingly greater intake, and those who are very inactive will have a lower ventilation rate. The higher intakes may be useful in modeling children who spend time at playgrounds or outdoor play areas near an air lead source. Changes in activity pattern can change ventilation rate in a child or in a neighborhood.

2.3.1.3 Indoor/Outdoor Activity Patterns

The range of values for outdoor time was established by EPA (U.S. Environmental Protection Agency, 1989a) as 1 to 2 h/day in the first year of life, 1 to 3 h at age 1, 2 to 4 h at age 2, and 2 to 5 h/day from ages 3 to 7. The default values in the Lead Model are 1, 2, 3, and 4 h/day at ages 0+, 1, 2, and 3+, respectively, roughly at the middle of these ranges. The outdoor air lead concentration provides a large part of the total air lead exposure, because the indoor air lead concentration is typically only about 30% of the outdoor concentration (U.S. Environmental Protection Agency, 1986). Site-to-site

differences may exist due to natural ventilation, climate, season, family activity, and community access to outdoor play activities.

2.3.1.4 Lung Absorption

The range of values for child lung absorption was established by EPA (U.S. Environmntal Protection Agency, 1989a) as 25 to 45% for young children living in non-point source areas, and 42% for those living near point sources. The default value used in the Lead Model is 32%. Changes in the source of airborne particulates may also affect lung absorption. No quantitative recommendations can be made.

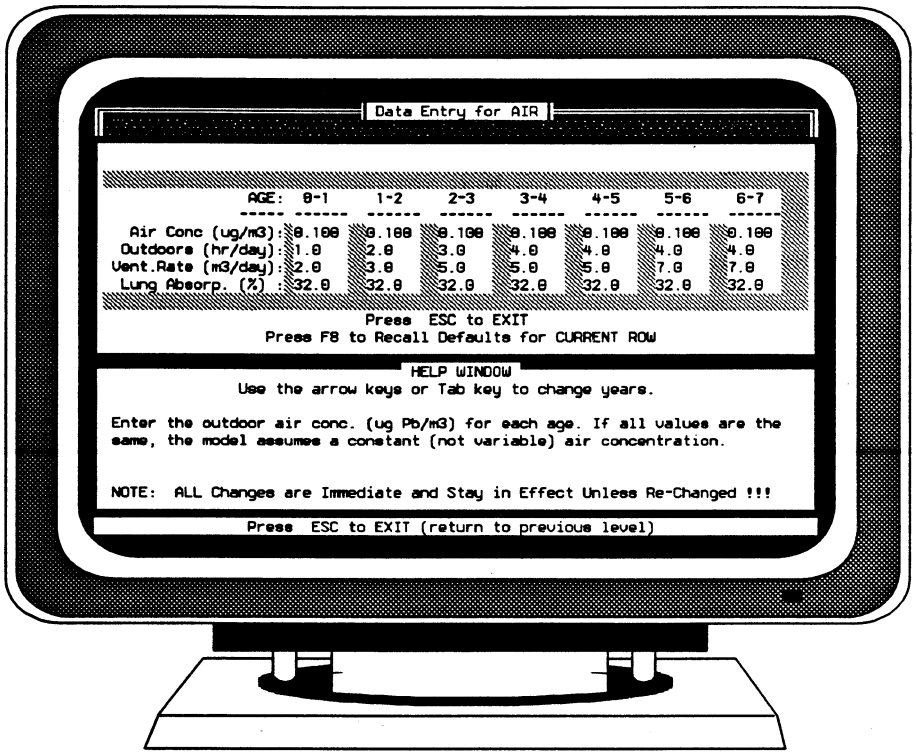
EXAMPLE 2-1: Characterizing Effects of Air Lead Phasedown on Inhalation Intake

If the Lead Model were to be used to estimate blood levels of children living in an urban area in previous decades, when the predominant sources of lead exposure for many U.S. children were air lead from combustion of leaded gasoline and dietary lead from lead-soldered food cans, it would necessary to use community air lead levels during that period of time. Representative values of air lead concentrations were presented in the EPA Air Quality Criteria Document for Lead (U.S. Environmental Protection Agency, 1986, Chapter 7, Table 7-2) for urban center or suburban locations in nine metropolitan areas for 1970 through 1984. The reductions in air lead from 1977 through 1988 attributable to the phasedown of leaded gasoline are quite evident in both urban centers and suburban areas. For example, for a retrospective estimate of blood lead levels in children in 1981, one would need to start with 1975 air lead levels to include prenatal exposure of children up to age 7 in 1981. Figure 2-10 shows that air lead exposure in 1981 would be at 0.48 $\mu g/m^3$, and so on. For a 5-year old child in 1981, air lead exposure, at age 0+ in 1975 is 1.2 $\mu g/m^3$, and so on. This adjustment in air lead concentration does not estimate the indirect effects of air lead changes on blood lead through gradual changes in soil and dust lead. This example is generic, not site-specific, however. The air lead data entry screen for children born in 1975 is shown in Screen 2-22.

2.3.2 Dietary Lead Menu

2.3.2.1 Total Dietary Lead Exposure

Data assembled from a variety of sources, including Market Basket Surveys (Pennington, 1983) and representing changes in consumer behavior over time, were used to construct dietary lead intake estimates as described in Chapter 7 of the EPA Air Quality Criteria Document for Lead (U.S. Environmental Protection Agency, 1986). The method is



Screen 2-22. Data entry for air. The user may input data from historical records of air lead concentrations on this screen.

based on U.S. FDA Market Basket samples in 231 food categories and has been updated to 1988 (U.S. Environmental Protection Agency, 1989a). Because two major sources of lead in food (lead-soldered cans and air deposition on food crops) have been greatly reduced or eliminated, dietary lead is believed to be relatively constant since 1990, especially for children under seven years.

Table 2-1 shows how estimated mean dietary lead intake depends on the child's age, and that this intake has changed very drastically with the near-elimination of lead solder from food cans and other food packaging in the United States since the 1970s. Where site-specific dietary levels are not available, it is recommended that the values from Table 2-1 be used for the appropriate years and ages, and that the most recent values (1988) be assumed for all future years. Seasonal effects are omitted here since the Lead Model uses annual values for dietary exposure parameters. For alternate exposure scenarios with seasonal intakes, the user may need to calculate time-weighted annual averages from seasonal data.

If the Lead Model is used in connection with historical exposures, for such purposes as model validation or retrospective dose reconstruction, the dietary intake data should be

TABLE 2-1. DIETARY LEAD INTAKE (μg/day) FOR U.S. CHILDREN BY AGE, FOR EACH YEAR FROM 1978 TO PRESENT

	Age						
	6-11 Mo	1 Year	2 Years	3 Years	4 Years	5 Years	6 Years
1978[1]	NE	45.8	52.9	52.7	52.7	55.6	NE
1979[1]	NE	41.2	48.0	47.8	47.8	50.3	NE
1980[1]	NE	31.4	36.9	36.9	36.9	38.7	NE
1981[1]	NE	28.3	33.8	33.7	36.8	35.8	NE
1982[2]	19.2	25.0	27.5	27.4	27.2	28.6	31.6
1983[2]	14.4	18.3	21.9	21.4	21.1	22.3	24.8
1984[2]	19.0	22.7	26.4	26.0	25.7	27.1	29.9
1985[2]	10.2	10.6	12.3	11.9	11.8	12.4	13.6
1986*	7.9	8.2	9.4	9.1	8.9	9.4	10.3
1987-Present[3]	5.5	5.8	6.5	6.2	6.0	6.3	7.0

NOTES: NE = Not estimated.
1 = Estimated by J. Cohen and D. Sledge, Table A-2 (U.S. Environmental Protection Agency, 1989a).
2 = U.S. Environmental Protection Agency (1986), updated with data from the FDA Market Basket Survey.
3 = Average of 1986 Q4 through 1988 Q3. Further decreases in food lead concentrations since 1987 are believed to be negligible.
* = Linear extrapolation between 1985 and 1987.

adjusted to the year when the data were collected. For prediction in future years, the most recent default value for each age may be used.

2.3.2.2 Dietary Lead Exposure by Additional Pathways

For some children, there are important dietary lead sources that are not characterized by the FDA Market Basket Survey data summarized in Table 2-1. Child-specific or site specific data will be needed to verify these alternative dietary lead sources. Local sources of fruit and vegetables are used in many small towns and in rural areas. Some individuals obtain much of their produce from their own gardens. If the local or home-grown produce is grown in soils with high concentrations of lead, or if the edible leafy portions are contaminated by airborne lead particles, then some fraction of the environmental lead may be added to the child's diet. The additional intake of lead in diet may become important if the

environmental lead concentrations are sufficiently high. This was important in evaluating the Bunker Hill Superfund site in Kellogg ID and was included in the Risk Assessment Data Evaluation Report (the "RADER") prepared by EPA (U.S. Environmental Protection Agency, 1990c). Additional pathways of dietary lead exposure are discussed in Example 2-2.

Dietary lead exposure is the product of the amount of food consumed in each category and the concentration of lead in the food item. Normal intakes are reported by Pennington (1983). To adjust for home gardens, a fraction of this intake may be allocated by the Alternate Diet Entry Menu to local produce, and the rest to Market Basket produce that is not grown locally.

Local game animals feeding on plants contaminated by lead in soil may also have elevated lead concentrations. Lead contamination of rivers and lakes by deposition and by erosion of leaded soils may also increase lead concentrations in local fish. Some rural families may use hunting and fishing as a significant supplement or even as their primary source of animal protein. See Baes et al. (1984) for a comprehensive approach to estimating pathways of trace elements in the food chain. A fraction of the meat and fish intake may be allocated by the Alternate Diet Entry Menu to local game and fish.

Other consumer products may have nontrivial potential for dietary lead exposure. These include lead-glazed or soldered cooking and food preparation utensils, ethnic or regional preferences for food products with high lead content, and the use of oral ethnic medicines such as "empacho" or "azarcon" that have high concentrations of lead and are known to have caused cases of acute lead poisoning in children (Trotter, 1990; Sawyer et al., 1985). No general recommendations about parameter values for these sources of lead can be made at this time. Approximate intake for oral medicines may be estimated from recommended or customary doses for young children.

EXAMPLE 2-2: Characterizing Indirect Dietary Lead Intakes for an Old Lead Smelter Community

Some data from the Human Health Risk Assessment (Jacobs Engineering, 1989) and the RADER for Kellogg ID may be useful (U.S. Environmental Protection Agency, 1990c). Table 2-2 shows that a large percentage of the population uses local produce, that the use of local produce increases toward the more rural Pinehurst area but the lead concentration decreases, and that the lead levels in local produce in 1983 were enormously higher than in

TABLE 2-2. ESTIMATES OF LEAD INTAKE FROM CONSUMPTION OF LOCAL PRODUCE BY CHILDREN, AGES 2 TO 6 YEARS, IN KELLOGG, IDAHO

Area	Percent Using Local Produce	Number of Gardens	Consumption (g/day) Leafy*	Consumption (g/day) Root*	Concentration (μg/g wet wt.) Leafy	Concentration (μg/g wet wt.) Root	Intake (μg/day) In Summer**
Smelterville	16%	2	25	15	6.1	4.5	220
Kellogg	36%	17	25	15	6.1+	4.5+	220+
Pinehurst	46%	20	25	15	3.5	2.2	121
National Market Basket	--	--	25	15	0.017	0.041	1

NOTES: *Leafy vegetables are lettuce and spinach. Root vegetables are carrots and beets.
+Average of Kellogg and Smelterville.
**Annual average is 1/4 of this.

Source: RADER Tables 5-8 and 5-4 (U.S. Environmental Protection Agency, 1990).
Jacobs Engineering (1988) Table 7-16.

the National Market Basket samples for the same period (1982 to 1984). The calculated increment of daily dietary lead intake during the summer months was 220 μg/day in the report. However, for the purposes of this example, we will assume that this total consumption occurs over the course of the year and includes fresh as well as frozen or canned produce to give an annual average increment of 55 μg/day.

Table 2-3 shows that the lead concentration in fish in nearby Lake Coeur d'Alene in 1985 was much higher than in the Columbia River and higher than fish at the average National Pesticide Monitoring Station lead concentration for 1976/1977. A moderate rate of consumption is two 2-oz fish portions per week, or 114 g/week = 16 g/day on average. The incremental intake from local fish is equal to the concentration difference, 0.80 to 0.34 = 0.46 μg/g times 16 g/day = 7.5 μg/day.

Screen 2-23 shows dietary lead intakes for a typical child born in 1983, and Screen 2-24 shows the extra exposure for intake from contaminated fish.

2.3.3 Drinking Water Lead Exposure Menu

2.3.3.1 Drinking Water Lead Default Exposure Parameters

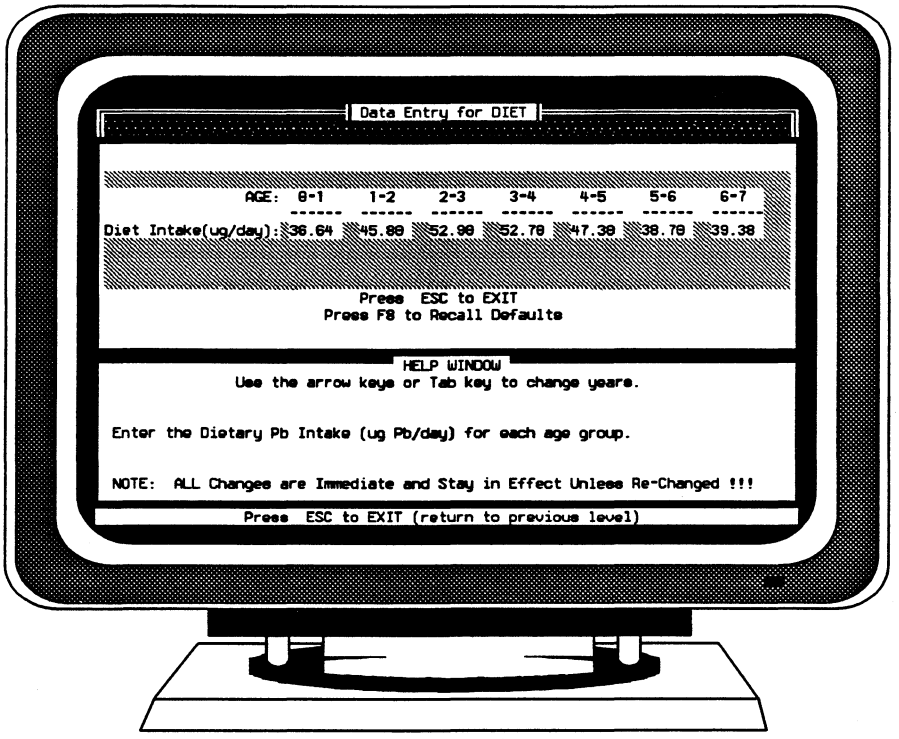
Water sampling methods may be as first draw standing samples, partially flushed samples, or fully flushed samples. The highest lead concentrations at the tap are usually obtained for lead pipes, lead-alloy solder on copper pipes, or lead-alloy brass faucets and

TABLE 2-3. ESTIMATES OF LEAD INTAKE FROM CONSUMPTION OF LOCAL FISH BY CHILDREN, AGES 2 TO 6 YEARS, IN KELLOGG, IDAHO

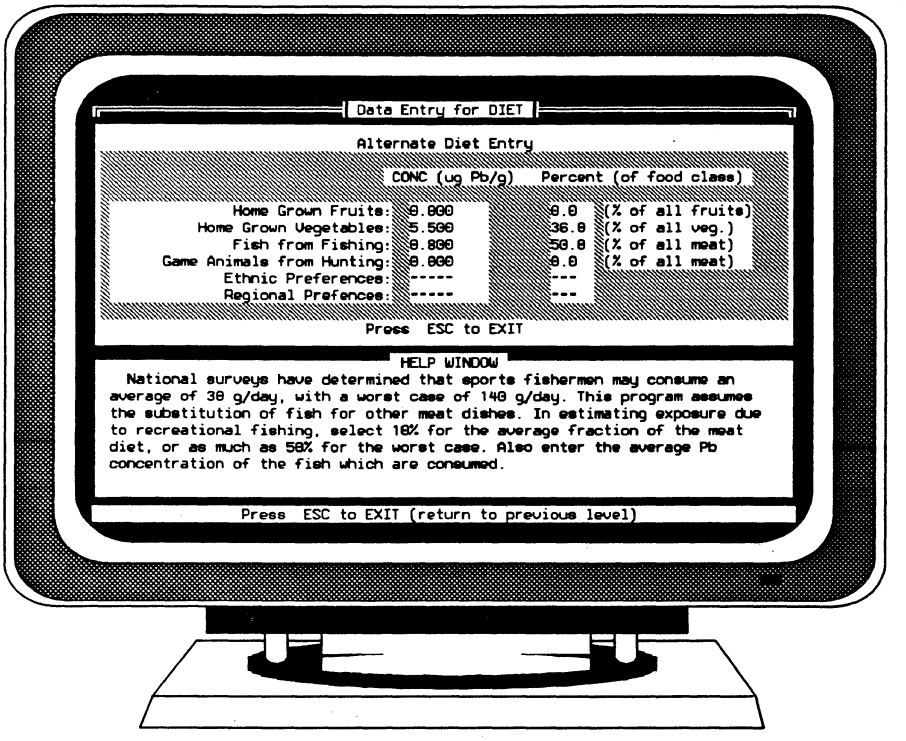
Source	Concentration (μg/g wet wt.)	Fish Consumption* (g/day)	Lead Intake** (μg/day)
Lake Coeur d'Alene (1985)	0.80	16	13.0
Columbia River (1986)	0.34	16	5.5
National Pesticide Monitoring Stations (1976-1977 August)	0.34	16	5.5

NOTES: *Two-ounce portions, twice a week.
**For annual average, multiply by fraction of year when local fish are consumed.

Source: RADER Tables 5-8 and 5-4 (U.S. Environmental Protection Agency, 1990).
Jacobs Engineering (1989) Table 7-16.



Screen 23. Using dietary lead intake for a child born in 1983 (see Example 2-2).



Screen 24. Using dietary intake from local vegetables and fish in Kellogg (see Example 2-2).

fittings in contact with corrosive water for several hours. The new EPA National Primary Drinking Water Regulation for Lead (NPDWR) requires public water systems to collect first draw samples, standing a minimum of 6 h, from a sample of homes targeted as potentially at risk. Water lead concentrations can be significantly different for different sampling protocols, depending on the sources of lead in water drawn through the tap. First draw samples generally have higher lead concentrations than flushed samples. The typical effects of different water sampling procedures are discussed in the Sampling Manual that is to accompany this model.

Drinking water lead concentrations in the Lead Model are held constant during the entire seven years of the child's exposure. In the Case Studies below, household-specific water lead concentrations are used. If no household-specific or relevant community water lead data are available, we recommend using the default value of 4 μg/L.

If a substantial fraction of the child's activity is spent outside the home, it may be useful to separate drinking water exposure into primary residence and secondary residence or daycare. A large number of U.S. children spend time during the weekday at daycare centers

or secondary residences. If adults and older children in the household are either at work or at school during the day, there may be two stagnation periods for drinking water during the day—overnight, and midday. In this case, a larger fraction of the child's water lead exposure can occur at the higher "first-draw" concentrations. Some exposure scenarios are discussed by Marcus (1991) in evaluating the risk from lead leached out of newly installed brass faucets. The default scenario is defined by setting 50% of the child's water intake to household first-draw consumption. The remaining intake consists of partially flushed intake inside the home (35%) and water consumed outside the home (15%). The total intake of lead in drinking water would then be:

$$\text{PbW} = 0.5 \times \text{PbW (first draw)} + 0.35 \times \text{PbW (flushed)} + 0.15 \times \text{PbW (fountain)}.$$

There is no general rule for estimating the amount of water ingested from water coolers in day care centers or other non-home locations. Since the child's activities outside the home are likely to be different than inside the home, it is unlikely that the ratio of non-home to home water intake is proportional to the amount of time spent away from the home versus at home. Two drinks per day, each about 60 mL (2 oz) or 120 mL, is a reasonable upper limit for day care intake. The default is 15% of the daily tap water intake, which ranges from 75 mL at age 1 year to 90 mL at age 6 years.

2.3.3.2 Alternate Drinking Water Exposure by Age

The default values in the IEUBK model (Table 2-4) are taken from the U.S. EPA Exposure Factors Handbook (U.S. Environmental Protection Agency, 1989c). A survey of drinking water consumption in U.S. children was reported by Ershow and Cantor (1989) in a study for the National Cancer Institute. These values have been smoothed and disaggregated into yearly values shown in Table 2-4. The range of values from the Ershow-Cantor data in Table 2-5 show that the default values for the IEUBK model are similar to but somewhat lower than the median values, but also contain information about the percentiles of the distribution of tap water intake, about gender differences in intake and other factors that you may find useful. A plausible scenario for elevated exposure to lead in drinking water would be to use larger tap water intakes, such as the 90th percentile values in Table 2-5. Note that for children receiving formula reconstituted with tap water, consumption of tap water would be much higher, perhaps closer to one liter per day. In an assessment addressing risks from lead in drinking water, the exposure to infants consuming reconstituted formula requires specific attention.

TABLE 2-4. AVERAGE DAILY WATER INTAKE IN U.S. CHILDREN

	Ershow-Cantor Study*				IEUBK Model**	
	Total (L/day)		Tap (L/day)			
Age (Months)	M	F	M	F	Age (Mo)	Tap Water Intake (L/day)
0-5	0.992	1.035	0.250	0.293	0-5	0.20
6-11	1.277	1.238	0.322	0.333	6-11	0.20
					12-23	0.50
					24-35	0.52
12-47	1.409	1.300	0.683	0.606	36-47	0.53
					48-59	0.55
					60-71	0.58
48-84	1.551	1.488	0.773	0.709	72-84	0.59

*Ershow and Cantor (1989).
**U.S. Environmental Protection Agency Exposure Factors Handbook (1989c).

TABLE 2-5. TAP WATER INTAKE (L/day) BY AGE CATEGORY

Age Category		Percentiles		
(Months)	Mean	10	50 (Median)	90
0 - 5	0.27	0	0.24	0.64
6 - 11	0.33	0	0.27	0.69
12 - 47	0.65	0.24	0.57	1.16
48 - 84	0.74	0.30	0.66	1.30

Source: Table 2-5, Ershow and Cantor (1989).

2.3.4 Soil/Dust Lead Exposure Menu

One of the most important uses of the IEUBK model is to compare risks among alternative soil lead and dust lead exposure scenarios. Many of these scenarios arise in assessing exposure reduction strategies. For example, in evaluating soil lead abatement at a particular residential yard, we might be interested in the following sequence of comparisons:

(1) Calculate the risk of an elevated blood lead level for the present soil and dust lead levels;

(2) Calculate the risk of an elevated blood lead level for the replacement of soil lead with soil having a lower lead concentration, along with cleaning up household dust;

The first scenario describes risk to occupants with present exposure levels. The second scenario describes risk to occupants in the distant future after lower new lead levels have been achieved by abatement. The IEUBK model can accept input data describing both of these exposure scenarios.

2.3.4.1 Soil and Dust Lead Default Exposure Parameters

The natural concentration of lead in soil, from weathering of crustal materials, is estimated as about 10 to 25 μg/g. A plausible urban background is 75 to 200 μg/g (U.S. Environmental Protection Agency, 1989a; HUD, 1990).

It is expected that lead concentrations in undisturbed soils may persist for many thousands of years. However, urban areas are hardly undisturbed environments and available data (von Lindern, 1991; Jacobs Engineering, 1990) suggest that near-surface soil lead concentrations may decrease by a few percent over a decade or so. It is usually adequate to assume a constant soil lead concentration unless soil abatement is included in the exposure scenario.

It is also possible that the soil becomes recontaminated over time, for example if surface soil is abated and then is recontaminated by ongoing atmospheric lead deposition from non-abated sites near by or by contamination from deteriorating exterior lead-based paint. Changes in soil concentration can be incorporated on an annual basis in developing the exposure scenario. This is done with the Option "2" on the Soil/Dust Data Entry Menu.

2.3.4.2 Exposure to Soil and Dust

The default value for total intake of soil and dust depends on age, and ranges from 85 to 135 mg/day. These values are within the ranges identified in the OAQPS staff paper that supported the first UBK model and have been reviewed by the EPA Clean Air Science Advisory Committee. Recent investigations by Binder et al. (1986), Clausing et al. (1987), Calabrese et al. (1989, 1991b), van Wijnen et al. (1990), and Davis et al. (1990) apply the trace element approach to quantify ingestion rate. These investigations currently constitute the most appropriate basis for estimating the quantity of soil ingested. The results are summarized in Table 2-6. The van Wijnen et al. data are discussed in Section 2.3.4.4. It is likely that the intake rate depends on the child's age, activity pattern, and the total

TABLE 2-6. DAILY INTAKE OF SOIL AND DUST ESTIMATED FROM ELEMENTAL ABUNDANCES

		Soil/Dust Intake, mg/day		
Study	Element	Median	Mean	Maximum
Davis et al. (1991)	Al	25	39	904
Ages 2-7 years	Si	59	82	535
	Ti	81	246	6,182
Calabrese et al. (1989)	Al	30	154	4,929
Ages 1-4 years	Ti	30	170	3,597
	Y	11	65	5,269
	Zr	11	23	838
Binder et al. (1986)	Al	121	181	1,324
Ages 1-3 years	Si	136	184	799
	Ti	618	1,834	17,076
Clausing et al. (1987)	Al	92	232	979
Ages 2-4 years	Ti	269	1,431	11,620
	AIR	106	124	302

AIR = Acid Insoluble Residue.

accessible dust and soil in the environment. It is *recommended* that soil and dust intake be defined by an age-dependent scenario shown in Table 2-7, as reviewed by the Clean Air Science Advisory Committee (U.S. Environmental Protection Agency, 1990b).

Two of the studies, Davis et al. (1991) and Calabrese (1989), measured the dietary (including medication) intake of the trace elements and subtracted this quantity in estimating soil ingestion. These studies therefore provide the most complete quantitation of ingestion. Because Binder et al. (1986) did not measure dietary intake, the results for this study are likely to provide an upper bound on ingestion among those subjects. Van Wijnen et al. (1990) did not measure dietary intake but attempted to compensate for this approach by using the lowest observed tracer result for each child and subtracted out a value obtained for hospitalized children who were assumed not to ingest soil or dust. The combination of these two techniques may lead to a downward bias in ingestion estimates.

TABLE 2-7. AGE-SPECIFIC SOIL AND DUST INTAKE

Age (Years)	Intake (g/day)	Adopted for Guidance Manual
0 - <1	0 - 0.085	0.085
1 - <2	0.080 - 0.135	0.135
2 - <3	0.080 - 0.135	0.135
3 - <4	0.080 - 0.135	0.135
4 - <5	0.070 - 0.100	0.100
5 - <6	0.060 - 0.090	0.090
6 - <7	0.055 - 0.085	0.085

Source: U.S. EPA (1989a).

The reader should also note that there are statistical problems in interpreting an observed median value from these studies. For example, in a population of children who all ingested very small amounts of soil on most days but occasionally ingested larger quantities, the median from a short term measurement study will be below the average daily quantity ingested by any of the children. The mean value is not subject to this bias, and therefore is judged to be a more meaningful measure of ingestion.

It should be noted that the 200 mg/d ingestion value presented in Superfund guidance can be supported as, roughly, an upper bound on mean ingestion considering the values seen in different ingestion studies. The values recommended for use in the model (85 to 135 mg/d) represent a more central value within the range of values seen in different studies.

The smaller study of Clausing et al. (1987) used methods similar to the later study of van Wijnen et al. The values shown for soil ingestion in Table 2-7 are uncorrected for dietary intake. The paper presents additional estimates using acid insoluble residue and tracer excretion by hospitalized children.

2.3.4.3 Sources of Dust Exposure

Contribution from Atmospheric Deposition and Soil

We recommend collecting household dust data. If that has not been done, then Option 3 may be used to estimate dust lead concentrations. The OAQPS Exposure Analysis and Methodology Validation (U.S. Environmental Protection Agency, 1989a), used for the earlier version of the model on which the current IEUBK Model is based, calculates the

contribution of atmospheric deposition and soil to house dust by linear regression models between dust lead, soil lead, and air lead. There is a relationship between dust lead concentration in $\mu g/g$ (denoted as PbD), soil lead concentration in $\mu g/g$ (denoted as PbS), and air lead concentration in $\mu g/m^3$ (denoted as PbA). In a number of studies, statistically significant relationship of the form:

$$PbD = \beta_O + \beta_S PbS + \beta_A PbA$$

This equation suggests that house dust lead concentration consists of three components: a soil component, which is the fraction β_S of the soil concentration, an air component, consisting of a coefficient β_A relating $\mu g/g$ lead in dust to $\mu g/m^3$ of lead in air, and a third component of β_O coming from unidentified sources.

As a default value in the model, we used $\beta_A = 100$ $\mu g/g$ per $\mu g/m^3$ based on several analyses. We recommend a default soil-to-dust coefficient of 0.70, which represents some real sites where soil is a major contribution to household dust. The reader should be aware that other values have been identified for other site-specific exposure scenarios.

Dust Lead Increment from School Dust

Dust ingestion while at school may be significant, depending on the amount of exposure on the floor or playground. While the IEUBK model deals primarily with preschool children, some children may be in school and subject to a more structured regimen of hygiene and reduced dust exposure. The amount of dust ingested and its implicit fraction of total dust ingestion is not necessarily proportional to length of time at the facility. Hygiene and dust loading are additional predictive factors. Playground geometric mean dust lead levels of 170 - 3,700 $\mu g/g$ were reported by Duggan et al. (1985) in a sample of 11 British schools.

Dust Lead Increment from Day Care

Dust ingestion while at daycare (including nursery school and kindergarten) may be significant, depending on the amount of exposure on the floor or outside play area. Dutch children who spent a considerable amount of time at a daycare center were known to ingest a large quantity of dust and soil, although apparently much less in rainy weather than in good weather (van Wijnen et al., 1990).

Dust Lead Increment from Second Home

Children often spend several hours per day in the home of a relative or in an informal daycare setting. Dust exposure information can often be collected and used in the same manner as for the primary home.

Dust Lead Increment Remaining from Primary Residence

When the Multiple Source Analysis option is selected on the Soil/Dust Data Entry Menu, the IEUBK model offers the opportunity to change the soil and air parameters of the regression equation set at 0.70 and 100, respectively as default values. The selection of a default value for the soil-to-dust coefficient was based on empirical data. In sites where soil-to-dust coefficients have been measured and where paint does not contribute greatly to dust, the range was from 0.09 to 0.85. Among the sites where soil-to-dust coefficients have been measured are the following: East Helena, 0.85 (0.81 and 0.89); Midvale, 0.70 (0.68, 0.72); Butte, 0.26; and Kellogg, 0.09. Recent data suggest the coefficient decreases over time at some sites where major sources of soil lead deposition are no longer active. The user is cautioned, however, that the contribution of soil to dust concentration varies greatly from site to site, and site-specific soil and dust data should be collected for use in the model. The user may choose to enter values for alternate sources of dust, including both an estimate of concentration (μg/g) and relative contribution (%) for each source. Of the five alternate sources, two (secondary occupational dust and lead-based paint in home) represent contributions to house dust lead within the home, and three (dust at school, dust at daycare, and second home dust) represent exposure outside the primary home. If no selection is made from any of these five, the house dust concentration remains as calculated from the linear equation. If any of the five options are selected, this percentage is subtracted from the house dust component, the contribution from all sources is calculated, and the average is shown on the Multiple Source Average line of the Soil/Dust Data Entry Menu. This line appears only if the Multiple Source Option is selected.

2.3.4.4 Fraction of Exposure as Soil or Dust

We recommend using the default assumption that 45% of the total dust intake is derived from soil. The ratio of soil intake to dust intake is not simply proportional to the ratio of the number of waking hours that the child spends outdoors versus indoors. Children spend only 15 to 30% of their waking hours playing outside but are more likely to be in contact with bare soil areas, in locations with large amounts of accessible loose particles, and are likely to wash their hands less often than when they are indoors. The default 45/55 ratio in the model represents our best judgement of a properly weighted ratio for this parameter.

The issue of intake of soil and dust has not been properly resolved in the scientific literature. The distinction is important because there is some indication that even if soil lead is the principal source of dust lead, there may be chemical or physical differences between soil and dust that may affect bioavailability. Calabrese (1992) has found that most of the soil and dust intake in a soil pica child was in the soil component, but this is hardly representative of a larger population that may have large differences in relative exposure to soil and dust.

Section 2.3.4.4 discusses the option to select the amount of dust and soil consumed by the child each day. The default values are age weighted from 85 to 135 mg/day, and this dust is ingested either during kitchen preparation of food or by hand-to-mouth activity during indoor and outdoor play activity. This section discusses the option to allocate a portion of the ingested dust to dust derived from soil that is ingested during outdoor play activity. This distinction is important when there are differences between the bioavailability of dust derived from soil and dust in the home, and when there are large differences in the concentration of dust from the two sources. When house dust is thought to be mostly of soil origin and each are expected to have similar bioavailability, the designation of this fraction is a moot point. It is in cases where house dust differs significantly from soil derived dust that the soil/dust ratio becomes important. One example might be the presence of interior lead-based paint. In this case the parameter can be effective in separating soil derived dust and paint derived dust into two components where both the amount ingested and percent absorbed can be correctly input into the model.

There is some evidence that the soil intake is very responsive to exogenous factors, such as weather and location. Data reported by van Wijnen et al. (1990), summarized in Table 2-8, show the lowest soil and dust intakes at daycare centers occurred in rainy weather, when the children had the least amount of outdoor activity.

There is an implicit assumption that the exterior dust that a child ingests during outside play activity is derived completely from soil, and we use soil as a surrogate for exterior dust exposure. These intakes were measured during a 3 to 5 day sampling period, when soil and dust intake estimates ranged from 33 to 88 mg/day for children aged 1 to 2 years and from 12 to 62 mg/day for children older than 3 years. The intake of soil and dust is describe in detail in Section 2.3.4.2.

In the absence of any better data, we have reanalyzed and reinterpreted the van Wijnen et al. data based on the assumption that the rainy-weather intake is only interior dust, and

TABLE 2-8. MINIMUM PERCENTAGE SOIL INTAKE AS A FUNCTION OF AGE IN DUTCH CHILDREN IN DAYCARE CENTERS[a]

	Estimated Geometric Mean LTM, mg/day		
Age (years)	Good	Rainy	Difference (mg/d)
<1	102 (4)	94 (3)	8
1 - <2	229 (42)	103 (18)	126
2 - <3	166 (65)	109 (33)	57
4 - <5	132 (10)	124 (5)	8

[a]Minimum daily ingestion of acid insoluble residue or other tracers, denoted LTM (Limiting Tracer Method) from Table 4 in Van Wijnen et al. (1990). Number of children shown in parenthesis.

that the good-weather intake is both interior and exterior dust although probably with a smaller amount of interior dust than in rainy weather. The authors also made the distinction between soil and dust in their discussion of the study. For our reanalysis, we took the rainy-weather intake by age as dust and the good-weather intake as soil plus dust, to estimate an age-related difference of 8 to 126 mg/day soil (Table 2-8). The difference between LTM during good weather and LTM during mostly rainy weather is believed to be a lower bound on the soil intake. The combined intakes of soil and dust estimated by other authors are of a similar order of magnitude, such as the median soil and dust intake of 25 to 81 mg/day found by Davis et al. (1991) for children of ages 2 to 7 years in Richland-Pasco-Kennewick, Washington. We therefore assume that a substantial fraction of the combined soil and dust intake in U.S. children is in the form of soil, as suggested by the large difference in Table 2-8 between good and rainy weather intakes, and a substantial fraction is in dust, as suggested by the large intake during rainy weather, in Table 2-8. The minimum intake, denoted LTM for Limiting Tracer Method, has not been corrected for food intake. However, it is likely that the differences between LTM intakes do not depend on food intake.

2.3.4.5 Bioavailability of Lead in Soil and Dust

The current assumption in the Lead Model is that 30% of dust and soil lead intake is absorbed into the blood. This is assumed to be partitioned into a nonsaturable component of 6% and a saturable component of 24%. Some investigators (Steele et al., 1990) argue that the bioavailability of lead in soil from some old lead mining sites is much less than that of dissolved lead salts for several reasons: (1) large lead particles may not be completely dissolved in the GI tract; (2) the solubility of chemical species commonly found in mine wastes, particularly lead sulfide, is much lower than that of other lead salts. These

hypotheses are based on studies in small laboratory animals such as rats (Barltrop and Khoo, 1975; Barltrop and Meek, 1979), and while the results may be qualitatively relevant to humans, it is not clear how they should be extrapolated to humans or to other large animals with similar physiological properties such as baboons or swine.

2.3.5 Alternate Source Exposure Menu

One possible use of the Alternative Source Exposure Menu is the direct ingestion of chips of lead-based paint (LBP). The user might assume that a child with pica for paint ingests one paint chip per day. If this chip weighs 0.3 grams and contains lead at 10% (100,000 μg/g), then the calculated ingestion is 100,000 μg/g $\times$ 0.3 g/day, or 30,000 μg/day each day for a year. Note that this exposure would be in addition to exposure to lead-based paint in housedust, which is Option 4 in the Multiple Source Menu of Soil and Dust. The limited information available on the bioavailability of lead in paint chips suggests that at doses this high, absorption mechanisms may be largely saturated (Mallon, 1983), which would indicate appropriate adjustments in bioavailability. The user is referred to Section 4.7, and is encouraged to review the literature on this topic prior to making a risk assessment decision. Similar calculations can be made for the ingestion of soil or other non-food items.

2.4 STARTING AND RUNNING THE MODEL

2.4.1 Loading and Starting the Model

The IEUBK Model is a stand alone software package that requires only an IBM compatible PC with DOS. The diskette accompanying this manual contains the following files:

LEAD99d.EXE (the main program file)
PBHELP99.HLP (a help file)

PBSTAT.EXE (the statistical package)

Several *.BGI files (for graphic output)

One or more EXAMPLE*.DAT (sample data sets)

Copy all files into a directory of your choice, then type LEAD99d at the DOS prompt to start the program. The initial screen gives the model name and version number. Several information screens with recent developments and other news items then follow. The Main Menu gives the user access to all of the menus described in this chapter.

While the LEAD99d.EXE file occupies only about 160 KB on the hard drive, it will expand to a much larger size when loaded into RAM. Normally, a PC with 640 KB has enough RAM to run the program, but there may be some conflicts with TSR (Terminate and Stay Resident) programs. It may be necessary for the user to remove some TSR programs in order to run the IEUBK Model.

The Model does not require a math co-processor, but calculations may take up to 20 times longer without a co-processor.

2.4.2 Running the Model

The user should fill in the worksheet in Figure 2-11, which defines the exposure scenario, before proceeding with the parameter entries and the computations.

2.4.2.1 Computation Options

The computation menus present the user with a set of computation choices. One choice is the iteration time step, Selection "2". These choices range from 15 minutes to 30 days. The default of 4 hours is adequate for most purposes. Setting this option on the RUN Menu also sets the iteration time for other computation modes, including the Batch Mode.

2.4.2.2 Output Options

At any time during the session, the program may be saved to a designated file. This gives the user the option of retrieving a set of parameters at some future session without reentering the parameters individually. After each model run, the user can select one of several plot options, which can be viewed on the screen, printed to file or sent to a printer. Most plots generated by the model can be printed by using the F10 key on the keyboard. The program presently interfaces with nine standard printer types or orientations. The Graphics Menu selection "7" allows user-specified scaling of the X-axis variable. Future versions of the model may have additional output options.

IEUBK MODEL WORKSHEET			
SITE OR PROJECT:	Model Version:	Date:	
Model Run Control Number:	Site Description:		
PARAMETER	DEFAULT VALUE	USER SELECTED OPTION	UNITS
AIR (constant)			
Outdoor air lead concentration	0.10		$\mu g/m^3$
Ratio of indoor to outdoor air lead concentration	30		%
AIR (by year)			
Air concentration Age = 0-1 year (0-11 mo), 1-2 years (12-23 mo) 2-3 years (24-35 mo) 3-4 years (36-47 mo) 4-5 years (48-59 mo) 5-6 years (60-71 mo) 6-7 years (72-84 mo)	 .10 .10 .10 .10 .10 .10 .10		$\mu g/m^3$
Time outdoors Age = 0-1 year (0-11 mo), 1-2 years (12-23 mo) 2-3 years (24-35 mo) 3-7 years (36-83 mo)	 1 2 3 4		h/day
Ventilation rate Age = 0-1 year (0-11 mo), 1-2 years (12-23 mo) 2-3 years (24-35 mo) 3-4 years (36-47 mo) 4-5 years (48-59 mo) 5-6 years (60-71 mo) 6-7 years (72-84 mo)	 2 3 5 5 5 7 7		m^2/day
Lung absorption	32		%
DATA ENTRY FOR DIET (by year)			
Dietary lead intake Age = 0-1 year (0-11 mo), 1-2 years (12-23 mo) 2-3 years (24-35 mo) 3-4 years (36-47 mo) 4-5 years (48-59 mo) 5-6 years (60-71 mo) 6-7 years (72-84 mo)	 5.53 5.78 6.49 6.24 6.01 6.34 7.00		μg Pb /day

Figure 2-11. Integrated exposure uptake biokinetic model sample worksheet.

DATA ENTRY FOR ALTERNATE DIET SOURCES (by food class)			
Concentration: home-grown fruits home-grown vegetables fish from fishing game animals from hunting	 0 0 0 0		μg Pb/g
Percent of food class: home-grown fruits home-grown vegetables fish from fishing game animals from hunting	 0 0 0 0		%
DATA ENTRY FOR DRINKING WATER			
Lead concentration in drinking water	4		μg/L
Ingestion rate Age = 0-1 year (0-11 mo), 1-2 years (12-23 mo) 2-3 years (24-35 mo) 3-4 years (36-47 mo) 4-5 years (48-59 mo) 5-6 years (60-71 mo) 6-7 years (72-84 mo)	 0.20 0.50 0.52 0.53 0.55 0.58 0.59		liters/day
DATA ENTRY FOR ALTERNATE DRINKING WATER SOURCES			
Concentration first-draw water flushed water fountain water	 4 1 10		μg/L
Percentage of total intake first-draw water flushed water (not a user entry; calculated based on entries for first-draw and fountain percentages) fountain water	 50 100 minus first draw and fountain 15		%
DATA ENTRY FOR SOIL/DUST (constant)			
Concentration Soil Dust	 200 200		μg/g
Soil ingestion as percent of total soil and dust ingestion	45		%

Figure 2-11 (cont'd). Integrated exposure uptake biokinetic model sample worksheet.

DATA ENTRY FOR SOIL/DUST INGESTION (by year)			
Soil/dust ingestion			
Age = 0-1 year (0-11 mo),	0.085		g/day
1-2 years (12-23 mo)	0.135		
2-3 years (24-35 mo)	0.135		
3-4 years (36-47 mo)	0.135		
4-5 years (48-59 mo)	0.100		
5-6 years (60-71 mo)	0.090		
6-7 years (72-84 mo)	0.085		
DATA ENTRY FOR SOIL (by year)			
Soil lead concentration			μg/g
Age = 0-1 year (0-11 mo)	0		
1-2 years (12-23 mo)	0		
2-3 years (24-35 mo)	0		
3-4 years (36-47 mo)	0		
4-5 years (48-59 mo)	0		
5-6 years (60-71 mo)	0		
6-7 years (72-84 mo)	0		
DATA ENTRY FOR DUST (by year)			
Dust lead concentration			μg/g
Age = 0-1 year (0-11 mo)	0		
1-2 years (12-23 mo)	0		
2-3 years (24-35 mo)	0		
3-4 years (36-47 mo)	0		
4-5 years (48-59 mo)	0		
5-6 years (60-71 mo)	0		
6-7 years (72-84 mo)	0		
DATA ENTRY FOR SOIL/DUST MULTIPLE SOURCE ANALYSIS (constant)			
Ratio of dust lead concentration to soil lead concentration	0.70		unitless
Ratio of dust lead concentration to outdoor air lead concentration	100		μg Pb/g dust per μg Pb/m^3 air
DATA ENTRY FOR SOIL/DUST MULTIPLE SOURCE ANALYSIS WITH ALTERNATIVE HOUSEHOLD DUST LEAD SOURCES (constant)			
Concentration			μg/g
household dust (calculated)	150		
secondary occupational dust	1,200		
school dust	200		
daycare center dust	200		
second home	200		
interior lead-based paint	1,200		

Figure 2-11 (cont'd). Integrated exposure uptake biokinetic model sample worksheet.

Percentage household dust (calculated) secondary occupational dust school dust daycare center dust second home interior lead-based paint	 100 minus all other 0 0 0 0 0		%
BIOAVAILABILITY DATA ENTRY FOR ALL GUT ABSORPTION PATHWAYS			
Total lead absorption (at low intake) diet drinking water soil dust alternate source	 50 50 30 30 0		%
Fraction of lead absorbed passively at high intake diet drinking water soil dust alternate source	 0.2 0.2 0.2 0.2 0.2		unitless
DATA ENTRY FOR ALTERNATE SOURCES (by year)			
Total lead intake Age = 0-1 year (0-11 mo), 1-2 years (12-23 mo) 2-3 years (24-35 mo) 3-4 years (36-47 mo) 4-5 years (48-59 mo) 5-6 years (60-71 mo) 6-7 years (72-84 mo)	 0 0 0 0 0 0 0		μg/day
DATA ENTRY MENU FOR MATERNAL-TO-NEWBORN LEAD EXPOSURE			
Mother's blood lead level at time of birth	2.5		μg/dL
DATA ENTRY MENU FOR PLOTTING AND RISK ESTIMATION			
Geometric standard deviation for blood lead, GSD	1.6		unitless
Blood lead level of concern, or cutoff	10		μg/dL
COMPUTATION OPTIONS			
Iteration time step for numerical integration	4		h

Figure 2-11 (cont'd). Integrated exposure uptake biokinetic model sample worksheet.

3. QUICK REFERENCE FOR THE EXPERIENCED USER

3.1 FINDING YOUR WAY THROUGH THE MENUS

The Lead Model is a menu driven program. There is no need to remember special commands, just a cursory understanding of the menu structure. Often you can find what you want just by exploring the various menu options, and familiarity with the model is the best way to shorten this journey. For your reference, a complete menu tree is given in Figure 3-1. Use caution with unfamiliar menu options. Detailed explanations are given in Chapter 2, and more complete documentation may be found in Chapter 4 for most menu options. These should be reviewed before final decisions are made on critical model runs.

3.2 PARAMETER LIST WITH DEFAULT VALUES

The values in Table 3-1 have been assumed for the parameters of the model. These are our best estimates for urban residents with no unusual lead exposures. The estimated blood lead levels with the default parameters represent our best estimate of the blood lead "background" levels that cannot be avoided. The adjustable parameters are listed by screen in the order in which they appear in the model.

Default values are provided for the convenience of the user, but these values may not be appropriate for specific applications. The user has the ultimate responsibility for justification of values used in the applications of the model. We recommend that the user review each of the parameter values in Table 3-1. Most of the parameters will not need to be modified, but the user should be aware of them. Sensitivity analyses on parameters will be useful in documenting results. Many default parameters in the model have only a minor effect on the results (i.e., a 10% change in the air lead concentration parameter will change blood lead levels by less than 1%), but some parameters may be more influential.

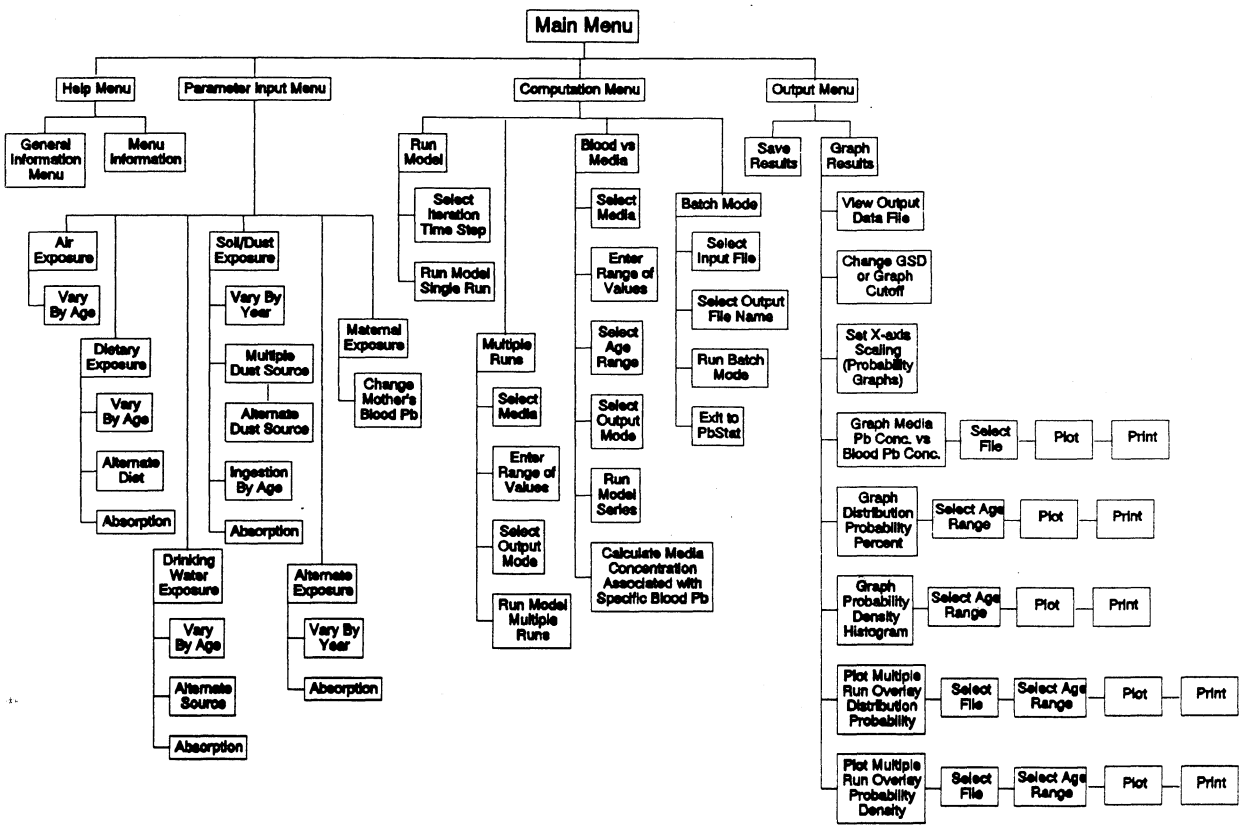


Figure 3-1. Lead model menu tree.

3.3 BATCH MODE INPUT FORMAT

You may find a number of circumstances in which it is convenient to enter input data for many similar exposure scenarios in a single run of the model. Option 4 of the Computation Menu allows you to use a different age or a different value of the lead concentrations in soil, dust, water, air, and alternate lead intake sources for each exposure scenario. The media intake and absorption parameters are the same for every exposure scenario in the run and must be specified before using this option, unless default values are used. These situations may include, but are not limited to:

TABLE 3-1. DEFAULT VALUES FOR MODEL PARAMETERS

PARAMETER	DEFAULT VALUE	UNITS
AIR (constant)		
Outdoor air lead concentration	0.10	$\mu g/m^3$
Ratio of indoor to outdoor air lead concentration	30	%
AIR (by year)		
Air concentration		
Age = 0-1 year (0-11 mo),	.10	$\mu g/m^3$
1-2 years (12-23 mo)	.10	
2-3 years (24-35 mo)	.10	
3-4 years (36-47 mo)	.10	
4-5 years (48-59 mo)	.10	
5-6 years (60-71 mo)	.10	
6-7 years (72-84 mo)	.10	
Time outdoors		
Age = 0-1 year (0-11 mo),	1	h/day
1-2 years (12-23 mo)	2	
2-3 years (24-35 mo)	3	
3-7 years (36-83 mo)	4	
Ventilation rate		
Age = 0-1 year (0-11 mo),	2	m^3/day
1-2 years (12-23 mo)	3	
2-3 years (24-35 mo)	5	
3-4 years (36-47 mo)	5	
4-5 years (48-59 mo)	5	
5-6 years (60-71 mo)	7	
6-7 years (72-84 mo)	7	
Lung absorption	32	%
DATA ENTRY FOR DIET (by year)		
Dietary lead intake		
Age = 0-1 year (0-11 mo),	5.53	μg Pb /day
1-2 years (12-23 mo)	5.78	
2-3 years (24-35 mo)	6.49	
3-4 years (36-47 mo)	6.24	
5-6 years (48-59 mo)	6.01	
5-6 years (60-71 mo)	6.34	
6-7 years (72-84 mo)	7.00	
DATA ENTRY FOR ALTERNATE DIET SOURCES (by food class)		
Concentration:		
home-grown fruits	0	μg Pb/g
home-grown vegetables	0	
fish from fishing	0	
game animals from hunting	0	

TABLE 3-1 (cont'd). DEFAULT VALUES FOR MODEL PARAMETERS

PARAMETER	DEFAULT VALUE	UNITS
Percent of food class:		
home-grown fruits	0	%
home-grown vegetables	0	
fish from fishing	0	
game animals from hunting	0	
DATA ENTRY FOR DRINKING WATER		
Lead concentration in drinking water		μg/L
Ingestion rate		
Age = 0-1 year (0-11 mo),	0.20	liters/day
1-2 years (12-23 mo)	0.50	
2-3 years (24-35 mo)	0.52	
3-4 years (36-47 mo)	0.53	
4-5 years (48-59 mo)	0.55	
5-6 years (60-71 mo)	0.58	
6-7 years (72-84 mo)	0.59	
DATA ENTRY FOR ALTERNATE DRINKING WATER SOURCES		
Concentration		μg/L
first-draw water	4	
flushed water	1	
fountain water	10	
Percentage of total intake		
first-draw water	50	%
flushed water	100 minus first draw and fountain	
fountain water	15	
DATA ENTRY FOR SOIL/DUST (constant)		
Concentration		
soil	200	μg/g
dust	200	
Soil ingestion as percent of total soil and dust ingestion	45	%
DATA ENTRY FOR SOIL/DUST INGESTION (by year)		
Soil/dust ingestion		
Age = 0-1 year (0-11 mo),	0.085	g/day
1-2 years (12-23 mo)	0.135	
2-3 years (24-35 mo)	0.135	
3-4 years (36-47 mo)	0.135	
4-5 years (48-59 mo)	0.100	
5-6 years (60-71 mo)	0.090	
6-7 years (72-84 mo)	0.085	

TABLE 3-1 (cont'd). DEFAULT VALUES FOR MODEL PARAMETERS

PARAMETER	DEFAULT VALUE	UNITS
DATA ENTRY FOR DUST (by year)		
Dust lead concentration		
1-2 years (12-23 mo)	0	μg/g
2-3 years (24-35 mo)	0	
3-4 years (36-47 mo)	0	
4-5 years (48-59 mo)	0	
5-6 years (60-71 mo)	0	
6-7 years (72-84 mo)	0	
DATA ENTRY FOR SOIL/DUST MULTIPLE SOURCE ANALYSIS (constant)		
Ratio of dust lead concentration to soil lead concentration	0.70	unitless
Ratio of dust lead concentration to outdoor air lead concentration	100	μg Pb/g dust per μg Pb/m^3 air
DATA ENTRY FOR SOIL/DUST MULTIPLE SOURCE ANALYSIS WITH ALTERNATIVE HOUSEHOLD DUST LEAD SOURCES (constant)		
Concentration		
household dust	150	μg/g
secondary occupational dust	1,200	
school dust	200	
daycare center dust	200	
second home	200	
interior lead-based paint	1,200	
Percentage		
household dust	100 minus all other	%
secondary occupational dust	0	
school dust	0	
daycare center dust	0	
second home	0	
interior lead-based paint	0	
BIOAVAILABILITY DATA ENTRY FOR ALL GUT ABSORPTION PATHWAYS		
Total lead absorption (at low intake)		
diet	50	%
drinking water	50	
soil	30	
dust	30	
alternate source	0	
Fraction of lead absorbed passively at high intake		
diet	0.2	unitless
drinking Water	0.2	
soil	0.2	
dust	0.2	
alternate source	0.2	

TABLE 3-1 (cont'd). DEFAULT VALUES FOR MODEL PARAMETERS

PARAMETER	DEFAULT VALUE	UNITS
DATA ENTRY FOR ALTERNATE SOURCES (by year)		
Total lead intake		
Age = 0-1 year (0-11 mo),	0	μg/day
1-2 years (12-23 mo)	0	
2-3 years (24-35 mo)	0	
3-4 years (36-47 mo)	0	
4-5 years (48-59 mo)	0	
5-6 years (60-71 mo)	0	
6-7 years (72-84 mo)	0	
DATA ENTRY MENU FOR MATERNAL-TO-NEWBORN LEAD EXPOSURE		
Mother's blood lead level at time of birth	2.5	μg/dL
DATA ENTRY MENU FOR PLOTTING AND RISK ESTIMATION		
Geometric standard deviation for blood lead, GSD	1.6	unitless
Blood lead level of concern, or cutoff	10	μg/dL
COMPUTATION OPTIONS		
Iteration time step for numerical integration	4	h

(1) comparison of predicted values from the Integrated Exposure/Uptake Biokinetic (IEUBK) model with actual blood lead levels observed in a blood lead and environmental lead field study such as illustrated in Table 3-2.;

(2) risk estimation using predicted values from the IEUBK model with actual environmental lead levels observed in an environmental lead field study;

(3) estimation of the effect of variability in environmental lead levels on the distribution of blood lead levels in the population;

(4) sensitivity analyses on the impact of environmental lead exposure.

The input data file for a batch run must be created outside the IEUBK model using whatever text editor the user prefers. The following conventions MUST be observed in creating the batch file:

TABLE 3-2. FORMAT FOR BATCH MODE INPUT DATA FILE (SIMULATED DATA)

Header line 1 > INPUT DATA FILE FOR A MONTE CARLO SIMULATION

Header line 2 > FIRST THREE COLUMNS RANDOM NOS. FOR SOIL, DUST, BLOOD

Header line 3 > ID FAM NBHD AGE PBS PBD PBW PBA ALT PBB

1	FP-1	PIONEER_HILL	18	510.0	457.8	4.0	0.1	0.0	2.6
2	FP-2	PIONEER_HILL	18	200.0	159.8	4.0	0.1	0.0	2.3
3	FP-3	PIONEER_HILL	18	373.1	475.3	4.0	0.1	0.0	3.4
4	FP-4	PIONEER_HILL	18	1042.5	1361.6	4.0	0.1	0.0	8.7
5	FP-5	PIONEER_HILL	18	519.2	332.7	4.0	0.1	0.0	2.9
6	FP-6	PIONEER_HILL	18	3123.6	1117.6	4.0	0.1	0.0	6.3
7	FP-7	PIONEER_HILL	18	1938.2	1295.8	4.0	0.1	0.0	4.9
8	FP-8	PIONEER_HILL	18	287.5	649.9	4.0	0.1	0.0	11.8
9	FP-9	PIONEER_HILL	18	1227.0	1997.5	4.0	0.1	0.0	23.3
10	FP-10	PIONEER_HILL	18	321.7	405.5	4.0	0.1	0.0	4.4
11	FR-1	RIVERSIDE	18	631.9	58.4	4.0	0.1	0.0	5.6
12	FR-2	RIVERSIDE	18	55.7	23.9	4.0	0.1	0.0	2.0
13	FR-3	RIVERSIDE	18	336.3	658.6	4.0	0.1	0.0	4.1
14	FR-4	RIVERSIDE	18	666.9	221.5	4.0	0.1	0.0	3.2
15	FR-5	RIVERSIDE	18	2005.6	1532.1	4.0	0.1	0.0	26.2
16	FR-6	RIVERSIDE	18	394.8	92.7	4.0	0.1	0.0	2.3
17	FR-7	RIVERSIDE	18	1183.3	692.8	4.0	0.1	0.0	2.7
18	FR-8	RIVERSIDE	18	450.8	83.6	4.0	0.1	0.0	2.4
19	FR-9	RIVERSIDE	18	210.2	94.7	4.0	0.1	0.0	1.5
20	FR-10	RIVERSIDE	18	650.6	682.0	4.0	0.1	0.0	4.5
21	FR-11	RIVERSIDE	18	238.4	314.2	4.0	0.1	0.0	2.0
22	FR-12	RIVERSIDE	18	256.6	48.0	4.0	0.1	0.0	2.0
23	FR-13	RIVERSIDE	18	636.2	219.6	4.0	0.1	0.0	4.4
24	FR-14	RIVERSIDE	18	100.3	31.5	4.0	0.1	0.0	3.2
25	FB-1	BRIDGE_ST	18	678.6	605.4	4.0	0.1	0.0	10.0
26	FB-2	BRIDGE_ST	18	249.5	136.3	4.0	0.1	0.0	2.0
27	FB-3	BRIDGE_ST	18	291.5	127.8	4.0	0.1	0.0	4.1
28	FB-4	BRIDGE_ST	18	750.9	2514.8	4.0	0.1	0.0	4.5
29	FB-5	BRIDGE_ST	18	89.3	135.4	4.0	0.1	0.0	3.3
30	FB-6	BRIDGE_ST	18	943.2	282.4	4.0	0.1	0.0	6.7
31	FB-7	BRIDGE_ST	18	1668.6	369.2	4.0	0.1	0.0	11.9
32	FB-8	BRIDGE_ST	18	1399.1	503.0	4.0	0.1	0.0	6.0
33	FB-9	BRIDGE_ST	18	1226.8	503.0	4.0	0.1	0.0	5.9
34	FB-10	BRIDGE_ST	18	1905.1	978.3	4.0	0.1	0.0	4.6
35	FB-11	BRIDGE_ST	18	366.3	2727.8	4.0	0.1	0.0	13.4
36	FB-12	BRIDGE_ST	18	62.5	464.7	4.0	0.1	0.0	3.9
37	FB-13	BRIDGE_ST	18	75.8	49.3	4.0	0.1	0.0	5.4
38	FB-14	BRIDGE_ST	18	393.5	88.6	4.0	0.1	0.0	1.2
39	FB-15	BRIDGE_ST	18	461.6	883.7	4.0	0.1	0.0	1.7
40	FB-15	BRIDGE_ST	18	461.6	883.7	4.0	0.1	0.0	1.9

- The input data file must be an ASCII file with no special characters.

- The data set must have a DAT extension (i.e., [name].DAT).

- The first three lines of the input data file can be any identifiers that the user requires; we usually use the first line for the run name, the second line for modelling options used in the run, and the third line as headers for variables in the data set;

- The data fields are entered format-free, although the use of regular spacings and alignment of decimal points are recommended to improve readability;

- Maximum width 80 columns;

- Variable values should be separated by spaces;

- Missing values must be shown by an isolated decimal point as in some examples in Chapter 5;

- Each line in the input data file must contain the following 10 variables:

  1. Child identifier or code
  2. Family or residence unit identifier or code
  3. Area or neighborhood identifier code
  4. Child's age in months
  5. Soil lead concentration in μg Pb/g
  6. Dust lead concentration in μg/g
  7. Drinking water lead concentration in μg/L
  8. Air lead concentration in $\mu g/m^3$
  9. Daily intake of lead from other sources, μg Pb/day
  10. Observed child blood lead level.

In Chapter 5 we will demonstrate an approach to using the IEUBK model in the batch mode option. Soil, dust, and blood lead "data" were simulated using realistic parameters for sites with active air lead point sources. The attached Table 3-2 shows a batch mode input data file for 40 children. All were assumed to be 18 months old and had default air, water, and alternate source lead values. The first three columns in Table 3-2 are the child identifier, the family identifier (note simulated twins as ID 39 and 40), and the "neighborhood". These fields could be any alpha-numeric identifiers defined by the user.

3.4 OUTPUTS FOR DOCUMENTATION, BRIEFING, AND PRESENTATION

3.4.1 Overview of Output Options

The IEUBK model includes some output options that facilitate presentation of the results and testing of the results for parameter sensitivity. These options may be a useful part of the documentation for decisions in which the IEUBK model plays a role. We will first describe the output options, and then show some of their applications. Some sensitivity analyses can be facilitated by the use of these options.

3.4.1.1 Plotting (Option 2)

Single-Plot Options (Selections 2 and 3)

Some plot options can be used with single runs of the IEUBK model, and others require multiple runs. Single-run options include:

- Plotting the log-normal probability density function of blood lead levels for a single exposure scenario predicting geometric mean blood lead (Selection 3);
- Plotting the cumulative probability distribution for exceeding any user specified blood lead level of concern for a single exposure scenario (Selection 2). This is sometimes called the exceedance probability distribution.

The probability density function gives most users a better idea of the spread of blood lead levels for children exposed to a single set of environmental lead concentrations. The exceedance probability distribution may be used to visually estimate the fraction of children above a blood lead level of concern for the single-exposure case (e.g., what fraction of children are above 10 μg/dL), or to visually estimate the blood lead level corresponding to a specified fraction of children (e.g., what blood lead concentration encompasses 95% of the children). The user may route the probability plots to a printer after viewing the display.

Multiple-Plot Options (Selections 1, 4, and 5)

There are additional features that allow the user to combine output from several runs onto single plots. These multiple-run options include:

- Overlaid plots of the log-normal probability density functions of blood lead levels for multiple exposure scenarios, where each run increases the lead concentration in a specified medium by a user-defined amount (Selection 5);

- Overlaid plots of the cumulative exceedance probability distributions of blood lead levels for multiple exposure scenarios, where each run increases the lead concentration in a specified medium by a user-defined amount (Selection 4);

- Plots of geometric mean blood lead levels versus environmental lead levels for the medium whose values are varied (Selection 1).

Selection 1 cannot be used unless the user has previously created an output file from the Computation Menu, designated *.PBM. Selections 4 or 5 cannot be used unless the user has previously created an output file from the Computation Menu, designated *.LAY.

The overlaid probability density functions give most users a better idea of how the probability of exceeding a blood lead level of concern increases with each increment in environmental lead. The exceedance probability distributions may be used to estimate the increases in the fraction of elevated blood lead levels or to visually estimate the environmental lead levels corresponding to a specified fraction of non-protected children above the level of concern.

3.4.1.2 Uses of Batch Mode Analysis (Option 4)

Results from multiple exposure scenarios can be accumulated using the batch mode options. For sensitivity analyses involving constant concentrations in air, water, dust, soil, or an alternate medium whose intake is constant, it is possible to create a batch mode input file in which each line represents a different case for the analysis. However, with Option 4 it is only possible to carry out sensitivity analyses in which the cases differ on the basis of concentration. Other types of sensitivity analyses require the accumulation of single runs in an overlay file.

Another application in which batch mode methods are useful is a Monte Carlo analysis in which all the modelled variability is assigned to differences in the environmental concentrations. The results can be stored in a batch mode output file which may then be used for statistical analyses.

3.4.2 Detailed Instructions on Output Options

3.4.2.1 Save Output from a Single Run

1. Develop an exposure scenario.

2. Run the model (Selection 2 on Computation Menu, or F5 from any Data Entry Menu).

3. Save results (Selection 2 after running the model). Results may be appended to the file RESULTS.TXT, or added to an overlay plot file defined by the user with name [name].LAY.

4. Results may be sent to a printer.

3.4.2.2 Save Output from Multiple Runs for Probability Plots (Option 3 on Range Selection Menu)

1. Develop an exposure scenario

2. Use the Multiple Runs option (Option 2) on the Computation Menu.
   1- Select the medium (Soil, Dust, Air, Water, Diet)
   2- Select the lower and upper values for the medium
   4- OUTPUT CHOICES
      - Select number of steps from small to large
      - Send results to overlay file RANGE(#+1).LAY, where the output file is automatically named by increasing the index of the largest numbered (#) current RANGE#.LAY file.

3. Results may be sent to a printer.

3.4.2.3 Save Output from Multiple Runs for Media-Level Plots (Option 3 on the Computation Menu)

1. Develop an exposure scenario

2. Use the Media Run option (Option 3) on the Computation Menu.
   1- Select the medium (Soil, Dust, Air, Water, Diet)
   2- Select the lower and upper values for the medium
   4- OUTPUT CHOICES
      - Select number of steps from small to large
      - Change the age range for calculating mean blood lead.
      - Send results to overlay file MEDBLD(#+1).PBM, where the output file is automatically named by increasing the index of the largest current MEDBLD#.PBM file.

3. Results may be sent to a printer.

3.4.2.4 Save Output from a Batch Mode Run (Option 4 on the Computation Menu)

1. Create a batch mode input data file, [name].DAT.

2. Use the Batch Mode Run option (Option 4) on the Computation Menu.

3. Load the [name].DAT file you have created.

4. Rename the output data file [newname].* if required in the Run step.

5. Run the model.

The output data sets are named [newname].ASC and [newname].TXT, or [name].ASC and [name].TXT if not renamed.

3.4.2.5 Probability Plots for Single Runs

For Current Runs Using Option 2 on Output Menu:

1. Run the model with user-defined exposure scenario in Option 2 on Output Menu.

2. Then choose Selection 2 or 3 in the Graphics Selection Menu.

3. Choose the Age Range.

4. Print graph, without exiting, by using the F10 key, then selecting printer type.

If the user has exited from the current Run, but has not done any further runs, then Steps 3 through 5 can be executed by returning to the Graphics Menu and executing Option 2 or 3.

For Current Runs Using Option 2 on Output Menu:

1. Run the model with user-defined exposure scenario in Option 2. If the user has aborted the runs in Option 2, but has not done any runs since, then the last complete run may be plotted as above. The procedure is:

2. Select Option 3 in the Main Menu, then option 2 on the Output Menu.

3. Then choose Selection 2 or 3 in the Graphics Selection Menu.

4. Choose the Age Range.

5. Print graph, without exiting, by using the F10 key, then selecting printer type.

3.4.2.6 Probability Plots for Multiple Runs

1. Run the model with user-defined exposure scenario in Option 2 on the Computation Menu. Do not abort the runs in Option 2.

2. Select Option 3 in the Main Menu, then Option 2 on the Output Menu.

3. Then choose Selection 4 or 5 in the Graphics Selection Menu.

4. Identify the *.LAY data set to plot.

5. Choose the Age Range.

6. Print graph, without exiting, by using the F10 key, then selecting printer type.

3.4.2.7 Multi-Level Plots for Blood Lead Versus Media Lead

1. Run the model with user-defined exposure scenario in Option 2 on the Computation Menu.

2. Select Option 3 in the Main Menu, then Option 2 on the Output Menu.

3. Then choose Selection 1 in the Graphics Selection Menu.

4. Identify the MEDBLD#.PBM data set to plot.

5. Print graph, without exiting, by using the F10 key, then selecting printer type.

Batch mode files can be used for display or documentation through the statistics module on the Batch Mode Menu, Option 4.

3.4.3 Recommendations on Multi-Level Soil Lead Exposure Scenarios

The IEUBK model carries out multi-level analyses by increasing the concentration of the user-specified medium by equal steps at each run, and holding everything else constant. When evaluating different soil lead exposure scenarios, it may be preferable to keep a constant soil-to-dust coefficient so that dust lead exposure increases with increasing soil lead exposure. This can be done by first invoking the Multiple Source Analysis for dust and defining the dust lead to soil lead coefficient. This is particularly important if some component of the soil lead abatement is expected to permanently alter the soil to dust pathway.

4. MORE ABOUT THE MODEL[1]

4.1 LEAD BIOAVAILABILITY

4.1.1 Background

The concept of bioavailability is important for site-specific risk assessments for lead. The concept springs from the fact that lead potentially available to produce harm and found in exposure pathways or in body receiving compartments (lung, skin, gut) must reach the biological sites of action in order for an adverse health effect to occur in exposed humans or ecological biota.

This section focuses primarily on the bioavailability of inorganic lead from soils and dusts. Lead bioavailability from air and drinking water is also important and is discussed in limited detail below. In order to provide coherent and useful guidance to the reader and user of this chapter, it is subdivided into (1) introductory material that includes definitions of bioavailability and resource material in the technical literature; (2) the close lead absorption-bioavailability relationships, including the physiological and biochemical mechanisms of lead absorption and the many, complex factors that influence such uptake; (3) the main focus of the chapter, bioavailability as it relates to human and experimental toxicology, including the various biophysico-chemical and environmental aspects of the lead exposure matrix, methodological approaches in toxicology for quantifying bioavailability, the increasingly important question of relevant experimental animal models for quantifying lead bioavailability in humans; and, finally, (4) a summary and critical overview, which attempts to spell out the appropriate uses of bioavailability information and limits to use this information in site-specific risk assessment.

4.1.2 Definitions

A clear agreement on a definition of bioavailability should be established before one presents a detailed discussion of this topic. The difficulty here is that there are various

[1]This chapter is intended to provide guidance on some technically advanced applications of the model. We have attempted to provide the best scientific documentation available but recognize that new information may become available in these rapidly advancing fields. The user is referred to Section 1.6 for information on how to get additional and more up-to-date assistance with specific applications of the model.

definitions of bioavailability depending on the scientific discipline using the term and the technical context of use.

Typically, the pharmacologist or toxicologist or others in biomedical disciplines are concerned with measuring bioavailability as that fraction of the total amount of material in contact with a body portal of entry (lung, gut, skin) that then enters the blood. For the purpose of describing the Integrated Exposure Uptake Biokinetic (IEUBK) Model, this is the definition to be used in this manual. However, an aquatic biologist may define bioavailability as that fraction of material solubilized in the water column under certain conditions of hardness and pH. An aquatic toxicologist might consider contaminants which are soluble under specific stream conditions to be bioavailable to fish or benthic organisms. A biochemist or biochemical toxicologist would consider bioavailability with reference to that fraction of a toxicant which is available at the organ or cellular site of toxicity.

The above definitions can be viewed as dosimetrically descriptive. There are quantitative methodological definitions that figure as well. As described later, bioavailability can be defined as being absolute or relative (comparative). Absolute bioavailability, for example, is the amount of substance entering the blood via a particular biological pathway relative to the absolute amount that has been ingested. Relative bioavailability of lead is indexed by comparing the bioavailability of one chemical species or form of lead with that of another form of lead. A second methodological description for bioavailability that is used by toxicologists is the ratio of areas under the dose-response curve for either of two forms of lead, or two methods of administration. Typically, the latter involves comparing injected with orally administered doses.

4.1.3 Literature Sources on Bioavailability

More detailed reviews and discussions of the topic of lead bioavailability in humans and experimental animals have been presented by Mushak (1991) and Chaney et al. (1988). As is evident from these reviews, our present understanding of lead bioavailability has developed from both human and animal studies. For further in-depth discussion of the various components of bioavailability, for example, lead absorption, the reader is also referred to the following documents: (1) the Air Quality Criteria Document for Lead (U.S. Environmental Protection Agency, 1986), and (2) the Proceedings of the Symposium on the Bioavailability and Dietary Exposure of Lead (1991).

Citations of key specific studies are provided in the relevant sections and subsections of this chapter rather than here, so as to be less disruptive to the reader.

4.1.4 Lead Absorption-Bioavailability Relationships

By definition, the absorption (uptake) of lead into the circulation is the critical kinetic component of the overall process called bioavailability. Not only the amount, but also the *rate of uptake* of that given amount is important, particularly under acute or subacute exposure conditions, and when dealing with lead-containing media in the gastrointestinal (GI) tract. Such material is itself moving through the GI tract within a relatively short time period. Consequently, the biological and physiological characteristics of absorption, the subcellular mechanisms of absorption, and the factors influencing its occurrence must be understood in order to understand the resulting phenomenon. The focus of this chapter is soil and dust lead ingested (swallowed) by populations at risk, requiring that lead uptake phenomena in the gastrointestinal tract be given most of the attention.

Species-specific anatomical and physiological determinants of GI absorption are the macroscopic factors that provide the basic means by which lead absorption occurs. As noted in more detail in Section 4.1.5, there are major structural differences in the anatomy of the GI tract of various mammalian species that would affect lead absorption. Similarly, it is the physiology of the mucosal lining (epithelium) of the mammalian GI tract that is the first dynamic determinant of lead movement from the GI tract to the bloodstream.

4.1.5 Cellular and Subcellular Mechanisms of Lead Absorption

Lead absorption is believed to proceed by several cellular mechanisms involving the enterocytes, cells lining the intestinal wall (Figure 4-1) (e.g., Mushak, 1991). Absorption also entails complex interactions with the uptake of essential nutrients such as calcium, iron and phosphate (Barton et al., 1978, 1981; Mahaffey-Six and Goyer, 1972).

The first uptake mechanism may be diffusion through the gut lumen driven by a concentration gradient from the luminal surface lining the intestine to the basolateral surface (vascular side). This mechanism is likely to depend to some extent on the concentration of ionic or unbound lead ion (Pb^{2+}), and consequently would depend on the solubility characteristics of lead species of interest. This may be a passive diffusion process requiring no energy input. It involves either intracellular or paracellular movement of lead across the

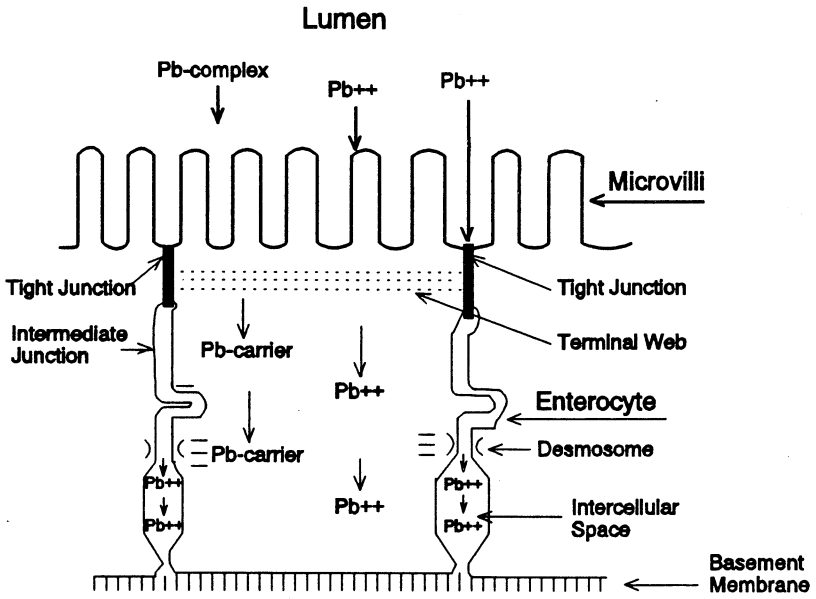


Figure 4-1. Schematic drawing of the enterocyte showing possible mechanisms for lead absorption. Possible mechanisms include: (1) an active or facilitated component; (2) a transcellular component perhaps involving pinocytotic mechanisms; and (3) a diffusion-driven paracellular route across tight junctions.

Source: Mushak, 1991, adapted from Morton et al. (1985).

wall. Paracellular transport would entail movement across the area between cells called "tight junctions."

In the second possibility, lead may enter the gut tissue (but not necessarily the bloodstream) by pinocytosis or other vesicular mechanisms. In pinocytosis, lead-bearing media in a liquid micro region of the gut are engulfed by the (enterocyte) cell membrane. Such encapsulating may involve lead in either a truly soluble or an emulsified/suspended form that is then carried to blood or to sites of toxic action. This process is biochemically analogous to handling of solid particles in phagocytosis.

Perhaps the quantitatively most important transport mechanism in environmental exposures typical for most individuals is energy-driven active transport, exploiting homeostatic transport mechanisms in place for calcium and iron transport (e.g., calcium binding protein [CaBP] or calbindin D), and under control of an enzyme—calcium, magnesium-dependent ATPase (Ca^{2+}, Mg^{2+}-ATPase)—involved in the absorption and regulation of blood calcium levels and located in the basolateral membrane of mucosal epithelial cells. This active component of lead absorption displays a strong age dependence,

being more important at younger ages. It is interesting that some of the transport systems that bring calcium into the body seem to have an even higher affinity for lead than for calcium (e.g., Fullmer et al., 1985).

While the results of experimental studies can be described quantitatively, the precise nature of biological and biochemical mechanisms in lead bioavailability is not yet completely understood. There is, however, a useful characterization of lead absorption mechanisms as either saturable (facilitated) or nonsaturable (passive). These various and complex biochemical/cellular mechanisms obviously have important implications for experimental models of human lead bioavailability, particularly with reference to comparison of in vivo to in vitro simple chemical simulation models.

4.1.6 Factors Affecting Lead Absorption

Lead uptake, especially from the GI tract, does not occur in a physiological vacuum but is the outcome of a complex set of interactions with other inorganic and organic substances, particularly such nutrients as calcium, iron, phosphate, vitamin D, fats, etc., as they occur in meals or with intermittent eating. In addition, uptake is a function of developmental stage (age), administered dose, the chemical species and the particle size of the lead-containing media.

It is well known that lead uptake is markedly lower with consumption of meals than under fasting conditions in adults (e.g., James et al., 1985; Rabinowitz et al., 1980) and presumably in children as well. Human data, in the aggregate, indicate that calcium, iron and other cations interact strongly as competitors to lead uptake so that lead uptake generally increases as dietary levels of these nutrients decrease (Mushak, 1991; U.S. Environmental Protection Agency, 1986). In rats, Garber and Wei (1974) showed that fasting increased the amount of lead taken up by the gut. Children are likely to be exposed to lead under a variety of fed or fasted (between meal) conditions. Therefore, any interpretations of lead bioavailability studies of site-specific characteristics should include the effect on uptake of food and time since eating.

There is a developmental or age dependency for the extent of lead absorption in both humans and experimental animals (Mushak, 1991; U.S. Environmental Protection Agency, 1986). Prepubertal children absorb more lead than do adults (Alexander et al., 1973; Ziegler et al., 1978). Experimental animal studies support the human data. Studies using rats showed that pre-weanling animals absorb 40 to 50 times more of a given dose of lead than

do adult animals (Kostial et al., 1971, 1978; Forbes and Reina, 1972), while infant monkeys will absorb 16 to 21 times more lead than adult monkeys (Munro et al., 1975). Possible mechanisms for this age dependence have been discussed (Weis and LaVelle, 1991; Mushak, 1991). The design or interpretation of bioavailability studies, aimed at assessing lead absorption for children, must consider age dependence of uptake of lead in any adjustments of the bioavailability parameter in the UBK model.

Human data indicate a dose dependence to the absorption of lead (Sherlock and Quinn, 1986). In duplicate diet studies of bottle-fed infants (5 to 7 kg) exposed to lead in water and in formula mixed with contaminated water, Sherlock and Quinn were able to quantify the dose dependence of lead absorption. Over the exposure range investigated in the study (40 to 3,000 μg/week), these investigators determined that the relationship between blood lead concentration and lead intake was curvilinear (Figure 4-2). This opportunistic human data describing the dose-dependence of lead absorption was considered by the Agency when establishing the kinetic approach to lead absorption used in the IEUBK Model.

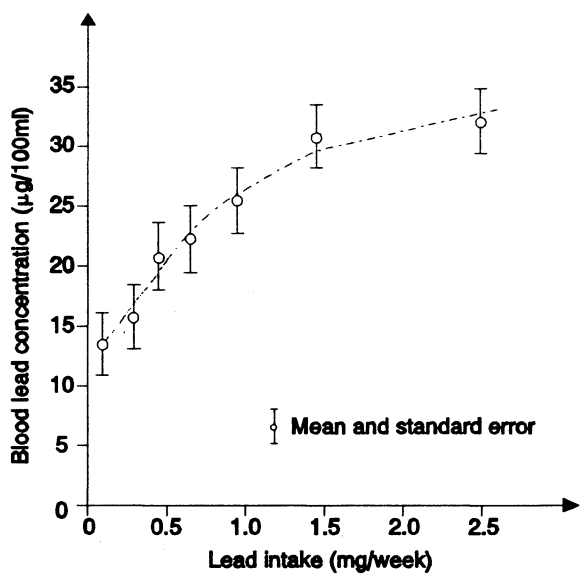


Figure 4-2. Dose-dependent relationship between dietary lead (formula mixed with water) and blood lead in infants.

Source: Sherlock and Quinn (1986).

Animal studies (e.g., Bushnell and DeLuca, 1983) indicate that GI lead absorption shows dependence on the level of oral dosing. Bushnell and DeLuca reported that lead uptake rates decreased when oral lead exposure concentration exceeded 10 to 100 ppm. This

dose-dependent inhibition of uptake is consistent with an active transport mechanism that requires lead-inhibited enzyme(s) for its operation and which also becomes saturated at higher lead dosings (Aungst and Fung, 1981; Mykkanen and Wasserman, 1981). Design and interpretation of studies to assess bioavailability of lead should also consider dose dependency in site-specific assessments.

Finally, the metal species and particle size may influence the solubility, and because of that, the bioavailability of lead. Experimental studies using relatively simple lead species showed that lead as the sulfide, chromate, naphthenate or octoate was less bioavailable (44 to 67%) relative to the more soluble carbonate (Barltrop and Meek, 1975). Barltrop and Meek (1979) also demonstrated an inverse relationship between lead uptake from leaded paint and particle size.

On the other hand, other investigators have documented that lead species that are relatively insoluble under simple in vitro conditions are as bioavailable as soluble salts under conditions of fasting (LaVelle et al., 1991; Rabinowitz et al., 1980).

4.1.7 Bioavailability of Lead in Soils and Dusts

Quantitative approaches to estimating bioavailability for purposes of the IEUBK model require consideration of three issues. The first, of course, is the physicochemical nature of the site-specific environmental media containing lead and what this suggests for behavior of lead-containing media in the GI tract (i.e., biophysico-chemical behavior). As noted earlier, particle size and chemical species are important. Equally important is the environmental matrix within which some particular chemical species of lead is to be found. The physicochemical complexity of these environmental matrices (e.g., dusts and soils, mining and process waste) considerably exceeds that of simple, laboratory forms. The second aspect is methodological: how one can quantify bioavailability in experimental or observational studies? Finally, it is critical that users of this manual and model understand the merits and the limits of the various types (classes) of bioavailability studies that can be done on a site-specific basis.

4.1.7.1 Biophysico-Chemical and Environmental Features of the Exposure Matrix

Types of Soil Lead Contamination

Environmental lead is found in a variety of chemical and physical forms. Lead-contaminated areas could be categorized according to the type of industry or lead-generating

processes associated with the site. Since we are concerned principally with lead in dusts and soils, these are the media of most site-specific concern.

Urban area sites are typically contaminated with those chemical forms arising from either the combustion of leaded gasoline (alkyl lead species such as tetraethyl lead used as anti-knock agents) at high levels in past years or from flakes, chips and dusts from exterior and interior lead-based paint.

Dust or soil lead originating from auto exhaust typically begins as lead-mixed halides (chloride, bromide) but undergoes transformation quickly to the oxide or sulfate (U.S. Environmental Protection Agency, 1986), two relatively bioavailable forms. Auto emission particulate is typically of small diameter (one micron or less), especially on residential surfaces farther away from roadways, where distant atmospheric transport is more favored than for the heavier particles that are deposited closer to the traffic sources. Such particles are also readily breathed into the lungs and readily stick to the hands of children, to family pets, etc. (U.S. Environmental Protection Agency, 1986; Mushak, 1991).

Paint lead is typically found as carbonate, chromate or octoate, and the element may represent up to 70% of the weight of the dried paint product. While lead-paint surfaces are intact, leaded paint would only become available as young children chew on accessible surfaces like painted furniture. In older structures, with surface aging, window and door frame abrasion, and deterioration of leaded paint surfaces, paint will flake, chip, chalk (interior) or weather (exterior) and become an important source of lead exposure for children. The nature of this material, especially as small adherent flecks and fine dusts, and its significant solubility are factors likely to favor significant bioavailability. The greatest numbers of lead-painted residential units are found in urban areas, but any unit anywhere built before 1978 may have lead-based paint.

Battery recycling plants, typically containing secondary lead smelting capacity, are often found as localized sources of environmental lead. Waste byproducts of this kind of lead processing include lead sulfate (sulfuric acid) on casings, and battery sulfuric acid itself, mobilizing lead into and through soils of limited buffering capacity. Lead from this material, either as feedstock or from secondary smelter stack emissions, is apt to be of small particle size as well. These factors warrant estimating bioavailability at the upper end of the range.

In nonferrous mining areas, lead is commonly found in a variety of material produced by hard rock mining, milling, and smelting processes. It is beyond the scope of this chapter

to present a detailed discussion of lead contamination with nonferrous mining, milling and smelting. The reader is referred to the review by Mushak (1991) for further details.

Mining waste can be broadly characterized as: (1) waste rock; (2) mill tailings; and (3) smelting waste. Waste rock is that material removed from the mine but having insufficient mineral economic value to warrant processing. This material is typically discarded at openings to the mine, consists of larger particles, and may or may not be enriched in heavy metals.

Mill tailing is material that has been processed by a variety of physical grinding, separating and enrichment processes. This material typically has smaller particle size than the less processed wastes and the material is enriched in toxic elements, including lead. Mineral content depends on the characteristics of the ore body and the milling process, and may range from soluble carbonates ($K_{sp} \approx 10^{-8}$) to extremely insoluble phosphates ($K_{sp} \approx 10^{-80}$) of lead. Furthermore, lead that is associated with mining waste may either be freely exposed at the particle surface or entirely encapsulated, so that the lead is not available to be dissolved in simple solvents like water.

Smelting waste may exist in many forms. Air- and water-quenched slags are strikingly different in their physical nature. Water-quenched material is typically of fine particle size, while air quenching results in large chunks of oxidized slag. Chemically, these slags consist of various metal oxides and include lead and silicon oxides. Bag house dust consists of the fine particulate matter trapped in the emissions stream by a simple bag filter prior to leaving the stack. This material is very high in toxic metal content, including lead, and occurs in very small particle size. These small particles include lead sulfate and oxide species. Dross is the foam or lighter fraction of the liquid product of the floatation process. When cool, it may be discarded, resulting in a potentially important exposure source.

4.1.7.2 Is There a Better Way To Classify Lead-Contaminated Sites?

It is often convenient to discuss lead-contaminated sites by classifying them as mining, smelting, urban or battery sites. As our understanding of the complexities of lead-contaminated sites improves, it becomes less and less useful to use these simplified descriptions. For example, mining areas typically are associated with present or historical milling and smelting. Significant smelter-related contamination may remain at closed and operating mines that can contribute to typical mine waste exposure concerns.

Mine wastes may consist of lead in a multitude of physical and chemical forms as discussed above, making generalizations about exposure or potential exposure (and bioavailability) inappropriate without additional applied research data. Mining and smelting areas may share exposure sources often associated with such urban areas. Adequate characterization of lead-contaminated media, for the purpose of estimating bioavailability, should include assessment of physical and chemical parameters (e.g., particle size and appropriate media solubility) as well as biophysico-chemical characteristics. Generalizations regarding the source of lead contamination which do not address risk-specific details of the physicochemical and biochemical nature of the waste are not as useful for predicting health risks from exposures.

4.1.7.3 Methodological Approaches to Quantifying Bioavailability

While lead can have severe toxic effects following a single very high exposure, we are primarily concerned in this chapter with relatively low levels of average exposure and average blood lead concentration (see Figures 4-3 and 4-4 for single versus multiple exposures and target organ concentrations).

The average near steady state (pseudoequilibrium) of an accumulating toxicant such as lead in blood following chronic (repetitive) exposure is proportional to the amount absorbed during each exposure. At low ingestion rates, where absorption and biokinetic processes are nearly linear, the following relationship applies between changes in blood lead and changes in chronic exposure:

$$\Delta \text{ PbB} = \frac{\Delta \text{ Pb-abs./day} * \text{ mean residence time in blood pool}}{\text{volume of distribution in blood pool}} .$$

Methods used to describe the fraction absorbed from exposure are well established and will be the primary focus of the following discussion.

4.1.7.4 Determination of Absolute Bioavailability

The methodology for quantifying absolute bioavailability in toxicology commonly compares (a) the area under the time-versus-blood-concentration curve (AUC) following intravenous (IV) injection with (b) an equivalent dose and a similar AUC measurement following ingestion of the substance being investigated. The ratio of AUC^{oral} to AUC^{IV} is then taken as a measure of percent absorption in the gut. From this, absolute bioavailability over a short time frame may be defined as:

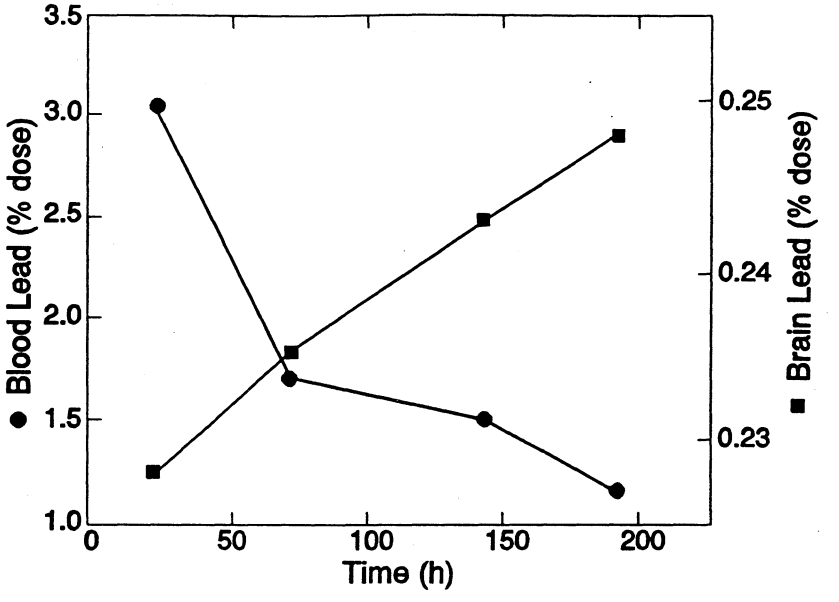


Figure 4-3. The time-course of bioavailability of lead in the blood (●) and in the brain (■) of juvenile rats following a single dose. Note that accumulation of lead in the target tissue (brain) continues as blood lead decreases. The significance of brain levels indicated is unknown.

Source: Adapted from Momcilovic and Kostial (1974).

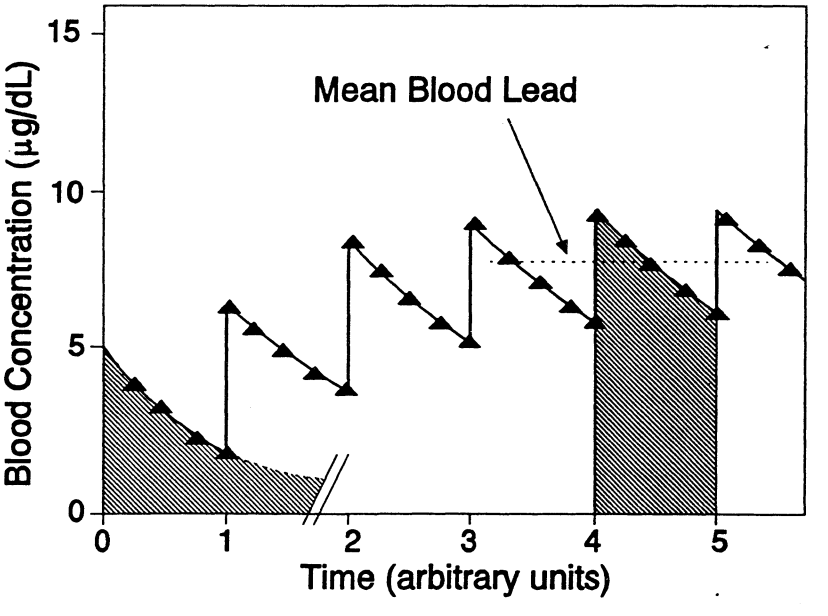


Figure 4-4. Kinetics of absorption during repeated dosing. At steady state, the area under the curve described by one dosing interval is equivalent to the area under the curve following a single, bolus dose.

$$\text{Absolute bioavailability} = \frac{(AUC)^{oral}\ (DOSE)^{IV}}{(AUC)^{IV}\ (DOSE)^{oral}} \times 100\%.$$

While careful attention must be given to presystemic elimination (the amount of chemical excreted via the GI tract prior to entry into the systemic circulation), this simple approach can provide, with appropriate sampling and analytical quality control, an effective estimate of the percent absorption into the blood following oral exposure. The longer term kinetics (concentration versus time) of chronic lead absorption are likely to be influenced by the accumulation of lead in peripheral compartments such as bone. Thus, bioavailability estimates conducted with longer-term exposures are preferable in developing quantitative estimates of lead bioavailability. The reader is referred to Gibaldi (1982) for a more detailed discussion of the kinetics of absorption and distribution of toxicants.

4.1.7.5 Absolute Versus Relative Bioavailability

It is usually the case that bioavailability is quantified in absolute terms: it is presumed to be equal to the absorbed fraction for a specific substance. For example, if $CdCl_2$ were 6% absorbed from some medium and CdS were 3% absorbed at equimolar concentrations, the absolute bioavailability for these compounds would be 6 and 3%, respectively.

There are occasions, however, where bioavailability may be specified not in absolute but in relative terms, relative to the bioavailability of some reference compound. Using the earlier examples, if $CdCl_2$ were the reference compound, then the relative bioavailability of the sulfide would be 50% (3%/6% × 100). This approach has much practical value, because one may not have direct bioavailability data for other than one or two forms when estimating risks.

This approach would therefore have value for comparative exposure risk when adjusting risk calculations at Superfund sites. Here, risks are usually calculated from Reference Doses (RfDs) and cancer slope factors that are nearly all based on administered, rather than absorbed, doses. If site-specific exposures involve different chemical/physical forms, it may be necessary to adjust intake dose to uptake dose values in order to account for differing bioavailability in estimating toxicity levels. In such cases, absolute bioavailability measurements may be useful for site-specific forms but are not required for relative risk determinations. While the lead model uses absolute bioavailability as the input parameter, knowledge of the relative bioavailability of ingested materials may be applied. If the relative bioavailability of the material of interest is known relative to a second material whose

absolute bioavailability can be assessed, then the absolute bioavailability of the first can also be estimated.

In addition to establishing the distinction between absolute and relative bioavailability, it is necessary to distinguish between biovailability and solubility. Solubility is a metabolically passive, simplified, in vitro characteristic of a substance that constitutes but one element in bioavailability. This distinction is explored in the following section.

4.1.7.6 Quantitative Experimental Models of Human Lead Bioavailability

Site-specific bioavailability studies of lead in soil have been conducted for several hazardous waste sites in the western United States (LaVelle et al., 1991; Freeman et al., 1991; Weis et al., 1994). In cases where (1) current exposure is significant, (2) soil characteristics preclude simple extrapolation from existing studies, and (3) estimated cleanup costs are sufficiently high, such studies may improve the accuracy and the reliability of the risk assessment process. Site-specific bioavailability studies can be expensive, can require time for completion, and do require considerable technical expertise for the design and conduct of the studies. This means that the remedial project manager (RPM) or risk assessment manager needs to obtain advice from individuals with training and experience in this area. If experimental studies are needed, the toxicology expert may recommend studies at one of the following levels, in order of increasing cost and complexity.

Class I Study

Studies in this class consist of simplified, in vitro approaches in which one determines aqueous solubility of lead from various solid species. This approach has little utility for quantitative human bioavailability assessments. First, solubility itself is but one factor, and a rather crude one, in net uptake of lead from the gut of humans or experimental animals. There are many physiological and biochemical processes occurring in the stomach and the intestines that are not addressed in crude or "bench top" solubility studies. A number of the biochemical factors not reflected in these in vitro, simple solubility approaches were noted by Mushak (1991) and include metal complexing with biochemicals, sustained acid output by the stomach with eating (any material), and uptake processes that are more complex than simple solubilization (e.g., pinocytosis of lead complexed in high molecular weight colloidal particles [micelles]).

A particularly flawed aspect of such in vitro studies is their inability to simulate the kinetically dynamic process that occurs in the intestinal regions (i.e., active transport from intestinal regions via carrier systems [see Section 4.1.5]). Such uptake, thermodynamically

speaking, induces a shift in intraintestinal equilibria among lead forms in the direction of greater dissolution (to compensate for the lead removed by active transport). Such active uptake produces a complex process that yields more bioavailability than predicted in simple in vitro approaches. This shift in equilibrium is compelled by a simple, widely-known principle of chemical processes, Le Chatelier's Principle, that states (CRC, 1978):

> If some stress is brought to bear upon a system in equilibrium, a change occurs, such that the equilibrium is displaced in a direction that tends to undo the effect of the stress.

In the present case, the stress is active intestinal uptake and the displacement to undo the effect is to dissolve more lead during its passage through the gut. Such a shift, relative to a simple bench-top system, is depicted in Figures 4-5 and 4-6.

Class II Study

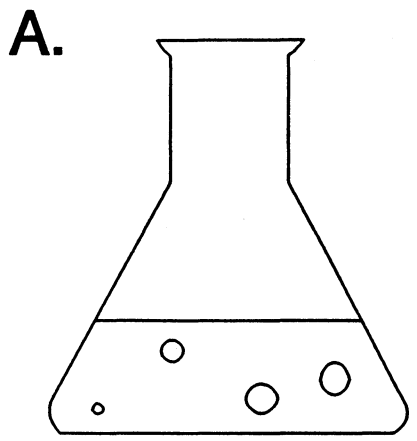
Class II and Class III studies involve in vivo animal models of human bioavailability of lead. They differ in their experimental specifics. Class II investigations are intermediate in vivo studies (i.e., carried out over a relatively short time). Such studies examine the bioavailability of lead within a time frame in which the dosing ends before pseudoequilibrium in the central (blood) compartment is reached. Since lead accumulates in critically important peripheral compartments such as bone and this accumulation will influence longer term uptake and distribution values, longer term studies are desirable for assessing target tissue bioavailability of lead in mammals.

Class II studies are useful in terms of providing a relative index of lead bioavailability, that is, comparison of several lead forms. Class II studies should, of course, consider all the factors already noted that influence any in vivo lead study, including the target population and pathway specifics for the site, age, concentration dependence of lead uptake in the dosing regimen, nutrition, physiology and anatomic structural characteristics.

In terms of model biology, physiology, and behavior, an appropriate selection for human simulation would take account of eating/feeding habits, human versus animal gastrointestinal tract differences, comparative biochemistry, etc.

Class III Study

Bioavailability investigations that have as their purpose the site-specific adjustment of the default bioavailability parameters in the IEUBK model may require a more complex approach. Such advanced studies should only be conducted after consultation with qualified,



$$PbX_{(s)} \rightleftarrows PbX_{(aq)} \rightleftarrows Pb^{2+} + X^{2-}$$

Figure 4-5. Under conditions of equilibrium, the amount of lead as the free ion (Pb^{2+}) is limited by mass balance dissolution of the solid phase (PbX).

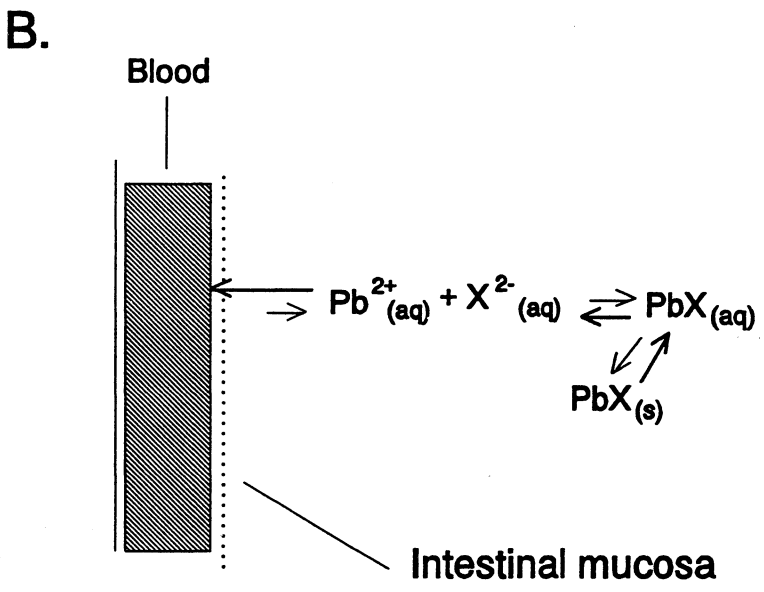


Figure 4-6. Under physiological conditions, free lead ion (Pb^{2+}) is removed from solution by active and passive absorption mechanisms potentially shifting the equilibrium of the dissolution process far to the left.

experienced individuals and should be subject to the most rigid quality assurance/quality control (QA/QC) protocols for study management. This especially applies to preserving the original physicochemical form of the lead-containing test materials from a particular site. The design and duration of Class III studies should be such that they assure achievement of near steady state (pseudoequilibrium) for the blood concentration versus time curves. As with Class II studies, Class III investigations need to take account of the site-specific target population and exposure pathways, age of subjects, nutritional and physiological state of the animal, etc.

4.1.7.7 Summary and Advisory Overview for Lead in Soils and Dust

Bioavailability studies are intended to provide valid information about the associations of site-specific physical and chemical properties of exposure media with bioavailability at a target tissue site. Properly designed studies can elucidate differences traceable to such factors as the physicochemical properties of the site's lead-containing media, lead chemical form, matrix species, particle size, mixture effects from other metals or other chemical species from matrix, diet, and such, and study animal or human population variables such as age and levels of exposure. These studies need to meet two fundamental qualifications:

(1) Doses used need to be low enough to be comparable to human exposure situations that are to be assessed. Basing calculations on high doses of lead may greatly weaken the utility of an experimental study.

(2) Animal models need to be carefully examined for their appropriateness to represent human gut processing and absorption of lead. The demonstration that absolute bioavailability is low in an animal model is of limited significance unless that model can be supported as being quantitatively relevant to humans.

Bioavailability factors can be validly adjusted to account for site-specific lead exposure characteristics in the IEUBK model. However, selection of a site-specific bioavailability parameter other than the model default value of 30% for soils and dusts requires considerable caution and warrants review by qualified technical experts.

4.1.8 Bioavailability of Lead in the Diet

The absorption of lead from food and liquid diet by infants up to six months old is known to be very high (Ryu et al., 1983; Marcus, 1989a), and much lower in adults

(Chamberlain et al., 1978; Blake and Mann, 1983; Rabinowitz et al., 1980; James et al., 1985). Less is known about changes in lead absorption from diet for older infants, toddlers, and children. A value of 50% was selected as an intermediate level in children and infants (U.S. Environmental Protection Agency, 1990b).

The exact form of the dietary lead absorption coefficient in humans is not known. There is evidence that the absorption of lead in food by infants is quite high, at least 40 to 50%. The range cited by the U.S. Environmental Protection Agency (1989a) is 42 to 53%. While this probably decreases after infancy, we have no direct evidence on how to interpolate this range for children of ages 2 to 6. A smoothing of the absorption data from infant to juvenile baboon in the studies by Harley and Kneip (1985) has been proposed as a basis for extrapolation by the U.S. Environmental Protection Agency (1989a). In view of the uncertainty about this, we have chosen to keep the same default value of 50% for ages 1 to 6. This value will, at worst, slightly overestimate dietary lead uptake in older children.

Lead absorption from diet depends on the lead concentration in the stomach, and on a host of other dietary cofactors such as zinc, iron, vitamins, and phytate. When dietary lead intake during meals is sufficiently high, absorption of lead through the gut lumen decreases, probably due to competition for the limited anionic lead-binding sites on the gut wall.

The absorption of lead has some similarities with the absorption of other metals (Mushak, 1991), especially alkaline earths such as calcium and strontium. Calcium researchers have hypothesized three possible mechanisms of gut absorption. The first is a type of saturable active transport. This may be a secondary process because the enzyme requiring energy input is on the basolateral membrane and not on the membrane of the gut lumen. It would be more accurate to describe this as a facilitated diffusion process. A second saturable facilitated process involving pinocytic mechanisms has also been hypothesized by calcium researchers, but is not well understood. These saturable diffusion processes are the dominant modes of transport at low concentrations. Processes requiring carriers are often called *facilitated* diffusion processes. For convenience, we may call either of these saturable processes *facilitated* diffusion processes. The third process, the dominant mode of transport at high concentrations, is probably a simple diffusion through tight junctions on the lumenal side and is not saturable. Binding and transport of calcium across the gut lumen involves a protein called calbindin. We have described this as a *passive* diffusion process. The last two processes have no specific inhibitors and are difficult to study. The extent to which lead absorption shares these calcium processes, or is quantitatively different, is not known. The study by Aungst and Fung (1981) on transport of

dissolved lead across the gut lumen in vitro in everted rat intestines shows that lead absorption is likely to consist of two distinct processes. The first process depends on a passive diffusion mechanism that is independent of gut concentration. The second process depends on a facilitated diffusion mechanism that is saturable, with a half-saturation concentration of about 120 μg/L (0.59 μmol). The quantitative extrapolation of this value to human children in vivo is uncertain.

The Glasgow duplicate diet study reported results on infant blood lead and dietary lead intake at a single time point, age 3 months. There appeared to be a very large non-dietary background source contributing about 12 μg/dL blood lead to these infants. This is attributed in part to the inhalation of leaded gasoline, which was still widely used in the United Kingdom, and in part to residual exposure pre-natally. The dietary lead intake in these infants is believed to constitute almost all of the ingested lead, since children at this young age are believed to have minimal contact with soil, house dust, or paint. Some small contribution of inhaled lead particles may be transferred to the ingestion route by mucociliary transport.

A non-linear regression model was fitted to the Sherlock and Quinn data in a form that is directly comparable to the Michaelis-Menten formula used to describe in vitro studies (Aungst and Fung 1981ab). The model that was fitted to all data was:

$$\log(\text{Blood lead}) = \log(B + L * \text{PbIntake} + K * \text{PbIntake} / (1 + \text{PbIntake} / M)).$$

The parameters have the following interpretation:

- B = background lead concentration from pre-natal and inhalation exposure;
- L = linear (passive) uptake coefficient between blood lead and dietary lead intake;
- K = non-linear (facilitated) uptake coefficient between blood lead and dietary lead intake;
- M = Michaelis-Menten type (non-linearity) parameter, the daily dietary lead intake rate at which the facilitated component of lead uptake is half saturated.

Three methods were used to estimate the parameters. The first two methods are based on weights for the grouped data shown in Figure 4-2 of Sherlock and Quinn (1986), shown in this document as Figure 4-1. The first set of weights was based on the estimated sample size within each bar on the graph. The second method was based on the normalized coefficients of variation from the standard error bars for each group. The third method was based on

using within-cell geometric mean blood lead and dietary lead intake values from Table 4-2 in their paper, with cell counts used as weights. The first method appears to be the most accurate, both absolutely and relatively. The fitted blood lead model is:

$$\text{Blood lead} = 10.85 + 0.0090\ \text{PbIntake} + 0.2981\ \text{PbIntake} / (1 + \text{PbIntake} / 90.33)$$

The total blood lead to lead intake regression coefficient at low intake levels (much less than the Michaelis-Menten coefficient M = 90 μg/day) is K + L = 0.0090 + 0.2981 = 0.307 μg/dl per μg/day. The goodness of fit of this non-linear lead uptake model of Michaelis-Menten form to 3-month old human children, combined with the similar piecewise linear model that could be fitted to the water lead studies, and the goodness of fit of the Michaelis-Menten model found for the data on blood lead and lead intake data in infant and juvenile baboons presented by Mallon (1983) support the use of this model for lead absorption in older children as well. The suggestion by Chamberlain (1984) that absorption in adults is greatly reduced at intake rates above 300 μg/d is also consistent with the infant estimate of 90 μg Pb/day.

4.1.9 Bioavailability of Lead in Water

The bioavailability of dissolved lead salts in drinking water is very high when consumed by adults between meals (James et al., 1985), and very low when consumed with meals. The maximum retention of lead in children probably exceeds that of adults, which is about 60% on an empty stomach, and absorption is likely to be only somewhat smaller than retention. Thus the value of 50% is recommended as plausible. A range of values for water lead absorption from the U.S. EPA/OAQPS Staff Paper (1989a), shown in Table 4-1, should be used as a basis for age-variable absorption coefficients.

The volume of water in a typical United States faucet is about 90 to 125 milliliters, and at least two or three faucet volumes must be drawn before the tap water lead concentration decreases to the level of the source water and water distribution line lead concentrations (Schock and Neff, 1988; Gardels and Sorg, 1989; Marcus, 1991a). The sample volume of first-draw water specified in U.S. EPA's drinking water regulation is 1 L (U.S. Environmental Protection Agency, 1991c). Water lead concentrations in most U.S. water supply systems are low (<5 μg/L), but geometric means may exceed 10 to 20 μg/L in first-draw samples from systems with highly corrosive water and a great deal of lead plumbing, which is not uncommon in older urban areas in the northeastern United States.

TABLE 4-1. PIECEWISE LINEAR REGRESSION MODELS FOR BLOOD LEAD VERSUS WATER LEAD IN THREE STUDIES

Parameter	Glasgow Infants N = 91	Edinburgh School Children N = 495	Hawaii Children and Adults N = 180
Intercept μg/dL	12.82	6.84[1]	*[1,2]
CONC. for SLOPE CHANGE μg/L	16.4	15.0	15.0
SLOPE (< CHANGE) μg/dL per μg/L	0.254	0.161	0.130
SLOPE (> CHANGE) μg/dL per μg/L	0.0426	0.0318	0.0242

[1]Intercept depends on other covariates.
[2]Not given.

Source: Marcus (1989b) and Maes et al. (1991).

Even if the community mean is low, lead in drinking water in some households may be sufficiently high to cause overt lead poisoning (Cosgrove et al., 1989).

4.1.10 Bioavailability of Lead in Air

Lead on aerosol particles must be inhaled and deposited before pulmonary absorption can occur. Particles inhaled but not deposited may be exhaled or trapped by the mucociliary lift mechanism and ingested. The number of inhaled particles of a given size range varies with the ambient concentration and size distribution and the breathing rate. The breathing rate varies with age and physical activity. Inorganic lead in ambient air consists primarily of particulate aerosols with a size distribution determined largely by the nature of the source and proximity to it. In rural and urban environments, This size distribution is usually from 0.05 to 1 micron. Near point sources, particles greater than 10 microns prevail.

Deposition in the respiratory tract can be by inertial impaction in the nasopharyngeal regions, where the airstream velocity is high, or by sedimentation and interception in the

tracheobronchial and alveolar regions, where the airstream velocities are lower. In the alveolar region, diffusion and electrostatic precipitation also become important.

Particles greater than 2.5 microns are deposited in the ciliated regions of the nasopharyngeal and tracheobronchial airways, where they are passed to the gastrointestinal tract by the mucociliary lift mechanism. Particles small enough to penetrate the alveolar region can be dissolved and absorbed into systemic circulation or ingested by macrophagic cells. Evidence that lead does not accumulated in the lungs suggests that lead entering the alveolar region is completely absorbed (Barry, 1975; Gross et al., 1975). Rabinowitz et al. (1977) found about 90% of the deposited lead was absorbed daily. In the IEUBK model the default assumption is that 35% of the inhaled lead is bioaccessible (reaches the absorbing surface), and 100% of this is absorbed.

4.2 USING THE INTEGRATED EXPOSURE UPTAKE BIOKINETIC MODEL FOR RISK ESTIMATION

4.2.1 Why Is Variability Important?

4.2.1.1 Intent of the Model and the Measure

The Geometric Standard Deviation (GSD) as used in this manual is a measure of the relative variability in blood lead of a child of a specified age, or children from a hypothetical population, whose lead exposures in a specified dwelling are known. *The GSD is intended to reflect the five types of individual blood lead variability identified below, not variability in blood lead concentrations where different individuals are exposed to substantially different media concentrations of lead.*

The IEUBK Lead Model is intended to be used for individual children who live at a residence, or for a hypothetical population of children who may live there in the future, or for hypothetical children who may some day live in a house built on a plot of now vacant land of appropriate size for future construction of a single residential dwelling unit.

4.2.1.2 Individual Geometric Standard Deviation

Why do different children have different blood lead levels? The answer to this question has two parts. The first part of the answer is that children are exposed to different levels of lead in their community environment. The second part of the answer is that individual

children, exposed to exactly the same measured levels of lead, will still have different blood lead levels for the following reasons:

- Different Environmental Context. Carpeting, other furnishings, and accessibility of yard soil affect contact with environmental lead in ways that are not easily measured.

- Behavioral Differences. Interaction with caretakers, with siblings and playmates, and other factors that affect mouthing behavior and play activity will modify lead intake from dust and soil.

- Different Exposures. The children will have different exposures due to differences in contact with soil, dust, water, and other environmental media that vary at different locations and different times, so that no single sample of environmental lead in any medium can be said to completely characterize the child's actual activity-weighted exposure to lead in that medium.

- Measurement Variability. The environmental lead measurements are not perfectly reproducible due to sampling location variability, repeat sampling variability, and analytical method error, so that equality of measured sample lead concentrations does not imply equality of the true exposure concentrations.

- Biological Diversity. Children are biologically diverse so that even children of the same age, weight, and height are expected to have differences in the biokinetic distribution and elimination of lead.

- Food Consumption Differences. A number of factors, including nutritional status and time of ingestion of lead relative to meal times, affect the uptake or absorption of lead ingested from a medium.

While sociodemographic factors underly many of these differences, it is not appropriate to assume any specific effect for future residents. Risk estimates should be applicable to any hypothetical resident, and this requirement adds to the variability associated with the estimate.

4.2.2 Variability Between Individuals Is Characterized by the Geometric Standard Deviation

Inter-individual variability is the starting point for risk analysis using the IEUBK model. Even if we knew the correct value for all of the environmental exposure variables, we could at best predict only the typical blood lead level expected for a child of a certain age who had that exposure. We will therefore assume that individual child blood lead levels can be divided into two parts, a *predicted* blood lead and a *random* deviation from the predicted blood lead level. A statistical model that has proven to be very useful and fits all of the blood lead studies we have analyzed is based on the following three assumptions:

(Assumption 1) Observed blood lead = (Predicted blood lead) * (Random deviation);

(Assumption 2) The random deviation is log-normally distributed with geometric mean or median = 1, and a geometric standard deviation (GSD) defined by GSD = exp (standard deviation of ln (blood lead). Here, exp(.) denotes the exponential function and ln(.) denotes the natural logarithm;

(Assumption 3) The GSD is the same for all values of the predicted blood lead (i.e., for all values of environmental exposure).

Risk is the probability of exceeding the blood lead level of concern. The IEUBK model calculates risk from these three assumptions. The user provides an exposure scenario from which the IEUBK model calculates a predicted blood lead. Then the user provides a blood lead level of concern, whose default value is now defined as 10 μg/dL based on health effects criteria, but can be modified by the user. This risk is calculated as the probability that a standardized, normally distributed random variable exceeds the level Z, where

$$Z = \ln(\text{blood lead level of concern/predicted blood lead}) / \ln(\text{GSD}).$$

If Z = 1.645, the risk is 5%. If Z = 1.96, the risk is 2.5%. If the GSD is increased, then Z is decreased, and the risk of a blood lead level exceeding the level of concern is increased (provided that the blood lead level of concern is larger than the predicted blood lead, which is usually true). This is illustrated in Figure 4-7. The default value of Z is

$$\begin{aligned} Z &= \ln(10/\text{predicted blood lead}) / \ln(1.6) \\ &= (2.3026 - \ln(\text{predicted blood lead})) / 0.47. \end{aligned}$$

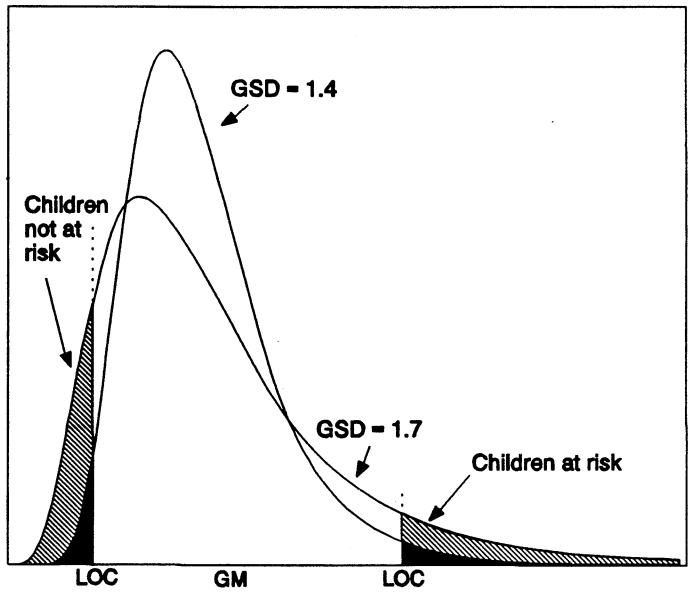


Figure 4-7. The impact of the relative positions of the level of concern (LOC) and the geometric mean (GM) on the proportion of children "at risk" for two populations with different GSDs. If LOC > GM, then the area for children at risk (shaded plus solid) for GSD = 1.7 is greater than the area (solid) for GSD = 1.4. If LOC < GSD, then the area for children *not* at risk (shaded plus solid in lower tail) for GSD = 1.7 is larger than the area for children not at risk (solid in lower tail) for GSD = 1.4.

The GSD has been estimated in a number of ways. The statistical model has the same form as the model used as the basis for estimation of slope factors reported in the Air Quality Criteria Document for Lead (U.S. Environmental Protection Agency, 1986). The GSD values were estimated by exp(s), where s denotes the residual standard deviation of the fitted ln (geometric mean blood lead) as a function of the environmental lead concentrations and of demographic cofactors. The residual standard deviation estimate for ln (blood lead) in a system of structural equations for lead was also used to estimate in some more recent studies.

Estimates of GSD for lead mining and smelter sites have increased towards larger GSD values as the geometric mean blood lead levels at those sites have decreased. This probably reflects the fact that at low to moderate levels of exposure, lead levels are likely to be influenced by several media with similar media-specific uptake rates, rather than by a single dominant medium. This condition tends to magnify individual differences in intake behavior or in biokinetics, and increases the GSD. The GSD estimates for several mining and smelter sites ranged from 1.30 to 1.79 (Marcus, 1992). We chose a value smaller than the

maximum that is consistent with the remaining variability after differences in the usual site specific soil lead and dust lead measurements have been removed. The remaining sources of variability include not only biological and behavioral variability in the children, but also repeat sampling variability, sample location variability, and analytical error. For empirical support in selecting a site specific GSD see Appendix A.

The default value is:

$$GSD = 1.6.$$

This default value is based on calculations of GSDs from specific sites. The median GSDs weighted for sample size within cells were estimated as 1.69 for Midvale, 1.53 for the Baltimore data of the Urban Soil Lead Abatement Demonstration Project, and 1.60 for the Butte study. This type of adjusted GSD calculation was chosen because of its treatment of outliers. Other types of adjusted GSDs, such as those derived from structural analyses are described below.

We must discourage the user from changing the GSD value by use of empirical site-specific data from a blood lead study. As discussed in Section 4.5 below, blood lead studies may be subject to subtle sampling biases and changes in child behavior in response to the study. The GSD value reflects child behavior and biokinetic variability. Unless there are great differences in child behavior and lead biokinetics among different sites, the GSD values should be similar at all sites, and site-specific GSD values should not be needed.

The user may wish to demonstrate that the variability in a specific well-conducted blood-lead study is consistent with the default assumption. In the next section, we will describe how to estimate a site-specific, inter-individual GSD when necessary. These analyses should be done only when necessary, and with thorough documentation of the reasons why the site may have more or less variation among child behavioral and biological parameters than at most other sites. We must remind the user that *it is not necessary to have site-specific blood lead data in order to appropriately use the model with the default GSD.*

4.2.3 Statistical Methods for Estimating the Geometric Standard Deviation from Blood Lead Studies

We have used several statistical methods to estimate GSD values recommended here. Two methods are described in detail in Appendix A. The first method is a direct method in

which environmental lead levels are fixed in ranges or intervals, and blood lead variability for children exposed to these concentrations is calculated directly. The second method is a statistical regression method appropriate to the generally skewed distribution of blood lead values and estimates the variability in blood lead concentrations after an empirical estimate of blood lead concentrations expected at each environmental lead concentration. The two methods give reasonably consistent results. The regression method uses child-specific age and lead concentration. The regression method crudely mimics the IEUBK model.

4.2.4 Choosing the Geometric Standard Deviation: Intra-Neighborhood Variability

There have been some cases in which the IEUBK Lead Model or a preceeding model was used to estimate the distribution of blood lead in a community when only community-level input was available, such as geometric mean soil, dust, and air lead. Further experience with the IEUBK model suggests that this application may be appropriate under some conditions in which certain mathematical assumptions are approximately correct. It also suggests that there are some other situations in which this approach is incorrect because the necessary mathematical assumptions are not satisfied. At this time, we recommend using the IEUBK Lead Model for neighborhood and individual blood lead assessment, but not for communities or for larger scale blood lead assessments without carefully evaluating the input assumptions. The neighborhood scale assessment requires stratifying the neighborhood by intervals of soil and dust lead.

A neighborhood is a spatially contiguous area that often has identifiable physical or geographical boundaries. For the purposes of this manual, a neighborhood is characterized according to the following guidelines:

- Boundaries such as a highway, railroad right-of-way, river, or by non-residential land uses such as commercial, industrial, agricultural, or park;
- Approximately 400 households with about 100 children;
- Church, school, and retail establishments within walking distances;
- Diameter about 1.5 kilometers (1 mile).

The neighborhood concept is used here to classify small areas of relatively similar childhood lead exposure, and will rarely be the same as a census tract, political locale such as a precinct or ward, or community association membership area.

Input parameters for the model at a neighborhood scale should be some measure that characterizes typical exposure concentration in a medium, such as the arithmetic mean or geometric mean, or the median. When activity pattern or behavior weighted exposure information is unavailable, we recommend use of the arithmetic mean to characterize soil lead concentrations in areas that are sufficiently small that any part of the area may be accessible to a typical child living at a random residence located within the area. This will certainly be applicable to the yard and adjacent play areas of a single residence.

Our recommended approach for risk estimation involves more calculations than the single-input soil and dust lead, but much less calculation than the use of each individual yard or housing unit. Our approach requires the division of the neighborhood into units that are larger than single yards or other sites, but smaller than the whole neighborhood, and clearly must depend on the scale of a risk assessment. Risk within a neighborhood can be assessed in a single model run only if media concentrations of lead are relatively homogeneous between different residential sites.

There is no definition of a "community" for model use. It is expected that older children will be able to play anywhere within a neighborhood, but are limited to their own neighborhood within the community. An alternative approach is to define "neighborhoods" by isopleths or contours of soil lead concentrations, but this is more likely to be useful in the vicinity of active or inactive smelter or battery recycling plants, where soil lead deposition has a definite point source pattern. No specific approach based on Geographic Information Systems (GIS) data bases has yet been adopted. The definition of neighborhood scale suggested here is roughly equivalent to an area of 4 to 10 city blocks in many urban areas (160 to 240 meters square). A neighborhood should not be larger than a one kilometer square.

4.2.5 Basis for Neighborhood Scale Risk Estimation

The basis of the neighborhood approach is that a few important environmental parameters largely determine the predicted geometric mean blood lead. Since the environmental lead concentrations are known to have some measurement error, there should be little loss of accuracy in grouping the environmental lead concentrations by small

intervals. For example, the interval ranges for soil lead concentration could be 0 to 249 μg/g, 250 to 499 μg/g, 500 to 749 μg/g, etc. Soil lead levels in an interval, for example from 250 to 499 μg/g, would be described by a single number in that range, such as the midpoint of the interval at 375 μg/g.

One of the most important determinants of blood lead concentration in children is lead in household dust. It is necessary to use small intervals of dust lead concentration along with small intervals of soil lead concentration. There are many other sources of lead in household dust in addition to soil lead, including dust lead from air lead deposition, from interior lead-based paint, and from workplace dust carried home by adults residing in the house. The actual range of dust lead concentrations corresponding to a soil lead interval is therefore generally much wider than the range of soil lead concentrations.

There may be circumstances in which other lead exposures in a neighborhood are known, and vary over a wide range. For example, there may be information on water lead concentrations in different houses. Some of the houses may have sufficiently high water lead concentrations that lead in water becomes another significant source of lead exposure. Additional stratification or classification of sites by this variable may also be useful.

Neighborhoods defined by small geographic areas are also much more likely to be homogeneous with respect to sociodemographic factors that affect blood lead variability. There should be some similarity in child activity patterns, household environmental contexts, behavioral patterns, and nutritional patterns within a neighborhood. Therefore, the individual GSD may be applied plausibly to the relatively homogeneous subpopulation within a neighborhood. If the neighborhood defined initially is very heterogeneous, then a larger GSD may be needed. It would be better to subdivide the neighborhood defined initially into more homogeneous subareas. This requires knowledge about the neighborhood residents, or an assumption about future residents.

4.2.6 Relationship Between Geometric Standard Deviation and Risk Estimation

The GSD is a very sensitive parameter for risk estimation. In this model, we use "risk" in the following specific ways:

- Individual risk is the probability that a hypothetical child living in a particular house or dwelling unit characterized by its environmental lead levels will have a blood lead concentration that exceeds a user-specified level of concern;

- Neighborhood or community risk is the fraction of children in a neighborhood or community characterized by a specified distribution of environmental lead concentrations that are expected to have blood lead concentrations exceeding a user-specified level of concern.

The assessment of potential health risk from environmental exposure to toxicants is one of EPA's most significant activities. We are using only part of this process. An elevated blood lead concentration (however one defines "elevated") is an index of internal exposure or body burden of lead. It is a useful index precisely because it changes in response to changes in exposure, with characteristic time scales of a few days or so in plasma and red blood cells, reflecting deeper changes of a few months in soft tissues, and years in hard bone. An elevated blood lead concentration is not precisely an adverse health effect by itself, but has been a very useful predictor of an increased likelihood of neurobehavioral deficits in children. The "risk" involved here is the risk of an increase in an easily measured index of lead exposure that is a predictor of adverse health effects.

The most general form of the model is multiplicative:

Blood lead = controllable factors * random factors.

For a single child, with defined sources of exposure, the IEUBK model estimates the geometric mean blood lead, or typical blood lead (i.e., the median when variability is log-normal, as it usually is). The model then is given by:

$$\text{Blood lead} = GM * \exp(Z * \ln(GSD))$$

where GM is the model-predicted geometric mean blood lead, exp(.) is the exponential function, ln(.) is the natural logarithm function, and Z is a normally distributed random variable. Therefore risk, defined as a probability for a single child, is calculated by the equation

Risk = Probability{Blood lead > level of concern for given exposure}

$$= \text{Probability}\{Z > (\ln(\text{level of concern}) - \ln(GM)) / \ln(GSD)\}.$$

When the level of concern is greater than the expected or typical blood lead at that exposure, then risk increases when GSD increases. Figure 4-7 illustrates the difference in "at risk" children for two populations, one with a GSD of 1.4 and another with 1.7. When the level of concern is above the geometric mean, the population with the higher GSD has a greater proportion of the children at risk. When the level of concern is less than geometric mean, the population with the lower GSD has a greater proportion of children at risk.

4.2.7 Risk Estimation at a Neighborhood or Community Scale

4.2.7.1 What Do We Mean by "Neighborhood" or "Community" Risk?

Representative questions of interest in assessing the risk of elevated child blood lead in a neighborhood are:

- What is the frequency distribution of risk of exceeding a blood lead concentration of concern, such as 10 μg/dL, within the neighborhood?

- What fraction of a hypothetical or actual population of children would be expected to exceed some specified blood lead concentration of concern if they resided in the representative sample of houses in this neighborhood for which we have soil and dust lead data?

- How much could we reduce high individual risk or the fraction of children with elevated blood lead concentrations by cleaning up soil to some specified level?

- What is the distribution of risks for a hypothetical population of children if housing units were constructed on soil at this vacant site?

The implicit definition of risk in these questions is the fraction of children living in a dwelling unit anywhere in the neighborhood who have elevated blood lead levels. We see that the neighborhood or community risk level has two distinct components of variability:

(1) Inter-individual differences, as in Section 4.2.4; and
(2) Inter-dwelling unit differences in lead exposure.

In some circumstances, these two can be combined and the same approach used to estimate the fraction of children at risk in a neighborhood. But, if there is a broad distribution of inter-dwelling unit differences, as is commonly observed, then a simplistic application of the IEUBK model may substantially under-estimate the real risk from the most contaminated parts of the neighborhood. Whatever the distribution of inter-dwelling unit or intra-neighborhood exposure levels, the "sum of risks" approach can always be applied. Note that there is a subtle difference between inter-dwelling exposure and intra-neighborhood exposure. Inter-dwelling exposure distribution would be the distribution of exposures measured in each home and would assume that the individual exposure is within the property boundaries of the dwelling unit. Intra-neighborhood exposure would include additional exposure from nonproperty sources, such as parks, schools and playgrounds.

4.2.7.2 Neighborhood Risk Estimation as the Sum of Individual Risks

Neighborhood risk is based on the expected number of children in the neighborhood who have elevated blood lead levels, here taken as greater than 10 μg/dL. Using the computer model, some of these questions can be addressed by the following procedure:

1. Set up a batch mode file in which each line represents the age and environmental lead exposure of each child in the real or hypothetical population.

2. Use the IEUBK Lead Model to estimate the geometric mean blood lead for each child in the batch mode file.

3. Apply an individual GSD to estimate the probability of exceeding the blood lead level of concern for each child or each household in the batch mode file.

4. Calculate the expected number of blood lead values exceeding the level of concern by adding up the probability of exceeding the blood lead level of concern across all children in the batch mode file.

   Note that even houses with low lead concentrations have a small positive risk for resident children. In houses with high lead concentrations, the risk of elevated blood lead is much larger, but some children (even in those high lead houses) will not have elevated blood lead concentrations. The total of all such risks characterizes neighborhood exposure.

5. Neighborhood risk is the ratio of the calculated expected number of blood lead values exceeding the level of concern to the total number of children in the batch mode file. This last point is illustrated in the following narrative.

4.2.7.3 An Example for the "Sum of Individual Risks" Approach

Suppose that there are data on four households with children in a neighborhood. Residents of each household are exposed to lead-contaminated soil. The first house has 250 μg/g lead in soil, the second has 250 μg/g, the third has 1000 μg/g, and the fourth house has 1000 μg/g. We have assumed dust lead concentrations as 70 percent of the soil lead concentration in houses 2 and 4, and as 15 percent of the soil lead concentration in houses 1 and 3. We have added 10 μg/g to dust lead as an estimate of the air lead contribution to dust lead at 0.1 μg Pb per cubic meter of air. The respective dust lead concentrations are thus 47.5 μg/g, 185 μg/g, 160 μg/g, and 710 μg/g.

The neighborhood is usually not just 4 houses. We may have samples at only these 4 houses, or there may be 100 houses at each of these 4 soil and dust lead concentrations. The assumption is that the samples are representative of the exposure distribution in the neighborhood. We are showing calculations for four houses only for the purposes of illustration. The risk estimates are intended to be unbiased estimates of potential risk for other years in which different children, not in the current sample, may occupy the same or other houses in the neighborhood. Obviously, a reliable estimate of neighborhood risk will require many more than 4 houses.

All other parameters are set to default values. We used a soil and dust absorption model with 30% absorption of lead from both dust and soil. (Smaller values of soil lead absorption may be needed for some sites—see Section 4.1). We assumed GSD = 1.6; larger values of GSD may be needed at some sites. The probability density of blood lead for four houses is shown in Figure 4-8.

For the house with soil lead at 250 μg/g and dust lead at 47.5 μg/g, we expect 0.55% of children to exceed 10 μg/dL. For the house with 250 μg/g soil lead and 185 μg/g dust lead, we expect 1.99% to exceed 10 μg/dL. For the house with soil lead at 1,000 μg/g and dust lead at 160 μg/g, we expect 21.06% of children to exceed 10 μg/dL. For the house with 1000 μg/g soil lead and 710 μg/g dust lead, we expect 42.68% to exceed 10 μg/dL. The sum of the risks for these four houses is 0.55% + 1.99% + 21.06% +42.68% = 66.28% children = 0.6628 children expected to exceed 10 μg/dL, or an average risk for the neighborhood of 66.28% / 4 = 16.57%, which is greater than the 5% neighborhood risk

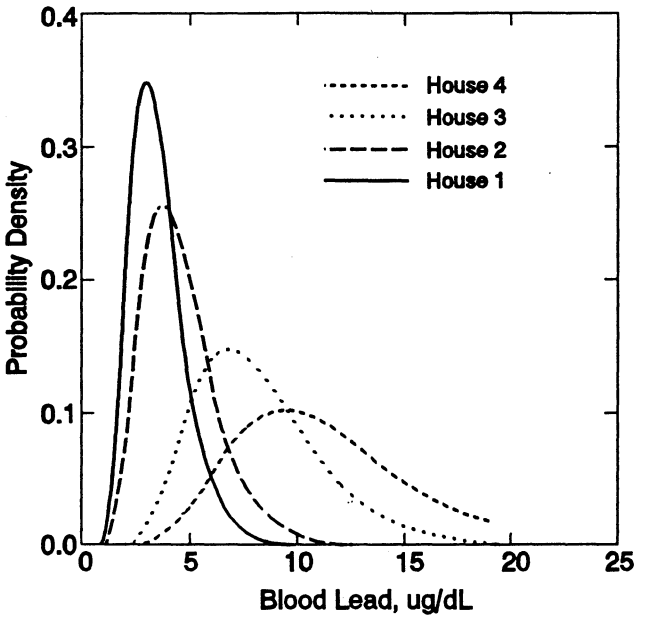


Figure 4-8. Probability density of blood lead in houses 1 to 4.

target used in this example. However, the major part of the risk falls in the one house with high soil and dust lead concentrations.

The use of aggregate neighborhood input data requires that we compare the probability density function (PDF) and elevated blood lead (EBL) risk calculated from aggregate parameters with the correct PDF and EBL risk functions, which are the mathematical composites of the individual PDF and risk functions. Expressed mathematically:

true neighborhood PDF = (PDF(site 1) + PDF(site 2) +...)/N
true neighborhood risk = (risk(site 1) + risk(site 2) +...)/N (Equation 4-1)

The approach we have outlined here does not require any mathematical assumptions about the distribution of soil and dust lead concentrations, nor of any other parameters or variables except for blood lead. We have assumed that the conditional distribution of individual blood lead is log-normal with a constant GSD (given specified values of lead exposure variables that determine the geometric mean blood lead for individuals with that exact environment). The method suggested here is the most convenient and flexible framework we have found for neighborhood assessment of the effect of soil lead abatement.

4.2.7.4 Assessment of Risk Using Grouped Data for a Neighborhood

The example in the preceding section had a "neighborhood" with only 4 houses, so that the amount of work required was not very burdensome. In the real world, the site manager or risk assessor may be dealing with relatively homogeneous neighborhoods or small communities with several hundred households. These calculations can be simplified by grouping soil and dust lead levels into small cells with fixed ranges of values. The grouped data within each cell are all assigned the same value, such as the midpoint of the interval.

Each cell is then assigned a statistical weight. The statistical weights could be:

(1) The number of housing units with soil and dust lead concentrations in the interval;

(2) The number of children observed or expected to live in housing units with soil and dust lead concentrations in the interval;

(3) The fraction of housing in a neighborhood that is expected to have soil and dust lead concentrations in the interval;

(4) The fraction of area in as-yet-undeveloped neighborhoods with soil and dust lead concentrations in the interval.

The probability density function (PDF) and risk of EBL children in then the weighted sum of the cell PDF or cell risks. If the respective weights are denoted weight (cell 1), weight (cell 2), etc., and the PDFs are denoted PDF (cell 1), PDF (cell 2), etc., and the risks are denoted risk (cell 1), risk (cell 2), etc., then:

neighborhood PDF = [weight (cell 1) * PDF (cell 1) + weight (cell 2) * PDF (cell 2) + etc.] / [weight (cell 1) + weight (cell 2) + etc.]

neighborhood risk = [weight (cell 1) * risk (cell 1) + weight call (cell 2) * risk (cell 2) + ...] / [weight (cell 1) + weight (cell 2) + ...]

The following hypothetical example may illustrate these points. Suppose that a random sample of 250 houses and apartments has been obtained in a neighborhood. The number of houses in each interval of 250 μg/g soil and 250 μg/g dust lead is shown in Table 4-2. This

TABLE 4-2. EXAMPLE OF NEIGHBORHOOD RISK ESTIMATION WITH GROUPED DATA

Hypothetical example of grouped data for a neighborhood with dust and soil samples of 250 sites of house yards. Intervals are 250 μg/g in soil and in dust lead.

Soil Interval	Soil Midpoint	Dust Interval	Dust Midpoint	Statistical Weight	Blood Lead[1] (μg/dL)	Risk[2] Percent
0-249	125	0-249	125	30	2.9	0.39
0-249	125	250-499	375	50	4.3	3.45
0-249	125	500-749	625	20	5.7	10.61
250-499	375	0-249	125	10	4.1	2.70
250-499	375	250-499	375	40	5.4	9.36
250-499	375	500-749	625	30	6.7	18.62
250-499	375	750-999	875	20	7.9	28.52
500-749	625	250-499	375	10	6.5	16.45
500-749	625	500-749	625	20	7.7	26.86
500-749	625	750-999	875	10	8.8	38.16
500-749	625	1000-1249	1125	3	9.9	47.56
750-999	875	1000-1249	1125	4	10.8	52.78
750-999	875	1750-1999	1875	1	13.6	72.73
1000-1249	1125	1250-1499	1375	2	12.5	66.93
TOTAL				250		14.28

[1]Calculated from IEUBK model with default parameters.
[2]Assuming GSD = 1.6.

TABLE 4-3. EXAMPLE OF NEIGHBORHOOD RISK ESTIMATION WITH COARSELY GROUPED DATA

Hypothetical example of grouped data for the same neighborhood as in Table 4-1, with intervals of 500 μg/g in soil and dust lead.

Soil Interval	Soil Midpoint	Dust Interval	Dust Midpoint	Statistical Weight	Blood Lead[1] (μg/dL)	Risk[2] Percent
0-499	250	0-499	250	130	4.2	3.05
0-499	250	500-999	750	70	6.8	19.81
500-999	750	0-499	250	10	6.4	15.45
500-999	750	500-999	750	30	8.7	36.05
500-999	750	1000-1499	1250	7	10.9	55.50
500-999	750	1500-1999	1750	1	12.8	66.92
1000-1499	1250	1000-1499	1250	2	12.4	64.01
TOTAL				250		14.41

[1]Calculated from IEUBK model with default parameters, ages 6 to 84 mo.
[2]Assuming GSD = 1.6.

same example is shown in Table 4-3 in intervals of 500 μg/g in soil and 500 μg/g in dust. There is no requirement that there be equal interval lengths in either soil or dust.

The user may then calculate neighborhood risk in three ways:

- Sum of risks for 250 housing units;
- Sum of risks for 14 cells or groups of width 250 μg/g soil and dust;
- Sum of risks for 7 cells or groups of width 500 μg/g in soil and dust.

The results of calculations are shown in the Tables 4-2 and 4-3. The total risk in Table 4-3 is calculated as:

$$(130 * 3.05\% + 70 * 19.81\% + 10 * 15.45\% + 30 * 36.05\% + 7 * 55.50\% + 1 * 66.92\% + 2 * 64.01\%)/250 = 14.41\%$$

The risk calculation in Table 4-2 is similar. If there are not too many cells, the amount of calculation can be strikingly reduced. However, as the intervals are made longer, there is a corresponding loss of accuracy in the neighborhood risk estimate. The extra effort in calculating risks with 250 μg/g intervals (14 cells) is probably compensated by the increased precision, with an estimate of 14.28% instead of 14.41%. The actual risk for the ungrouped sample with 250 simulated houses in 14.13%.

4.2.7.5 Assessment of Risk with Neighborhood or Neighborhood-Scale Input

There are situations in which it is either inconvenient or impossible to apply the IEUBK model at the intended household residence scale. For example, if only neighborhood mean values or geometric mean values of input parameters such as soil and dust lead are available, the model estimate may be far less reliable than if individual residential measurements were made. Another possibility is that there are a substantial number of soil and dust lead measurements at a site, but not at houses or locations within the site where blood lead and EBL risk estimates are needed, for example, to compare with blood leads observed at residences where there are no environmental data. There are some circumstances in which this is clearly not a valid application of the model. As we do not clearly understand the range of conditions under which the IEUBK model may be used with large-scale input data at this time, we must discourage use of the IEUBK model except with single-residence or residential lot-sized input data, or with data grouped into cells as in Section 4.2.7.4.

4.3 ENVIRONMENTAL PATHWAY ANALYSIS

4.3.1 Concept of Pathway Analysis

Environmental pathways for lead have been a subject of interest for EPA for a long time. Methods for analyzing with multi-media exposure pathways from air lead were used in developing slope factors for blood lead versus air lead, dust lead, and soil lead in EPA's Air Quality Criteria document (U.S. Environmental Protection Agency, 1986). Even though the focus was on exposure to air lead as a primary source, it was clearly recognized that whatever the source of lead in air, paint, or soil, the primary exposure vector for young children was through fine particles of surface soil and household dust that adhered to the children's fingers and were ingested in the course of normal hand-to-mouth contact at ages one to five years. Thus the total impact of air lead exposure had to be evaluated as the sum of exposure over several pathways (Figure 4-9).

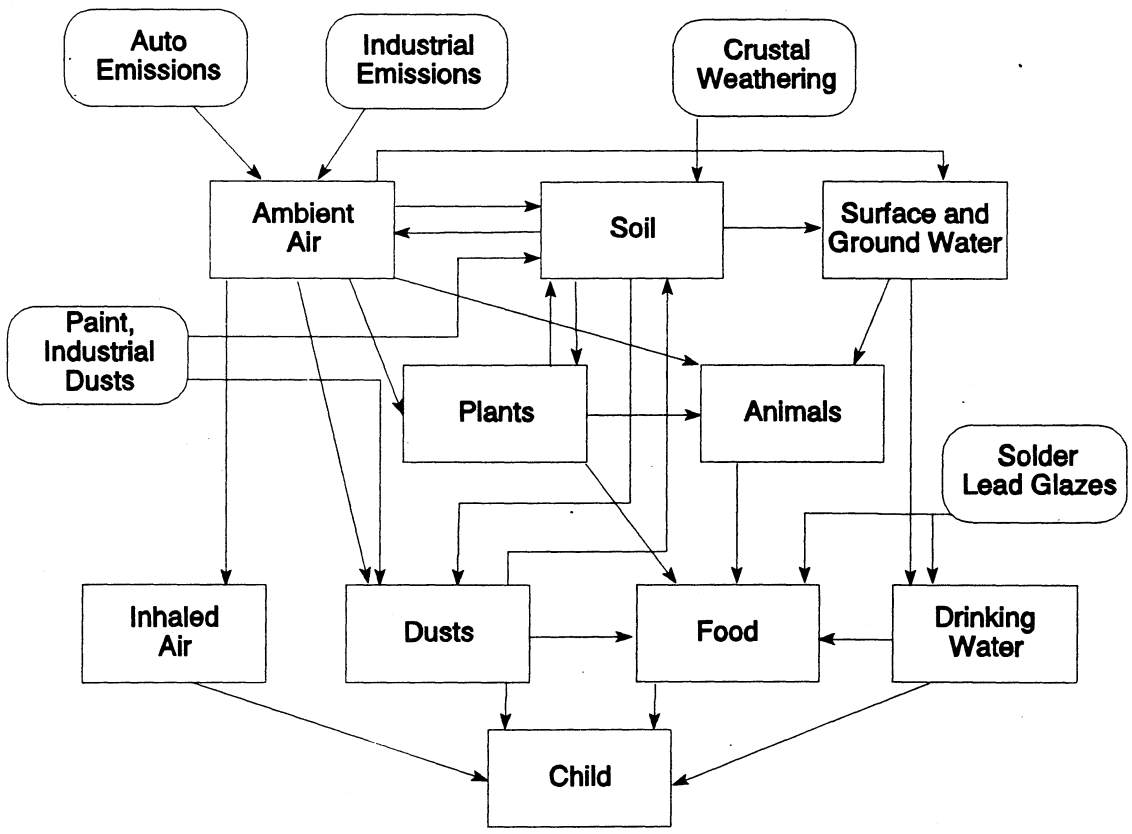


Figure 4-9. Exposure pathways of lead in the environment.

The IEUBK model assists the user in defining critical pathways for each exposure scenario. For example, there are two places on the Multiple Source Analysis Menu for household dust where pathway information may be inserted:

(1) the soil-to-to-dust pathway coefficient may be entered in the first line of the Multiple Source Analysis Data Entry Menu, replacing the default value of 0.70 μg/g dust per μg/g soil lead;

(2) the direct air-to-dust pathway coefficient is on the second line of the Multiple Source Analysis Data Entry Menu, replacing the default value of 100 μg/g dust lead per $\mu g/m^3$ air Pb.

The following paragraphs provide the basis for some of the default parameters used in the IEUBK model, and suggest some methods for estimating alternate coefficients from site-specific data, provided the user has some knowledge of statistical regression. While physical measurement methods such as a comparison of stable lead isotope composition ratios have been used for source apportionment studies (Yaffee et al. 1983; Rabinowitz 1987), most users will probably have to infer site-specific pathway parameters by statistical analyses of field data.

4.3.2 Pathway Analyses by Linear Regression

The slope factor approach, described in Section 1.5, determines the linear relationship between two pathway components. This methods was used for the EPA Exposure Analysis Methodology Validation (U.S. Environmental Protection Agency, 1989a) to show that there is a clear relationship between lead in air (PbA), lead in soil (PbS), and lead in dust (PbD). This relationship may be approximately linear, depending on properties of soil and dust lead particles; if not linear, then it is at least a positive cause and effect relationship. The relationship was established using data from air lead point sources such as primary and secondary lead smelters, other non-ferrous metal smelters, and lead battery plants. The analysis, using mean values, found the relationship:

$$PbD = b_{D0} + b_{DA}\ PbA + b_{DS}\ PbS \qquad \text{(Equation 4.3-2)}$$

where b_{DS} = 0.364 for all point source communities, but = 0.894 for the East Helena primary lead smelter community. This suggests that there may be substantial differences among communities in terms of soil-to-dust transfer.

The direct air-to-soil relationship was also estimated:

$$PbS = b_{S0} + b_{SA}\ PbA \qquad \text{(Equation 4.3-3)}$$

When estimating slope factors by a sequence of regression equations the user should be aware that the "measurement errors" in pathway equations will almost certainly attenuate the size of the regression coefficients, and could even reverse the sign of the coefficients (Kupper 1984). Structural equation modeling techniques attempt to resolve this problem by the simultaneous estimation of coefficients in pathway models in the face of measurement errors.

4.3.3 Pathway Analysis Using Structural Equation Models

Systems of linear equations in which the output of one equation (such as PbD predicted from PbS and XRFI) is used as the input or predictor in another equation (such as PbB from PbD) can be reliably estimated using a method known as structural equation models (Bollen 1990). This method was introduced in the analysis of blood lead data by Bornschein et al. (1985) and Clark et al. (1985) in their analyses of data from the Cincinnati Prospective Childhood Lead Study. Several authors have extensively explored applications of the method to environmental lead data (Marcus 1991; Burgoon and Menten 1991). Two different approaches were compared, and found to produce very similar results.

The first approach uses linear equations without logarithmic transformation, but with a robust method of estimation that is not sensitive to skewness or to instability of measurement error variances. (The software implementation in the EQS program (Bentler 1989) was particularly convenient.) For a lead mining community, or an urban area in which air lead levels are so low as to be negligible predictors of blood lead, A typical small system of equations might be:

$$PbB = b_{B0} + b_{BS}\ PbS + b_{BD}\ PbD + b_{BXI}\ XRFI \qquad \text{(Equation 4.3-6)}$$

$$PbD = b_{D0} + b_{DXI}\ XRFI + b_{DS}\ PbS \qquad \text{(Equation 4.3-7)}$$

$$PbS = b_{S0} + b_{SXE}\ XRFE + b_{Sage}\ \text{House-age} \qquad \text{(Equation 4.3-8)}$$

where: PbB = blood lead concentration (μg/dL)

PbS = soil lead concentration (μg/g)
PbD = dust lead concentration (μg/g)
XRFI = interior measurement of lead-based paint by XRF (mg/cm^2)
XRFE = exterior measurement of lead-based paint by XRF (mg/cm^2)
b_{nm} = raw regression coefficient where the subscript refers to: response variable n on predictor m,
B0 = intercept
BD = blood to dust
BXI = blood to XRFI
D0 = intercept
DXI = dust to XRF (interior)
DS = dust to soil
S0 = intercept
BS = blood to soil
SXE = soil to XRF (exterior)
Sage = soil to house age

This model assumes that there is direct ingestion of interior lead paint, which also contributes to household dust, but no direct ingestion of exterior lead-based paint. The exterior lead-based paint contribution is subsumed in the paint to soil to dust pathway. Because of the linear equation formulation, partial effects of lead source terms are preserved:

$$PbB = c_{B0} + c_{BS}\, PbS + c_{BXI}\, XRFI \qquad \text{(Equation 4.3-9)}$$

$$PbB = d_{B0} + d_{BXE}\, XRFE + d_{BXI}\, XRFI \qquad \text{(Equation 4.3-10)}$$

$$c_{BS} = b_{BS} + b_{BD}\, b_{DS} \qquad \text{(Equation 4.3-11)}$$

$$d_{BXI} = b_{BXI} + b_{BD}\, b_{DXI} \qquad \text{(Equation 4.3-12)}$$

$$d_{BXE} = (b_{BS} + b_{BD}\, b_{DS})\, b_{SXE} \qquad \text{(Equation 4.3-13)}$$

where: c_{Bm} = composite regression coefficient for blood on predictor m
d_{nm} = composite regression coefficient for indirect pathways from predictor m to response n

The second approach uses logarithmic transformation of the equations in the system Equations 4.3-6 through 4.3-8:

$$\log(PbB) = \log(b_{B0} + b_{BS}\ PbS + b_{BD}\ PbD + b_{BXI}\ XRFI) \quad \text{(Equation 4.3-14)}$$

$$\log(PbD) = \log(b_{D0} + b_{DXI}\ XRFI + b_{DS}\ PbS) \quad \text{(Equation 4.3-15)}$$

$$\log(PbS) = \log(b_{S0} + b_{SXE}\ XRFE + b_{Sage}\ \text{House-age}) \quad \text{(Equation 4.3-16)}$$

This system can be estimated using SAS PROC MODEL or similar programs for non-linear systems modelling. All of the coefficients were constrained to be non-negative, since negative coefficients are non-interpretable. However, the appearance of a negative estimate for an intrinsically positive coefficient should be taken as a diagnosis of some statistical problem, such as multi-colinearity or the omission of important predictive variables.

4.3.4 Regression Analyses for Multiple Exposure Pathways: Soil Example

The variables for regression analyses were described briefly in Section 1.5. The use of a regression coefficient in risk assessment is a complicated matter, because one can use either *aggregate* regression coefficients, which combine information on all exposure pathways, or *disaggregate* regression coefficients in which each exposure pathway has its own slope coefficient. The exposure of young children to air lead includes soil and dust pathways, as well as direct inhalation. This is discussed in detail in the OAQPS staff papers (U.S. Environmental Protection Agency, 1989ab) based on earlier work by Brunekreef (1984). The aggregate blood lead regression coefficient for air lead, including soil and dust exposure pathways, is c_{BA} = 5 to 6 μg Pb/dL blood per μg Pb/m^3 air, whereas the direct inhalation coefficient b_{BA} is only about 2 μg Pb/dL blood per μg Pb/m^3 air. For a simple soil lead pathway model,

soil → dust → hands → child
soil → hands → child

whose equations are given by

$$PbB = b_{B0} + b_{BS}\ PbS + b_{BD}\ PbD \quad \text{(Equation 4.3-17)}$$

$$PbD = b_{D0} + b_{DS}\ PbS \quad \text{(Equation 4.3-18)}$$

the aggregate blood lead vs. soil lead regression coefficient should be

$$c_{BS} = b_{BS} + b_{BD}\, b_{DS} \qquad \text{(Equation 4.3-19)}$$

An empirical regression coefficient approach would use only the three coefficients b_{BS}, b_{BD} and b_{DS}. In the absence of data from a well-conducted child blood lead study at the same site or at some similar site, including both soil and dust lead data matched to each child's total lead exposure, there is no basis for calculating the aggregate soil lead coefficient. However, the use of a model like the IEUBK model allows estimation of the parameters b_{BS} and b_{BD} in Equation 4.3-8 from a synthesis of many diverse studies and does not require blood lead data at the site. Any additional information about site-specific exposure and soil or dust lead characteristics would progressively refine the model predictions, even without a child blood lead study. Site-specific soil and dust lead data are needed in either approach. The IEUBK model has a parameter in the Multiple Source Analysis for Dust in which the soil-to-dust coefficient b_{DS} can be inserted.

4.4 USE OF DATA FROM BLOOD LEAD STUDIES

4.4.1 Overview

In general, data from well-conducted blood lead studies of children at a site can provide useful information to the risk assessor and site decision maker. The purposes of this chapter are to explain what type of information a well-conducted blood lead study can provide, how blood lead study data can be used when assessing exposure to lead, and how to interpret model predictions when blood lead data for a site are also available.

Proper design and conduct of a blood lead study are critical if the results of the study are to be considered by the risk assessor. Blood lead data alone, without environmental lead exposure data and without elements of study design that control rapid changes in exposure prior to sampling, or without adequate control for sampling and analysis, should not be used to assess risk from lead exposure or to develop soil lead cleanup levels. However, a well-designed and conducted blood lead study can be useful in conjunction with site-specific environmental data in evaluating risk to children.

Blood lead concentrations are widely held to be the most convenient, if imperfect, index of both lead exposure and relative risk for various adverse health effects (U.S.

Environmental Protection Agency, 1986). In terms of exposure, however, it is generally accepted that blood lead concentrations yield an index of relatively recent exposure because of the rather rapid clearance of absorbed lead from the blood. Such a measure, then is of limited usefulness in cases where exposure is variable or intermittent over time, as is often the case with pediatric lead exposure.

According to the EPA Science Advisory Board in its 1992 report, "Review of the Uptake Biokinetic Model for Lead" (U.S. Environmental Protection Agency, 1992a), blood lead concentrations are responsive to abrupt or unanticipated changes in recent lead exposure for children. Since internal exposure is a function of lead intake (concentration multiplied by intake rates) and uptake, these changes can be environmental, behavioral, and physiological. For example, leaving a child in a house where lead-based paint has just been sanded would likely result in a significant elevation in that child's blood lead concentration. Reduction in a child's blood lead concentration may result from altered behavior that reduces exposure to lead (i.e., more frequent house cleaning, more attention to child's cleanliness, etc.). Cross-sectional blood lead studies (all done within a short time interval) are most useful when there is no reason to believe that child lead exposure has changed significantly within the last few months due to changes in environment or behavior.

A blood lead value may say little about any excessive lead intake at an early age, even though early childhood exposure may have resulted in significant irreversible toxicity. On the other hand, analyses that are retrospective in nature such as whole tooth or dentine analyses can only be done after the particularly vulnerable age in children—under 4-5 years—has passed. Such a measure, then, provides little basis upon which to implement regulatory policy for environmental or clinical intervention.

Furthermore, over a relatively broad range of lead exposure through some medium, the relationship of lead in the external medium to lead in blood is curvilinear, such that relative change in blood lead per unit change in exposure level generally becomes increasingly less as exposure increases. This behavior may reflect changes in tissue lead kinetics, reduced lead absorption, or increased excretion. In any event, modest changes in blood lead concentrations with exposure at the higher end of this range are in no way to be taken as reflecting correspondingly modest changes in body or tissue uptake of lead, (U.S. Environmental Protection Agency, 1986).

Data from good quality blood lead studies can be useful in examining the predictiveness of the model. The IEUBK Model predicts blood lead concentrations in children younger

than 84 months based on environmental inputs for soil, house dust, water, air, and dietary lead intake. It would be logical to assume that the distribution of blood lead concentrations predicted by the model using site-specific data would be generally similar to those measured in the population, provided that the actual blood lead study was well designed and conducted. The IEUBK Model may not be able to account for all sources of exposure. If the predicted blood lead concentrations are not similar to those observed, an attempt should be made to identify the reasons for those differences.

It is important to recognize that most implementations of the lead model now rely on the assumption that exposure to lead in soil and dust is primarily residential in nature. However, in an actual population of children, there will be substantial opportunity for non-residential lead exposures. Periods of time spent away from the home may also have the effect of reducing the residential exposures that would otherwise occur. The fact that the model applications cannot now track all aspects of nonresidential of lead sources that a child may encounter implies that a precise match between calculated and predicted blood lead distributions cannot be expected. Nevertheless, due to the importance of residential exposures to lead in children, a reasonable overall agreement should be anticipated in such comparisons. These considerations argue that reliance on P-values from statistical tests is not an appropriate basis for judging the comparability between observed and predicted blood lead concentrations. It should be noted that calculations of blood lead concentrations on the assumption of residential exposure is a useful endpoint in site risk evaluation, as many children will indeed experience primarily residential exposures to lead.

It is important to understand that the model should not necessarily be expected to reproduce the observed blood lead concentrations exactly. The model predicts the geometric mean blood lead level corresponding to a given set of exposure inputs. Probability distribution estimates produced by the model for a given GSD can be used to define a prediction interval for blood lead concentrations. As long as the interval includes the observed blood lead corresponding to the same exposure inputs, the model has performed adequately. Even when a predicted blood lead interval for a set of exposure inputs does not overlap an observed blood lead level, there may be plausible explanations owing to the complex nature of multi-media exposures and the difficulty in characterizing all the relevant determinants of these exposures, and the degree of inter-individual variation in blood lead concentrations that is known to exist even when exposure is very well characterized.

4.4.2 Data Quality

The quality of blood lead data can be specified by Data Quality Objectives (DQOs) which are established prior to the data collection effort. This DQO effort, as outlined in the Guidance for Data Useability in Risk Assessment, Part A (U.S. Environmental Protection Agency, 1992b), should result in a sampling and analysis plan which details the chosen sampling and analysis options, and provides goals for confidence intervals. The data quality indicators of completeness, comparability, representativeness, precision, and accuracy can provide quantitative measures of data quality of both sampling and analysis for blood leads concentrations.

The data quality indicators for sample collection and analysis are presented in detail in the Centers for Disease Control and Prevention protocols for blood collection and analysis. Those protocols also cover the elements of QA/QC for specimen collection, specimen preservation and shipping, analytical method performance, bench and blind quality control material, and data integrity. The following guidance is given by CDC on selecting a proficient laboratory and interpreting the results from that laboratory (Centers for Disease Control and Prevention, 1991):

> "Laboratories where blood is tested for lead levels should be successful participants in a blood lead proficiency testing program, such as the program conducted jointly by CDC, the Health Resources and Services Administration, and the University of Wisconsin. In interpreting laboratory results, it should be recognized that a proficient laboratory should measure blood lead levels to within several μg/dL of the true value (for example, within 4 or 6 μg/dL of a target value). The blood lead level reported by a laboratory, therefore may be several μg/dL higher or lower than the actual blood lead level."

In terms of evaluating the design of a sampling plan for blood lead, perhaps the most important data quality indicator is that of representativeness. Representativeness is the extent to which the data defines the true risk to human health for the population living at that site. For consideration in the risk assessment process, the sampling must adequately represent each exposure area and exposure scenario. Sampling that is nonrepresentative increases the potential for false negative or false positive results. A statistically based sampling plan is needed in order to achieve representativeness. Most studies have tried to include all children less than 84 months of age, or a random subsample of that age group. A substantial non-response rate, or attrition rate in a longitudinal study, will undermine the reliability of the

study findings. Opportunistic or selective samplings may occur with a medical referral program, a daycare center recruitment, or a community-wide request for volunteer participation, and are likely to be non-representative for the whole population. Studies in which respondent families are identified by telephone may miss families without phones, that may include transient populations and poorer populations who are possibly at greater risk.

4.4.3 Age of the Population Tested

The IEUBK Model contains uptake parameters and pharmacokinetic algorithms for children younger than 84 months of age, and predicts blood lead levels only for those ages. Infants and children younger than 84 months of age, that is, 6 months to 7 years old, have been identified as the subpopulation most susceptible to the adverse effects of exposure to low levels of lead (U.S. Environmental Protection Agency, 1986). For this reason, the blood lead study data that are to be evaluated in conjunction with the results of the IEUBK Model should consist only of those children younger than 84 months of age. If age groups older than 84 months are included in the study, it will be necessary to remove the data for these children from the data set, and to remove their contribution to the statistical results.

4.4.4 Time of the Year When Testing Was Done

Blood lead concentrations show seasonal fluctuations due to factors such as the relatively short half-life of lead in blood, reduced outdoor exposures in the wintertime, and perhaps to physiological (hormonal) changes. Cold weather, attending school, and snow cover tend to reduce the amount of time a child spends outdoors, and the child's direct contact with contaminated soil. The amount of this fluctuation is variable depending on physiological and behavioral factors as well as climatic ones. Seasonal fluctuations in blood lead concentrations as great as 4 to 6 μg/dL have been observed in some studies (Stark et al., 1982; Rabinowitz et al., 1984; Menton et al., 1994).

Hence, a blood lead study conducted in August would not be comparable to one conducted in March. In the 1979 to 1982 Boston lead study (Rabinowitz et al., 1984; Menton et al., 1994), blood lead concentrations associated with fluctuations in air lead and dust lead (probably from combustion of leaded gasoline) were at their maximum during the May to August period. Depending on the climatic conditions at a site, the peak summer months are an optimum time to conduct blood lead testing when soil lead is the primary source. The children are more likely to have been playing outdoors for 2 to 3 months and have had the greatest opportunity to be exposed to outdoor sources of lead.

The amount of time a child has been exposed to a specified environment is also a concern when evaluating the testing period. Because of the relatively long amount of time required for a child to come to nearly complete equilibrium with his or her environment, it is recommended that children who have lived at their current residences for less than three months or who spend more than 80% of their time away from their residences be excluded from the statistical analyses if only environmental lead data from their current residence are available. Blood lead results for these children may not be representative of the true health risk at the current residential site.

Because there are few data to quantify the impact of seasonal fluctuations on childhood blood lead, the model was calibrated using data collected during the peak summer months. Blood lead studies conducted at other times of the year should be adjusted to compensate for this seasonal difference.

4.4.5 Concurrent Characterization of Lead Sources

If a blood lead study is to be evaluated in the risk assessment process, it is important that all of the sources of lead exposure at the site be characterized and quantified. The most useful data bases contain "paired" data sets (i.e., each child's blood lead would be paired with the environmental data that represents the child's integrated exposure to lead). This pairing of environmental data with blood lead data allows the risk assessor to examine the relationship between a child's blood lead and his or her sources of exposure. At a minimum, the environmental data would include the lead concentration in soil and in house dust at the child's residence.

When the blood lead concentrations predicted by the model vary significantly from those observed in the population, this pairing of environmental and biological data provides the risk assessor with a tool by which to examine those differences. For example, were all of the children's predicted blood lead values systematically higher or lower than those observed? If so, perhaps an important source of lead exposure in the community was overlooked, perhaps assumptions about intake rates or uptake may be invalid, or perhaps unidentified behavioral variables affecting the source lead-blood lead relationship are operating. If a few individual children show particularly striking deviations of observed blood lead from predicted blood lead, then the contaminant concentrations or demographic/behavioral data for those children should be re-examined.

4.4.6 Demographics and Behavioral Factors That Affect Lead Exposure

Prior to sample collection, a well-designed blood lead study will have obtained information on the demographics and behavioral factors that affect lead exposure in a community. Such a community survey asks families about occupations, hobbies, social and economic status, house cleanliness, interior/exterior paint condition, children's mouthing behavior, etc. All of these questions are designed to identify factors that can modify the extent to which a child is exposed to the concentrations of lead in his or her environment (i.e., in media around the child). The Demographics Workplan for the California Gulch Study Area is an example of one such survey (Woodward-Clyde, 1991).

The results of the community survey can be used to evaluate differences between blood lead concentrations predicted by the model and those observed. Affirmative answers to "Have you sanded the paint in your home recently?" or "Does your child eat paint chips frequently?" may highlight why some predicted and observed levels differ. With the information from these surveys, a risk assessor can evaluate differences between observed and predicted blood concentrations due to behavioral or demographic factors.

4.4.7 Effect of Public Awareness or Educational Intervention

Whether or not a community's awareness of the hazards of lead exposure can cause its members to act to alter blood lead levels is an unresolved question. It is possible that an enhanced awareness of lead exposure in a community could prompt that community to alter behaviors to reduce lead exposure, and subsequently, reduce blood lead concentrations in that community. However, the empirical data on this phenomenon are very limited. Anecdotal evidence suggests that one-on-one counseling and educational intervention targeted specifically toward high risk children is effective in reducing individual blood lead concentrations (personal communications: R. Bornschein, 1992; I. Von Lindern, 1992). We are not aware of any study that has been designed specifically to test the effectiveness of educational intervention. A good study design is needed to avoid both statistical and sampling biases.

Whether or not a general type of awareness in a community may elicit a similar response has yet to be determined. The differential effectiveness of public awareness campaigns about soil and dust lead hazards in different subpopulations has also not been investigated. A study in Raleigh, NC, found that the greatest response to the city's offer to

test tap water for lead (at no cost to the water customer) was from the higher income neighborhoods of the city (Simmons, 1989).

Therefore, when a risk assessor is evaluating a blood lead study, he or she should keep in mind the potential effect of public awareness on blood lead concentrations. If active educational intervention and counseling programs are being conducted at a site prior to blood lead collections, or if there is a high level of citizen concern about contaminated sites, the results of that blood lead study may be different than it would have been otherwise.

4.4.8 Comparison of Observed and Predicted Blood Lead Concentrations

4.4.8.1 Were Important Sources of Lead Exposure Overlooked?

Unless site-specific data are provided by the user to the IEUBK Model for soil, house dust, air, drinking water, and diet, the model will assume a standard default value for intake from each medium. For example, at a site where the soil lead concentrations are elevated and homegrown fruits and vegetables are a large part of the diet, the diet pathway may be contributing more significantly than the model assumes to total lead exposure. The standard diet default value in the model is based on recent FDA market-basket survey information and pertains to lead concentrations in store-bought food. It doesn't consider the contribution of lead from homegrown fruits and vegetables, which may vary from site to site depending on the soil lead concentration, soil conditions, type of produce, climate, etc. Communities that have large ethnic minority populations may also have unique sources of childhood lead exposure in folk medicines or cosmetics that use lead compounds, or in foods imported in lead-soldered cans.

Ingestion of paint chips is another source of exposure that may be overlooked. Exposure to lead occurs from deteriorating house paint via ingestion of paint chips, and via ingestion of fine particles of paint in household dust. Exposure to fine particles of lead-based paint in dust and soil is handled through the soil/dust menu. For ingestion of paint chips, however, the IEUBK Model assumes a standard default of 0 μg/day for lead from paint chips and other alternate sources.

In addition to examining the possibility of overlooking an important source of lead exposure, the risk assessor should examine the representativeness and accuracy of the environmental data that were collected. For example, is the model input value for lead concentration in drinking water based on first draw tap samples, groundwater samples, or estimates from public water company records? A weighted combination of first draw and flushed tap water samples (plus water from school or day care fountains, if applicable)

provides the most appropriate representation of the average lead values in a child's drinking water. The farther away you move from these sources of information, the less accurate and more uncertain your input to the model will be.

Is the soil lead input based on the average of soil lead concentrations over the entire yard or is it based on composite samples from a child's yard? If there is substantial variability in soil concentrations at different locations about the yard, as is often true, an average of the entire yard may not be an accurate estimate of risk. An integrated assessment using the perimeter, play areas, and bare areas from each child's residence would provide an alternative basis for estimation.

Ideally, the inputs to the model should represent the integrated daily exposures each child might be expected to have. The absence of data specifically collected to estimate the integrated exposure will limit the accuracy of an analysis. Refining the accuracy and representativeness of the environmental data values provided to the model may be useful in resolving differences noted between estimated and observed blood lead concentrations.

4.4.8.2 Are There Interrupted or Enhanced Exposure Pathways at the Site?

A mistake that is often made is equating contaminant concentration with exposure or risk, where the risk assessor assumes *potential* exposure is *actual* exposure. Briefly, if there is no exposure, there is no risk. If an exposure pathway is diminished or enhanced, then regardless of contaminant concentration, the resulting exposure or risk is also diminished or enhanced. For example, at the same concentration of lead in soil, exposure to bare soil may be greater than if the soil has a good vegetation cover.

4.4.8.3 Are the Assumptions About Site-Specific Intake Rates and Uptake Parameters Valid?

Internal (systemic) exposure for humans is a function of contaminant concentration, intake rate and uptake. Environmental sampling can be designed and conducted to obtain a reasonably accurate representation of the lead exposures a child might experience at a site, thereby reducing some of the uncertainty in the exposure estimate. However, it is more difficult to reduce the uncertainty about the site-specific intake rates (i.e., soil ingestion rate, water ingestion rate) and uptake parameters.

At this time, the empirical evidence on these assumptions is limited and variable. In other words, there is a degree of imprecision and uncertainty in the intake rates and uptake parameters. For example, bioavailability of lead from soil is one uptake parameter to which the model is very sensitive. The model assumes a standard default of 30% for

absorption of lead from soil in the gastrointestinal tract, yet existing bioavailability studies in animals show values ranging from 5 to 40%. Concerns exist about the design of, and animal models used in, these studies (Section 4.1). Site-specific adjustments in the uptake parameters require strong justification.

A risk assessor should first explore all of the other rationales for differences between observed and predicted blood lead concentrations (i.e., sources of lead that were overlooked, incorrect assumptions about pathways, inaccurate estimates of environmental intake, and inadequate information about important or relevant demographic/behavioral factors). The risk assessor should then have strong site-specific justification before exploring non-default assumptions about uptake parameters.

4.5 ASSESSING THE RELATIONSHIP BETWEEN SOIL/DUST AND BLOOD LEAD

4.5.1 Assessing Reductions in Blood Lead

The IEUBK model can be used to estimate the change in geometric mean blood lead from reducing lead exposure, provided the exposure has remained stable for at least three months and there is a sufficiently detailed characterization of post-reduction lead exposure. This means that it is necessary to calculate the post-reduction levels for the controlled medium, the recontamination of the controlled medium by sources of lead exposure that are left after reduction, changes in the other exposure media from different pathways, and changes in physical or chemical properties of all media that may affect access, intake, and bioavailability to children.

There are not many data on post-abatement environmental lead concentrations for nonurban sites, such as smelters or lead mining sites. As an example, suppose that a primary lead smelter has been closed down. This immediately reduces or eliminates air-borne leaded particulates. Over the next few months, fine surface particles in household dust not otherwise trapped by carpets, upholstered furniture or inaccessible nooks and crannies, will be gradually swept, washed, or blown out of the house. If replaced by new surface soil particles, these will be much lower in lead than before the smelter was shut down, so that the household dust lead concentration may be expected to decrease within characteristic time scales of a few months to a new quasi-equilibrium value. The surface soil that had high concentrations of lead before the smelter was shut down may gradually be worn

away by wind or water erosion, but over a period of many years. This pattern is an informal description of what has actually been observed at the Bunker Hill site in northern Idaho.

The IEUBK model may be used with long-term post-abatement values to predict blood lead concentrations in children occupying these residences long after abatement has been carried out, without worrying about the dynamics of soil and dust lead changes over time. However, the post-abatement soil and dust at a specific site may not be the same as pre-abatement soil and dust at the same site. If highly aggregated soil is replaced by loosely consolidated fine particles in clean fill soil, and is not adequately covered by grass or sod, then the post-abatement soil may be both more easily transported into the house and more bioavailable than before abatement. Conversely, if the grass or sod cover is maintained well after abatement, then the post-abatement soil-to-dust lead coefficient in the IEUBK model may be different than the pre-abatement value. The validity of the IEUBK model predictions for post-abatement risks is limited by the validity of the input parameter assumptions for post-abatement exposures.

At present the definition of elevated blood lead (EBL) is the level of concern of 10 μg/dL defined by USEPA (1990b) as the lower limit of the range of known possible adverse neurobehavioral effects in young children. The protection level most often used in practice is a maximum 5 percent risk of elevated blood lead (EBL) for children in a given household.

The user has the responsibility for using model input parameters that are appropriate to the site. Collecting an adequate number of representative soil and dust samples, and determining their lead concentrations and physical or chemical properties that affect transport and bioavailability, are generally the minimum site-specific data collection and analyses that are needed. The ideal input data includes (1) a multimedia household environmental lead study that includes soil, dust, paint, water and air; (2) information on lead exposures outside the child's home; and (3) information on family demographics and child behavior patterns in the community that may affect access to lead sources; (4) characterization of physical and chemical properties that affect bioaccessibility and bioavailability.

Interest has been growing in the potential uses of the IEUBK model for sites at which there is presently no residential housing, or at sites at which children may be exposed without residential dwelling units being physically on the site. Since the IEUBK model calculates expected geometric mean blood lead concentrations and EBL risks for hypothetical populations of children, the model can be used for these applications. This can be done only

if there is sufficient information on child exposure to estimate time-weighted or activity-weighted soil lead and dust lead concentrations, combining both residential and on-site exposures.

4.5.2 Situations in Which the Use of the Integrated Exposure Uptake Biokinetic Model Is Uncertain

4.5.2.1 Assessment of Risk with Community or Neighborhood-Scale Input

There are situations in which it is either inconvenient or impossible to apply the IEUBK model at the intended household residence scale. For example, only mean values or geometric mean values of input parameters such as soil and dust lead may be available for a group of households. Another possibility is that there are a substantial number of soil and dust lead measurements at a site, but not at houses or locations within the site where blood lead and EBL risk estimates are needed. We have little information on applications of the IEUBK model with larger-scale input data, and we must caution the user against using the IEUBK model for this purpose, because little is known about blood lead variability in such situations.

4.5.2.2 Use of Surrogate Input Data from Models or Surveys

When modeled or survey data is to be used as input in the Lead Model, the user should consider the collection time and scale of the data in order to obtain maximum predictability in the output. Applicability to the individual home, neighborhood area or community should also be demonstrated. For example, housing age can provide a useful screening variable for field measurements of lead in tap water and lead-based paint, but it is not likely to be an adequate substitute for the lead concentration data unless a quantitative predictive relationship can be established by other studies in the same home, neighborhood or community. Such screening variables may be useful in screening for areas of concern for lead exposure sources. At the same time, the output values should not be construed as accurate representations of the actual child blood lead levels in these areas.

4.5.2.3 Use of the Model To Assess Risk of Elevated Blood Lead at the Regional or State Level

There is no empirical basis whatever for using the present version of the IEUBK model at this scale. We have serious concerns that large-scale input data may be totally inadequate characterizations of the spatially confined exposure for any individual child.

4.5.2.4 Use of the Model To Assess Trigger Levels for Soil Abatement at the Community, Regional, or State Level

Use of the present version of the IEUBK model at this scale is discouraged, because risks cannot be estimated adequately.

4.5.3 Factors That Constrain or Limit the Use of the Model

4.5.3.1 Data and Data Sets Used as Input for the Integrated Exposure Uptake Biokinetic Model

Residential Versus Commercial/Industrial Sites

The IEUBK Model uses site-specific data on the lead concentrations in air, water, soil and household dust, and average daily intake of lead from diet and from direct ingestion of paint chips, to estimate the geometric mean blood lead in children exposed to environmental sources of lead. The data input requirements assume a residential exposure, and thus the output of the IEUBK Model with default assumptions is probably not predictive for industrial or commercial sites at which exposures for small children are restricted, except perhaps in assessment of future use scenarios, or as additive components to a residential exposure scenario. Development of model estimates in such situations would require adequate specification of soil and dust ingestion derived from the contaminated site.

Age Group for Which Data Is Available

The IEUBK Model contains data and algorithms to determine intake, absorption, excretion and movement of lead between body pools for children from 6 months to 7 years of age. The IEUBK Model is only predictive for children in this specified age range or any subinterval within this range. Future versions of the IEUBK Model may be expanded to include data on metabolic processes in older children and adults, and thus allow characterization of blood lead levels in these populations.

At present, the IEUBK Model cannot be used to characterize blood lead levels in children older than seven years or in adult populations.

Other Critical Subpopulations

The IEUBK Model does not predict the blood lead levels of *pregnant women*, given either default or site-specific exposures. A parameter input for the maternal blood lead level has been provided in the IEUBK Model to capture the effect of prenatal exposure in unusual circumstances of exposure, i.e., in occupational settings. In general, maternal lead exposure during pregnancy is not well characterized for changes that occur from pre-pregnancy baseline. The adverse effect of prenatal lead exposure on neurobehavioral and physical

development is highly significant, and future versions of the IEUBK Model may include a prenatal exposure component based on the transfer of lead from the mother's blood to the fetus at the time of birth.

The IEUBK Model contains no specific data to differentiate the adverse effects of lead on different racial or ethnic groups, nor is there sufficient published data to develop this component. However, exposure scenarios for a specific subpopulation may be provided by the user if data are available.

Residency Requirements

The IEUBK Model does not allow entering rapid time-varying changes in exposures to lead sources. The IEUBK Model has been developed using blood lead data from children who have had at least a three-month exposure to their residential sources prior to blood sampling for lead analysis, that is, a minimum three-month residential requirement for inclusion in blood lead studies. The three month residency requirement guarantees that predicted blood lead attributable to the current residential exposure will be nearly at a steady state level. If residency requirements have not been met or if lead exposures are changing rapidly, the IEUBK Model can be expected to give less than accurate predictions, because exposures at prior residences may still be a major determinant of blood lead.

Timing of Data Collections

Because of the variability in child blood lead levels with seasonal exposure and the corresponding variability in environmental lead levels (i.e., changes in household dust lead levels with seasonal and activity changes) strict attention should be paid to the timing of data collections if the data is to be used as input in the IEUBK Model to make predictions about individual or community blood lead levels in children. This is especially important if the predicted blood lead levels are to be compared with the results from a community blood lead study, to assure that the two studies measure the same population at the same period in time, same season of the year. The parameters for the IEUBK model were developed from diverse animal and human studies. Collectively, these studies reported ranges of values for these parameters. The first stage in model validation was a calibration stage, using paired data—measurements of lead in environmental media and in blood collected from children under the age of six, taken within a short period. Comparison of observed and predicted blood levels suggested modifications of the parameters, within the range of plausible values suggested by the literature or by our analyses of research data. After there adjustments, the model obviously could not appropriately be tested again using the same set of data. Therefore,

validation tests were performed using the sets of community blood lead data paired with environmental exposure data for the same child.

4.5.3.2 Biological and Exposure Parameters Used in the Integrated Exposure Uptake Biokinetic Model Bioavailability of Soil Lead

The bioavailability of lead from different sources may be variable due to differences in lead concentration, lead speciation, particle size and mineral matrix (Barltrop and Meck, 1975; Barltrop and Meck, 1979; Heard and Chamberlain, 1982; Rabinowitz et al., 1980; Cotter-Howells and Thornton, 1991; Aungst and Fung, 1981). Additionally, bioavailability may vary as a function of physiological parameters such as age, nutritional status, gastric pH, and transit time. The IEUBK Model uses a default of 30 percent lead absorption from soil, which is constant across all concentrations and soil sources. Site-specific data on the soil and dust bioavailability may improve the accuracy of the blood lead level predictions.

Other Lead Exposure Inputs

Child default values for dietary lead intake are provided by year and by age of the child in the IEUBK Model. The use of default values is appropriate unless the dietary lead intake is very high, due perhaps to a high intake of home-grown fruits and vegetables or the intake of lead-contaminated ethnic food or drugs.

Exterior lead-based paint can make a significant contribution to soil lead, and is usually considered as part of this exposure source. The contribution of lead-based paint to indoor household dust is harder to estimate because the condition of the paint varies from house-to-house and the rate of incorporation into house dust is variable. If the household lead-based paint contribution is highly variable in a community, care should be taken to avoid combining all homes in a single run of the IEUBK Model, as the output results may not be applicable to the population.

Children can eat chips or strips of deteriorating lead-based paint directly from painted surfaces, even when the total area of lead-painted surfaces is so small that the total contribution of lead-based paint to interior household dust or exterior soil is too small to identify. Paint chip intake reflects child-specific behavior, including observed ingestion of paint chips, observed contact of the child's mouth with painted surfaces and the frequency of mouthing of non-food objects.

Blood Lead Variability

The variability of individual blood lead levels with respect to the geometric mean blood lead level predicted by the IEUBK Model is characterized by a single number: the geometric

standard deviation. The GSD is used as a single number to characterize the relative variability of the log-normal distribution representing the aggregate uncertainty in all sources of population variability: biological, uptake, exposure, sampling and analytical.

A common misconception is that the IEUBK Model predicts the community geometric mean blood lead and the fraction of children at risk when the input is the arithmetic mean or geometric mean across households of household-specific lead concentrations. This use of the IEUBK Model may cause seriously misleading interpretations of the output of the model, when the true extent of variability is not known. A correct approach to neighborhood risk estimation is given in Section 4.2.5.

Prior Body Burden

Child blood lead level predictions obtained using the IEUBK Model reflect the contributions from lead sources entered into the model; they do not take into account any existing body burden which may be the result of prior exposures not known to the user. Current blood lead levels depend on prior exposure history as well as present exposure. If past exposure levels have been greatly elevated, the results obtained from the IEUBK Model may not be accurate. Where children have had high prior exposures, that prior exposure affects blood lead levels for at least three months after the exposure ends, a "washout" period. Future estimates are based on present conditions. If those conditions change (e.g., deteriorating paint that might change house dust lead concentrations), the exposure and consequent risk will be different.

Alternate Exposure Locations

Child blood lead levels obtained using the IEUBK Model refect input lead sources at the household level or neighborhood level. They do not necessarily take into account increased or reduced lead exposures which may have taken place at parks, preschool, homes of babysitters, neighbors or relatives, or other locations frequented by the child, unless these exposures are measured and explicitly entered into the model as inputs. Thus, the results obtained from the IEUBK Model may not be accurate unless the child's activity patterns have been well documented.

Socioeconomic Status

The blood lead levels of two children with identical lead exposure scenarios, but living in different family behavior patterns might vary greatly. The difference in socioeconomic status might be reflected in differences in household repair and cleaning, washing of children's hands and toys, food preparation methods, concern for balanced meals and

improved nutritional status, more regular eating patterns, etc., all of which may impact blood lead levels. Use of the IEUBK Model should be preceeded by adequate characterization of information on behavioral and other socioeconomic differences, and advice from regional offices on appropriate adjustments, if warranted.

Intervention/Public Education Programs

Intervention and public education programs can inform the community of the adverse health effects of lead exposures and how to reduce them. These activities may result in reductions in blood lead levels in portions of a community that may be temporary, depending on how well the information is conveyed and received. These temporary changes in blood lead concentrations might occur during a one-time blood lead survey and cannot be predicted using the IEUBK Model. Some of the examples in Chapter 5 describe the correct application of the model in this situation.

4.6 WHAT YOU NEED TO KNOW ABOUT BIOKINETICS

4.6.1 Description of the Biokinetic Model

The IEUBK model has a very detailed biokinetic modelling component. This component of the model is not accessible to the user because, in our judgement, most users will neither wish to change the biokinetic parameters nor have the need to change any of the biokinetic parameters. The biokinetic parameters are used to define intrinsic biological variables that do not change from one exposure scenario to another, once a child's age is specified. The basis for the biokinetic parameters are described in the Technical Support Document: Parameters and Equations Used in the IEUBK Model for Lead in Children (see Section 1.2.2).

The biokinetic model is a compartmental model, in that it assumes that all of the lead in the child's body can be attributed to one of seven kinetically homogeneous compartments and that transfer between these compartments occurs through normal physiological processes. The compartments in this model are:

Plasma and extra-vascular or extra-cellular fluids (denoted ECF);
Red blood cells
Kidney
Liver
Other soft tissues

Trabecular (spongy) bone
Cortical (compact) bone

The distribution of lead in the body is only approximated by a compartmental structure, even in so-called physiologically-based pharmacokinetic models, because no tissue compartment is, in reality, completely homogeneous. However, the compartmental method is so useful and accurate that it has been almost universally adopted.

Realistic growth equations are used for each organ or tissue pool (biokinetic compartment) from newborn status to age 7 years. The transfer times (equivalently, fractional transfer rates) among compartments are scaled according to organ volume or weight, or body volume or weight, using allometric scaling consistent with organ or body surface-area scaling. The basis for the compartmental transfer times are the reanalyses we have done for data from studies in infant and juvenile baboons, using data in (Mallon 1983) and (Harley and Kneip 1985). A wide variety of studies in human children and adults, in other species, and in other metals was used to estimate biokinetic parameters not estimatable from the baboon studies. Growth equations were derived from Altman and Dittmer (1962), Spector (1956), and Harley and Kneip (1984). The literature review revealed 17 adult and 3 pediatric studies for evaluating the transfer time from blood to urine. An allometric scaling factor, based on the correlation between body surface area and glomerular filtration rate (West, 1948), was applied to the transfer time composited from the 17 adult studies to provide an estimate of the blood to urine transfer in children. An estimate of transfer from blood to feces and blood to urine for adults was taken from Chamberlain et al. (1978) and Rabinowitz et al. (1976), and for transfer from blood to soft tissues from Rabinowitz (1976), and equations for compartment to blood lead concentration ratios from Barry (1981).

The flow of lead from external media into the body and the distribution and elimination of lead is shown graphically in Figure 4-10. Transfer of lead to and from plasma and extravascular fluids is governed by first-order kinetics, in that the rate of change of the lead content in each compartment is a function of the current state of the system as defined by the lead content of each of the compartments. If the dependence of the rate of change of lead content is a linear function of the contents of all of the compartments, then the biokinetic model is described as a first-order linear kinetic model. The IEUBK has almost linear kinetics, except that we assume that the lead-binding capacity of the red blood cells can be saturated when lead uptake into the body is very high. Uptake of lead can occur through the lungs into the plasma-ECF pool, or through the gut into the plasma-ECF pool. While the

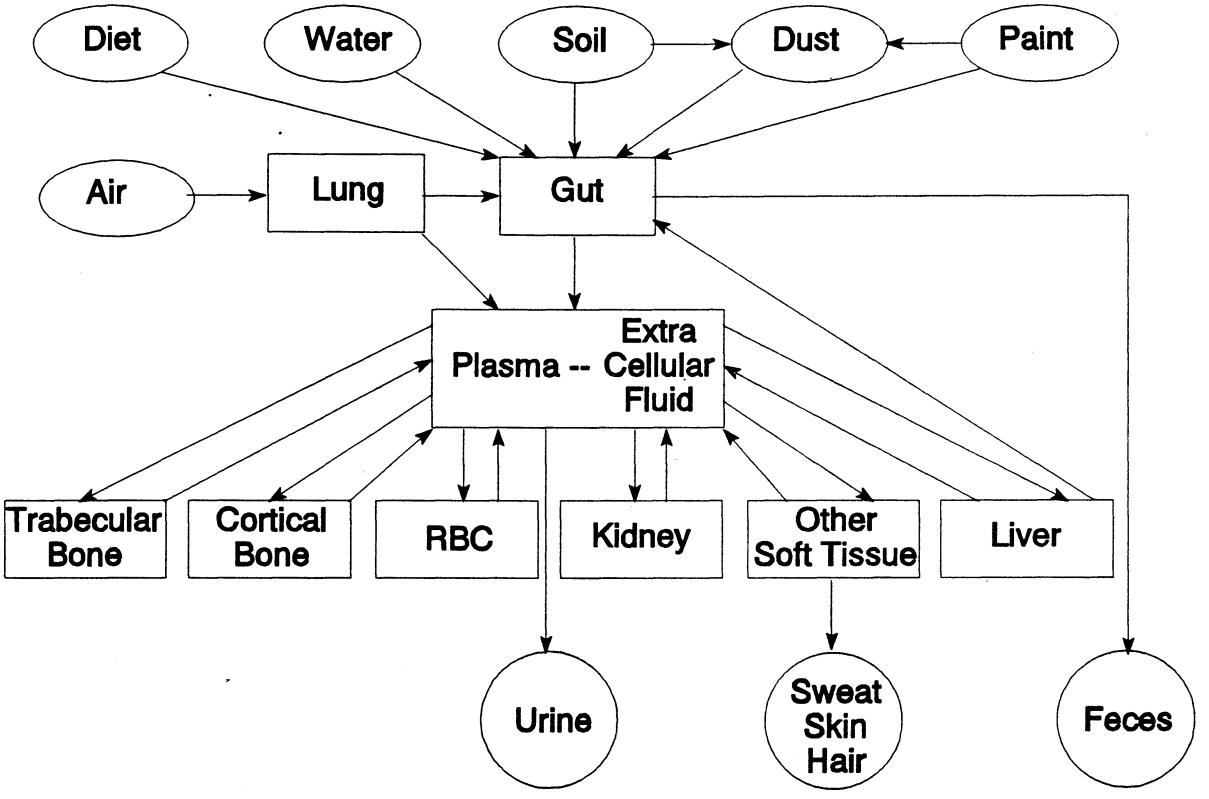


Figure 4-10. Biokinetic compartments, compartmental lead flows, and uptake pathways in the integrated exposure uptake biokinetic model.

plasma-ECF pool may be viewed as the central pool or compartment in this system, the usual observable is the blood lead concentration, which combines both the lead in plasma-ECF pool and the lead in the red blood cells.

4.6.2 Consequences of Biokinetic Parameters for Site-Specific Risk Assessment

The exposure scenarios that can be used in the IEUBK model change only once a year. Since most of the transfer times for children are on the order of 1 hour to 1 month, the IEUBK calculations of lead levels in blood and soft tissues may be assumed to be in a quasi-steady state condition with respect to exposure. The quasi-steady-state condition may allow the use of simple linear approximations to blood lead vs. media concentration or media intake of lead at different ages. But the time scale for release of lead from bone is much

longer, on the order of 1 to 3 years, so that the bone lead level quickly builds up and the skeleton contains 60 to 70 percent of the total body burden of lead by age 2 years. There is not be a true steady-state blood lead level during the 7-year interval used in the IEUBK model for young children. As bone lead burdens increase, so will there be a growing component of lead in blood that comes from release of lead from the skeleton or from resorption of bone in growing children.

Because of this release of bone lead, there may be a large component of blood lead levels in children that will respond only slowly to any changes in environmental lead exposure. This is particularly noticeable in evaluating soil lead abatement studies and strategies, where a child may have accumulated a large body burden of lead before the abatement. In the first year or two after the abatement, the internal or endogenous source oflead stored in the skeleton may cause a moderately elevated blood lead level to persist in the child. Children who were never exposed to the elevated environmental lead, or who did not accumulate a large body burden of lead before the abatement even though the environmental exposure was high, will not have this residual elevation of blood lead from resorbed bone lead.

4.7 ISSUES IN USE OF THE MODEL FOR PAINT CHIPS

4.7.1 Inappropriateness of Use of IEUBK Model for Paint Chip Ingestion

The IEUBK model, Version 1.0, does not contain an explicit component for lead-based paint ingestion outside of the Alternate Source Option in the Soil/Dust Menu. The correct use of the IEUBK model is to estimate geometric mean blood lead levels and distributions of blood lead levels in young children who have long-term chronic exposures to lead. It has long been known that the ingestion of even tiny quantities of paint chips on a single occasion can cause serious lead intoxication. Chisolm and Harrison (1956) show photographs of small paint chips weighing several grams that can easily be removed and eaten by a child. Since old lead-based paints can contain in excess of 50 percent lead, the child may ingest several million micrograms of lead in a single episode. The IEUBK model is not intended to address this situation. The IEUBK model is intended to address the situation where the child ingests typical quantities of household dust that have been contaminated by leaded soils and by deterioration of old lead-based paint from interior surfaces. The inclusion of lead-based paint in the dust menu implicitly assumes that paint has fallen off the painted surface as fine particles, or has fallen off as discrete flakes or chips of paint and has been reduced to small

particles in situ on the floor, carpet, furniture or other surfaces. Interior lead-based paint may not wear as rapidly as exterior paint due to the near-absence of sunlight on most household surfaces, but common observation finds many deteriorated lead-painted interior surfaces in older housing, especially in wet rooms such as kitchens, bathrooms, or laundry rooms (HUD, 1991).

The following data are presented to assist the user who wishes to develop an exposure scenario in which there is long-term ingestion of chips of lead-based paint, in addition to the interior household dust lead contribution that is already included in the IEUBK model. An exposure scenario with paint chip ingestion can be entered in the Other Source Menu of the model. The data for construction of an alternative lead-based paint chip menu were reviewed by the EPA Technical Review Work Group, who concluded that these data were not adequate to be recommended as default values. There are greater uncertainties about paint chip exposure and uptake than about other exposure media. These uncertainties include:

(1) The quantity of paint chips ingested on a long-term or chronic basis is unknown; however, even small quantities of ingested paint chips can produce a lead intake of millions of micrograms per day, overwhelming all other sources.

(2) Lead levels in housing are most typically measured as surface loadings using portable XRF analyzers. While there are several proposed relationships between lead paint surface loading and daily lead intake, these require making assumptions about other uncertain relationships, such as the "area" of surface ingested the child, or the thickness of the paint chip and the relationship between lead concentration and lead loading. We will describe these relationships, but we believe that they do not yet have an adequate empirical basis.

(3) Paint chips are, by definition, discrete units. Even if paints chips are at least one millimeter in diameter, or even larger, they may not be completely dissolved in the stomach or completely absorbed in the intestines. Observations of child fecal samples sometimes find discrete paint chips. Radio-opaque samples in stool may be lead or some mixture of lead with other heavy metals such as barium or chromium commonly found in leaded paint pigments.

(4) Lead paint absorption by rats has been found to depend significantly on particle size and chemical speciation of paint particles. Many chemical species are found in lead-based paint, most often including lead octoate (as a dryer), lead carbonate, and lead chromate. The sequence of absorption or bioavailability is probably

$$\text{carbonate} \geq \text{octoate} > \text{chromate}$$

based on rodent studies (Barltrop and Meek, 1979). While the ranking is probably similar in human children and other primates , direct evidence is limited to baboons (Cohen, 1975; Mallon, 1983). Studies are currently in progress using miniature swine as closely analogous models of human gastro-intestinal absorption of nutrients and contaminants, but results on absorption of lead from actual lead paints have not yet been reported. It is clear in any case that estimates of lead bioavailability in paints may require a much more complete site-specific characterization by particle size and chemical speciation than does soil.

4.7.2 Daily Intake of Paint Chips

The American Academy of Pediatrics (1972) has used a provisional estimate of one square inch (6.25 cm^2) of paint surface ingested per day. This appears to be a nominal value for purposes of risk estimation, and no empirical basis for this value has been provided. They cite evidence that 1 cm^2 of one layer of interior paint may weigh 5.0 to 8.2 mg (average 6.5 mg), and that six layers of paint weighed 37.0 to 40.6 mg (average 38.8). Thus, using data that may represent Providence RI in 1972, where six layers of paint were typical, ingestion of 6.25 cm^2 of painted surface through a single painted layer would correspond to 40.6 mg/day intake, and a thick chip containing six layers would average 233 mg/d paint chip intake. Even if the ingested paint chips were square-inch monolayers with one percent lead, the daily lead intake would be 400 ug Pb/d. We cannot provide any realistic estimate of the uncertainty of this estimate. It is likely that there is some correlation between the size, thickness, and lead content of ingested paint chips, since additional lead is reported to add a sweet taste to the chips that may appeal to a child with pica for lead paint chips.

These estimates were also cited in a report by the National Academy of Sciences (NAS, 1973) to the Consumer Product Safety Commission (CPSC). They concluded that the

quantitative evidence was inadequate "to promulgate a standard based on knowledge of the essential quantitative relations that link the lead content of paint to symptoms of intoxication. However, this is not unusual in public-health practice. Many useful standards have been established by informed people who make judgments based on whatever facts are available" (NAS, 1973, pp. 25-26).

In view of the lower quality of information on paint chip intake than on intake of soil and dust, diet, and drinking water, and the usefulness of providing baseline risk assessments in the absence of lead-based paint, we have used a default value of 0 μg/dL in the model.

4.7.3 Relationship of XRF Lead Paint Surface Loading to Lead Paint Concentration

The estimate of lead intake from paint chip ingestion depends on a lead concentration for the ingested chips. However, this is not available in field samples without removing a piece of paint from the wall or trim. Therefore, the use of non-destructive field sampling methods such as portable XRF analyzers has become the common method for determining paint hazard. We can calculate

$$\text{lead concentration } (\mu g/g) = 0.001\ (\mu g/mg) * \text{lead loading } (mg/cm^2) \ /$$

$$\text{thickness of paint (cm)} * \text{paint density } (g/cm^3).$$

Calculations from the EPA Lead Reference Materials Workshop (EPA 1991) assuming a seven-layer thickness of paint (40 mil = 1 mm) and a density of 2 g/cm^3 calculates 5,000 μg/g equivalent to 1 mg/cm^2. This is reasonably concordant with some analyses of measurements of paint loading and concentration that we had calculated from data in the Boston Brigham and Women's Hospital Longitudinal Lead Study. However, this relationship is likely to vary so greatly from house to house that we cannot recommend its use without site-specific verification.

4.7.4 Dissolution of Paint Chips in Acid Environments

Not all of the lead in a large lead paint chip may be available for absorption. Roberts et al. (1974) report that "20 to 60 percent of the lead in surface soil was extractable in 0.1N HCl compared with less than 10 percent extractable from paint samples." Particle dissolution is a component of lead bioavailability.

4.7.5 Absorption of Lead Paint In Vivo

The absorption of lead-based paint particles by rats is described in (Barltrop and Meek 1979). They conclude that "The physical form of particles derived from paint film would seem to modify the availability of Pb compounds contained in them for absorption. Little is known of the physical or chemical changes which paint flakes undergo after ingestion, although it is known that some paint flakes remain relatively intact when swallowed by a child and may be observed radiographically in the gut lumen, or on inspection of feces. In spite of this, sufficient absorption of Pb resulting in childhood poisoning is known to occur, and in many cases the ingested flakes become too finely divided to be visible macroscopically. Thus the composition of the paint and the chemical nature of the added Pb compounds may determine its stability in the gut and hence the availability of Pb for absorption. Long-term feeding of paint flakes identical to those used in this work, but of larger size (500 to 1,000 microns) have been reported to result in minimal absorption by the rat (Barltrop and Meek, 1975)."

Table 4-4 summarizes their results. Lead absorption can be characterized by the difference in blood lead levels between exposed and control rats. The increase in blood lead for rats fed lead octoate in particles between 500 and 1,000 microns diameter is about 60 percent of the absorption of lead octoate particles <50 microns, and absorption of lead chromate paint in particles of 500 to 1,000 microns is about 45 percent of the absorption of lead chromate paint in particles of 500 to 1,000 microns. For particles <50 microns, the increase in blood lead for lead octoate particles is about 60 percent of the increase from lead acetate. It is not clear how these results can be used quantitatively for humans to determine absolute or relative bioavailability of LBP.

Juvenile and infant baboons were exposed to oral intakes of lead salts and prepared lead paint samples from New York City (Mallon, 1983). The lead salts and paint samples were fed in gelatin capsules to sedated baboons. The relative bioavailability could be estimated from differences in the steady-state blood lead levels achieved after 5 or 6 months of chronic exposure. These are shown in Tables 4-5 and 4-6. The increase in blood lead in infant baboons (age 6 months at the start of the study) was 23 μg/dL (no s.e.) for 2 baboons exposed to lead acetate and 6.125 μg/dL for 8 baboons exposed to New York city paint at a controlled dose of 100 μg/kg/day (roughly 250 to 350 μg/day in baboons who grew from 2.5 to 3.5 kg body weight). At higher doses, the increases in blood lead were clearly nonlinear with respect to dose rate. In juvenile baboons (ages 20-24 months at the beginning of the study) the increase in blood lead was 11.7 μg/dL (no s.e.) for 2 baboons exposed to

TABLE 4-4. PERCENTAGE INCREASE IN BLOOD LEAD LEVELS IN INFANT MALE WISTAR RATS WITH 48-HOUR ORAL EXPOSURE TO LEAD ACETATE, AND TO LEAD OCTOATE AND LEAD CHROMATE PAINTS OF DIFFERENT PARTICLE SIZES

Paint Chip Size (mm)	Lead	Dose Rate μg/kg/d	Blood Lead (S.E.) μg/dL	Blood Lead - Control μg/dL	Percent of PbAc
-	CONTROL	0	8.1 (1.9)	-	-
-	ACETATE	33000[1]	38.3 (4.0)	30.2 (4.4)	-
0.5-1	OCTOATE PAINT	33000[1]	19.3 (3.7)	11.2 (4.2)	37.1
<0.05	OCTOATE PAINT	33000[1]	27.2 (4.0)	19.1 (4.4)	63.2
0.5-1	CHROMATE PAINT	33000[1]	14.5 (3.2)	6.4 (3.7)	21.1
<0.05	CHROMATE PAINT	33000[1]	22.8 (2.2)	14.7 (2.9)	48.7

[1]Calculated as 0.02% lead in diet, per 31 to 33 g diet in 48 h, per 96 g body weight (range 90 to 103 g).

Source: Adapted from Barltrop and Meek (1979).

TABLE 4-5. PERCENTAGE INCREASE IN BLOOD LEAD LEVELS IN INFANT BABOONS WITH CHRONIC EXPOSURE TO LEAD PAINT, LEAD ACETATE, AND OTHER LEAD COMPOUNDS

Age	Lead	Dose Rate μg/kg/d	Blood Lead (N) μg/dL	Blood Lead - Ctrl. μg/dL	Percent of PbAc
5-6 mo	CONTROL	0	9 (1)	-	-
	ACETATE	100	32 (2)	23	-
	ACETATE	200	42 (2)	33	-
	ACETATE	1000	72 (1)	63	-
	CARBONATE	1000	69 (1)	60	95.2
	OCTOATE	100	90 (1)	81	352
	PAINT	100	15.12 (8)	6.12	26.6

Source: Adapted from Mallon (1983).

lead acetate and 33.7 μg/dL for 1 baboon exposed to lead octoate at 100 μg/kg/d, but only 3.7 μg/dL (no s.e.) in 2 baboons exposed to New York city paint at a controlled dose of 200 μg/kg/day. The increase in blood lead was 31.7 μg/dL (no s.e.) for 2 baboons exposed to lead acetate and 93.7 μg/dL for 1 baboon exposed to lead octoate at 500 μg/kg/d, but only 12.7 μg/dL in 2 baboons exposed to New York city paint at a controlled dose of 500 μg/kg/day. Therefore, the bioavailability of lead in actual paint samples was at most

TABLE 4-6. PERCENTAGE INCREASE IN BLOOD LEAD LEVELS IN JUVENILE BABOONS WITH CHRONIC EXPOSURE TO LEAD PAINT, LEAD ACETATE, AND OTHER LEAD COMPOUNDS

Age	Lead	Dose Rate μg/kg/d	Blood Lead (N) μg/dL	Blood Lead - Ctrl. μg/dL	Percent of PbAc
20-24 mo	CONTROL	0	12.33 (3)	-	-
	ACETATE	100	24 (2)	11.67	-
	ACETATE	500	44 (2)	31.67	-
	OCTOATE	100	46 (1)	33.67	288.6
	OCTOATE	500	106 (1)	93.67	295.8
	PAINT	200	16 (2)	3.67	31.4[1]
	PAINT	500	25 (1)	12.67	40.0

[1]Calculated relative to 100 μg/kg/d lead acetate.

Source: Adapted from Mallon (1983).

25 to 40 percent of the bioavailability of lead acetate administered during chronic exposure studies at dose rates roughly comparable to those assumed in the American Academy of Pediatrics report. The much higher relative bioavailability of the pure lead octoate compound remains to be explained. The absolute bioavailability of lead acetate in diet estimated by Mallon was estimated by Mallon was 24 percent at a dose rate of 12 μg/kg/d, 8 percent at 100 μg/kg/d, and 6 percent at 200 μg/kg/d in infant baboons; 12 percent at 12 μg/kg/d, 3 percent at 100 μg/kg/d, and 1 percent at 1,000 μg/kg/d in juvenile baboons. The estimates of absolute bioavailability of oral lead acetate developed by Marcus (1992) using a saturable absorption mechanism to account for the bioavailability were higher, about 28 percent and 20 percent at dose rates that were much less than 200 μg/kg/day. The bioavailability of these lead-based paints must then be taken as less than 7 percent and 5 percent respectively. A detailed characterization of the chemical composition and size distribution of the prepared paint samples would have been useful, but was not presented.

5. APPLICATIONS WITH EXAMPLES

5.1 APPLICATIONS FOR POPULATION ESTIMATES

The purpose of this chapter is to provide concrete examples complete with explanations that can guide the user through specific applications of the model. These examples are taken in part from past applications of the model, but they have been modified for the purposes of illustration and do not represent any specific site or risk management decision. While the user should find some guidance in these examples, they are not meant to be comprehensive of all possible model applications, nor should they be generalized to any particular site.

EXAMPLE 5-1. Default Values

As stated earlier in this manual, the model can predict geometric mean blood lead levels in a population of children with residential and neighborhood exposures, provided that the distribution of environmental lead parameters is not widely dispersed. The following is an example of a simple simulation using only default values.

From the main menu shown in Screen 2-1, enter "2" (Computation), then on the Computation Menu enter "1" (Run). The results shown on the monitor display the average of monthly geometric mean blood lead concentrations in one-year intervals, along with the daily lead uptakes from each medium in μg Pb/day. These results are the geometric mean blood lead concentrations and lead uptakes within each one-year age interval, assuming constant environmental lead concentrations from birth through each age interval. They can be interpreted as representing the results for a "typical" child in contact with these or similar lead concentrations. See Example 5-4 for an extension of this example to risk estimation.

5.2 APPLICATIONS WHERE ENVIRONMENTAL LEAD CONCENTRATIONS CHANGE OVER TIME

EXAMPLE 5-2. Reductions in Air and Dietary Lead Levels from 1975 to 1981 Decrease Baseline Blood Lead Concentrations

This example illustrates the estimation of historical exposures and baseline U.S. blood lead concentrations from 1975 to 1981.

- Air: The user should first enter the 1975 air lead levels from Figure 2-10.

- Diet: Then the user should enter the dietary lead values for the same time period, as in Table 2-1. However, no dietary lead intake values for children are shown for 1975 to 1977. We estimated the 0-11 month value for 1975 as 80 percent of the 1-year value for the 1978 value, that is 80 percent of 45.80 μg/d = 36.64 μg/d, since the 6-11 month dietary lead intake values for 1982-1984 are about 80 percent of the respective 1-year-old values. We then assumed that for a child born in 1975, the 1975 value was 36.64 μg/d, the 1976 value (age 1 year) was the same as the 1978 1-year-old value of 45.80 μg/d, the 1977 value (age 2 years) was the same as the 1978 2-year-old value of 52.90 μg/d, the 1978 value (age 3 years) was 52.70 μg/d as in Table 2-1, the 1979 value (age 4 years) was 47.30 μg/d as in Table 2-1, the 1980 value (age 5 years) was 38.70 μg/d as in Table 2-1. We assumed that the 1981 value (age 6 years) was 110 percent of the 1981 value at age 5 years or 110 percent of 35.80 μg/d = 39.38 μg/d, since the 1982-1984 6-year-old values are about 10 percent larger than the respective 5-year-old intake values. The input values for dietary lead intake are shown in Table 5-1.

- Water: Water lead concentrations were kept at the default values.

- Soil: Adjustments should be made for lead in soil and household dust. We assumed that soil lead levels, even in areas not heavily impacted by automobile traffic, would have been somewhat larger in 1975 than in 1981. In the absence of better information, we assumed that soil lead concentrations consist of two components, a genuine baseline of about 200 μg/g which is the current default, and a small increment from air lead deposition that adds about 100 μg/g soil lead per $\mu g/m^3$ air lead. This assumption implies a relatively small contribution of 10 μg/g to soil lead from current air lead levels of 0.1 $\mu g/m^3$. Thus the 1975 soil lead level is about 324 μg/g, the 1976 level about 322 μg/g, and so on, as shown in Table 5-2.

TABLE 5-1. USER-SELECTED ENTRIES FOR IEUBK MODEL WORKSHEET FOR EXAMPLE 5-2, CHILD BORN IN 1975

PARAMETER	DEFAULT VALUE	USER SELECTED OPTION	UNITS
DATA ENTRY FOR DIET (by year)			
Dietary lead intake			
Age =0-1 year (0-11 mo),	5.53	36.64	μg Pb /day
1-2 years (12-23 mo)	5.78	45.80	
2-3 years (24-35 mo)	6.49	52.90	
3-4 years (36-47 mo)	6.24	52.70	
4-5 years (48-59 mo)	6.01	47.30	
5-6 years (60-71 mo)	6.34	38.70	
6-7 years (72-84 mo)	7.00	39.38	

TABLE 5-2. USER-SELECTED ENTRIES FOR IEUBK MODEL WORKSHEET FOR EXAMPLE 5-2, CHILD BORN IN 1975

PARAMETER	DEFAULT VALUE	USER SELECTED OPTION	UNITS
DATA ENTRY FOR SOIL (by year)			
Soil lead concentration			
Age =0-1 year (0-11 mo) (1975)	0	324	μg/g
1-2 years (12-23 mo) (1976)	0	322	
2-3 years (24-35 mo) (1977)	0	320	
3-4 years (36-47 mo) (1978)	0	310	
4-5 years (48-59 mo) (1979)	0	290	
5-6 years (60-71 mo) (1980)	0	256	
6-7 years (72-84 mo) (1981)	0	247	

- Dust: The Multiple Source Analysis method for household dust should be used, since soil lead and air lead levels are changing over time. Since particles from leaded gasoline emission are believed to contribute significantly to surface soil transported into the house during these years, we have assumed that the soil-to-dust coefficient is 0.85 appropriate for this historical example, although the current default is 0.70, and the air-to-dust coefficient is 100. This was shown in Screen 2-10. These changes are reported to the user in the main Data Entry Screen for Soil/Dust.

The model can be run by returning to the Computation Menu and using Option 1, or by pressing the F5 key from any of the main media data entry screens. The results are shown on the display. The results are reasonably consistent with the decrease in child blood lead concentrations in the U.S. from about 15 μg/dL to 10 μg/dL found in the 1976-1980 NHANES II survey (U.S. Environmental Protection Agency, 1986). However, this exposure scenario follows a single child born in 1975 for six years through 1981. Direct comparison with NHANES II would require representative blood lead estimates for 1-year-olds in 1976, 2-year-olds in 1977, 3 year-olds in 1978 etc.

The importance of a worksheet in developing and documenting the exposure scenario should be clear to the reader. The worksheets for this example are shown in Tables 5-1 and 5-2. Since the exposure scenario here is for a typical urban child and is not specific to a site or neighborhood, the user should not try to extend these results for risk estimation purposes without incorporating interindividual variability and site-specific information concerning exposure variability.

The IEUBK model is a biokinetic model, and therefore has the ability to estimate changes in blood lead in response to yearly changes in environmental lead exposure for children of different ages. The following examples are presented to encourage the user to explore some of the IEUBK model's capabilities for evaluating age-dependent changes in lead exposure when this exposure changes over time.

EXAMPLE 5-3. Example for Children Moving From a Lower to a Higher Soil Lead Concentration

This example demonstrates the effects of change from a constant environmental lead concentration to a higher constant environmental lead concentration. Assume that a child

moved into a housing unit with a soil lead concentration of about 2000 μg/g, from a previous housing unit with a soil lead concentration of about 100 μg/g. Assume also that soil is a significant source of dust in household dust, and that the soil lead contribution to household dust lead is 70 percent of the soil lead concentration. The user can assess the maximum effect of new exposure to elevated soil lead (e.g., moving into a new residence). This assessment is for children of different ages, in an ordered sequence of runs. This sequence studies the effects of new exposure at later ages.

The work sheet for this example is similar to the segment shown in Table 5-2. In fact, a sequence of work sheets is needed to study the effects of moving at different ages. There are two variables to be considered here. The first variable is the age of the child, which is used in the IEUBK Model calculations, and is entered as the left-hand column of the work sheets. The second variable is the age at which the child moves into the new exposure environment. Thus, in Table 5-3(a), if the child moves at age 0 years, the child is exposed to 2000 μg/g lead in soil and 1400 μg/g lead in dust derived from soil from birth through age 6 years. However, if the child moves at age one year, the correct work sheet is shown in Table 5-3(b). In the work sheet in Table 5-3(b), the child is exposed to 100 μg/g lead in soil and 70 μg/g lead in household dust at age zero years, but to 2000 μg/g lead in soil and 1400 μg/g lead in dust from soil at ages 1 through 6 years. Similarly, if the child moves at age two years, the correct work sheet is shown in Table 5-3(c). In the work sheet in Table 5-3(c), the child is exposed to 100 μg/g lead in soil and 70 μg/g lead in household dust at ages 0 and 1 years, but to 2000 μg/g lead in soil and 1400 μg/g lead in dust from soil at ages 2 through 6 years.

The worksheets for Tables 5-3(a-c) are combined and shown as columns 2 to 4 in Table 5-3(d). The last 4 columns in Table 5-3(d) summarize the soil lead work sheet entries if the hypothetical child moves at ages 3, 4, 5, or 6 years respectively. For example, in the extreme right-hand column, if the child moves at age 6 years, he or she is exposed to 100 μg/g lead in soil from birth through age 5 years, then to 2000 μg/g at age 6 years.

The IEUBK Model simulation for this example is run 7 times, each run corresponding to a column in Table 5-3(d) or to a work sheet 5-3(a-c) or analogous work sheets for older children. The results, as annual averages of predicted geometric mean blood lead concentration, are shown in Table 5-4 in exactly the same order as in Table 5-3(d).

TABLE 5-3a. SOIL LEAD DATA ENTRY WORKSHEET FOR CHILD EXPOSED TO 2000 μg/g SINCE AGE 0 (BIRTH)

PARAMETER	DEFAULT VALUE	USER SELECTED OPTION	UNITS
DATA ENTRY FOR SOIL (by year)			
Soil lead concentration			
Age = 0-1 year (0-11 mo)	0	2000	μg/g
1-2 years (12-23 mo)	0	2000	
2-3 years (24-35 mo)	0	2000	
3-4 years (36-47 mo)	0	2000	
4-5 years (48-59 mo)	0	2000	
5-6 years (60-71 mo)	0	2000	
6-7 years (72-84 mo)	0	2000	

TABLE 5-3b. SOIL LEAD DATA ENTRY WORKSHEET FOR CHILD EXPOSED TO 2000 μg/g SINCE AGE 1

PARAMETER	DEFAULT VALUE	USER SELECTED OPTION	UNITS
DATA ENTRY FOR SOIL (by year)			
Soil lead concentration			
Age = 0-1 year (0-11 mo)	0	100	μg/g
1-2 years (12-23 mo)	0	2000	
2-3 years (24-35 mo)	0	2000	
3-4 years (36-47 mo)	0	2000	
4-5 years (48-59 mo)	0	2000	
5-6 years (60-71 mo)	0	2000	
6-7 years (72-84 mo)	0	2000	

TABLE 5-3c. SOIL LEAD DATA ENTRY WORKSHEET FOR CHILD EXPOSED TO 2000 μg/g SINCE AGE 2

PARAMETER	DEFAULT VALUE	USER SELECTED OPTION	UNITS
DATA ENTRY FOR SOIL (by year)			
Soil lead concentration			
Age = 0-1 year (0-11 mo)	0	100	μg/g
1-2 years (12-23 mo)	0	100	
2-3 years (24-35 mo)	0	2000	
3-4 years (36-47 mo)	0	2000	
4-5 years (48-59 mo)	0	2000	
5-6 years (60-71 mo)	0	2000	
6-7 years (72-84 mo)	0	2000	

TABLE 5-3d. WORKSHEET FOR YEARLY SOIL LEAD CONCENTRATION FOR HYPOTHETICAL CHILDREN MOVING FROM A RESIDENCE WHERE SOIL CONCENTRATION IS 100 μg/g TO A RESIDENCE WHERE SOIL CONCENTRATION IS 2000 μg/g

AGE OF CHILD (YEARS)	AGE AT TIME OF NEW EXPOSURE (YEARS)						
	0	1	2	3	4	5	6
0	2000	100	100	100	100	100	100
1	2000	2000	100	100	100	100	100
2	2000	2000	2000	100	100	100	100
3	2000	2000	2000	2000	100	100	100
4	2000	2000	2000	2000	2000	100	100
5	2000	2000	2000	2000	2000	2000	100
6	2000	2000	2000	2000	2000	2000	2000

TABLE 5-4. PREDICTED ANNUAL AVERAGE BLOOD LEAD CONCENTRATIONS (μg/dL) FOR HYPOTHETICAL CHILDREN MOVING FROM A RESIDENCE WHERE SOIL CONCENTRATION IS 100 μg/g TO A RESIDENCE WHERE SOIL CONCENTRATION IS 2000 μg/g

AGE OF CHILD (YEARS)	AGE AT TIME OF NEW EXPOSURE (YEARS)						
	0	1	2	3	4	5	6
0	16.2	2.8	2.8	2.8	2.8	2.8	2.8
1	18.6	16.3	3.0	3.0	3.0	3.0	3.0
2	17.7	17.7	14.5	2.8	2.8	2.8	2.8
3	17.3	17.3	17.2	13.5	2.6	2.6	2.6
4	14.7	14.7	14.7	14.5	10.2	2.3	2.3
5	12.6	12.6	12.6	12.6	12.2	8.6	2.1
6	11.3	11.3	11.3	11.3	11.2	10.8	7.5

The changes in exposure scenario are made by first using the parameter selection menu (Option "1" on the Main Menu), Option "4" on the parameter selection menu, and then entering selection "2" in the soil concentration box of the Soil/Dust menu. This allows the entry of separate values for soil lead exposure concentration at each age. The default value of 200 μg/g for each age may be replaced by 100 or by 2000, as indicated by the scenario on the work sheet. When finished, the user must return to the Soil/Dust menu. In order to change the dust lead exposure from the default, a constant 200 μg/g, the user must move the cursor down to the dust lead entry box in the Soil/Dust Menu and enter selection "3", the multiple source menu. The default soil-to-dust coefficient of 0.70 is activated by entering the Multiple Source Menu, and may be changed as needed. We will not modify either the soil-to-dust coefficient of 0.7, nor the air-to-dust coefficient of 100 μg/g per μg/m^3. The complete input file may be saved by returning to the Soil/Dust Menu and using the F6 key. The model may then be run by using the F5 key.

The results of the seven runs are shown in Table 5-4, which is analogous to Table 5-3(d). The second column shows blood lead concentrations for a typical child exposed to 2000 μg/g lead in soil since birth. The peak blood lead concentration of 18.6 μg/dL is reached at age one year. If the initial exposure to 2000 μg/g occurs later, the peak blood lead concentration is lower.

Most of the blood lead response to a change in exposure or a change in environmental lead concentration occurs in the first 3 months after the change. The change in blood lead during the first three months after changing exposure is at least 50 to 60 percent of the total difference in quasi-state-state blood lead concentration before and after the change. The remaining difference will slowly decrease during the next 2 years. We thus suggest that cross-sectional blood lead studies or baseline blood lead concentrations measured in longitudinal studies require that all children shall have lived at their present address for at least 3 to 6 months prior to the blood lead sample.

EXAMPLE 5-4. Example for Children in a Residence Where the Soil Has Been Abated

This sequence of runs considers soil lead exposure decreased from 2000 to 100 μg/g, and the soil contribution to dust decreased from 1400 to 70 μg/g, at ages 0 (i.e. constant exposure without soil and dust lead after birth), at age 1, age 2, and so on. This assessment studies the effects of abatement on children at different ages. The entries for this example are similar to those of Example 5-3. The summary of seven data entry worksheets is shown in Table 5-5(d), and the results are shown in Table 5-6.

TABLE 5-5a. SOIL LEAD DATA ENTRY WORKSHEET FOR CHILD WITH SOIL ABATED TO 100 μg/g SINCE AGE 0 (BIRTH)

PARAMETER	DEFAULT VALUE	USER SELECTED OPTION	UNITS
DATA ENTRY FOR SOIL (by year)			
Soil lead concentration			
Age = 0-1 year (0-11 mo)	0	100	μg/g
1-2 years (12-23 mo)	0	100	
2-3 years (24-35 mo)	0	100	
3-4 years (36-47 mo)	0	100	
4-5 years (48-59 mo)	0	100	
5-6 years (60-71 mo)	0	100	
6-7 years (72-84 mo)	0	100	

TABLE 5-5b. SOIL LEAD DATA ENTRY WORKSHEET FOR CHILD WITH SOIL ABATED TO 100 μg/g SINCE AGE 1

PARAMETER	DEFAULT VALUE	USER SELECTED OPTION	UNITS
DATA ENTRY FOR SOIL (by year)			
Soil lead concentration			
Age = 0-1 year (0-11 mo)	0	2000	μg/g
1-2 years (12-23 mo)	0	100	
2-3 years (24-35 mo)	0	100	
3-4 years (36-47 mo)	0	100	
4-5 years (48-59 mo)	0	100	
5-6 years (60-71 mo)	0	100	
6-7 years (72-84 mo)	0	100	

TABLE 5-5c. SOIL LEAD DATA ENTRY WORKSHEET FOR CHILD WITH SOIL ABATED TO 100 μg/g SINCE AGE 2

PARAMETER	DEFAULT VALUE	USER SELECTED OPTION	UNITS
DATA ENTRY FOR SOIL (by year)			
Soil lead concentration			
Age = 0-1 year (0-11 mo)	0	2000	μg/g
1-2 years (12-23 mo)	0	2000	
2-3 years (24-35 mo)	0	100	
3-4 years (36-47 mo)	0	100	
4-5 years (48-59 mo)	0	100	
5-6 years (60-71 mo)	0	100	
6-7 years (72-84 mo)	0	100	

TABLE 5-5d. WORKSHEET FOR HYPOTHETICAL CHILDREN IN A NEIGHBORHOOD WHERE SOIL CONCENTRATION IS REDUCED FROM 2000 μg/g TO 100 μg/g

AGE OF CHILD (YEARS)	AGE AT TIME OF ABATEMENT (YEARS)						
	0	1	2	3	4	5	6
0	100	2000	2000	2000	2000	2000	2000
1	100	100	2000	2000	2000	2000	2000
2	100	100	100	2000	2000	2000	2000
3	100	100	100	100	2000	2000	2000
4	100	100	100	100	100	2000	2000
5	100	100	100	100	100	100	2000
6	100	100	100	100	100	100	100

TABLE 5-6. PREDICTED BLOOD LEAD CONCENTRATIONS (μg/dL) FOR HYPOTHETICAL CHILDREN IN A NEIGHBORHOOD WHERE SOIL CONCENTRATION IS REDUCED FROM 2000 μg/g TO 100 μg/g

AGE OF CHILD (YEARS)	AGE AT TIME OF ABATEMENT (YEARS)						
	0	1	2	3	4	5	6
0	2.8	16.2	16.2	16.2	16.2	16.2	16.2
1	3.0	5.4	18.6	18.6	18.6	18.6	18.6
2	2.8	2.8	6.1	17.7	17.7	17.7	17.7
3	2.6	2.6	2.7	6.6	17.3	17.3	17.3
4	2.3	2.3	2.3	2.5	6.9	14.7	14.7
5	2.1	2.1	2.1	2.1	2.55	6.2	12.6
6	1.9	1.9	1.9	1.9	2.0	2.4	5.8

A sequence of work sheets is needed to study the effects of abatement at different ages. The two variables to be considered here are the child's age, which is a variable used in the IEUBK Model simulation, and the age of the child when the abatement was carried out, which is different for each run in the sequence of 7 runs. In Table 5-5(a), if the soil is abated at age 0 years, the child is exposed to 100 μg/g lead in soil and 70 μg/g lead in dust

derived from soil from birth through age 6 years. However, if the soil is abated at age one year, the correct work sheet is shown in Table 5-5(b). In the work sheet in Table 5-5(b), the child is exposed to 2000 μg/g lead in soil and 1400 μg/g lead in household dust at age zero years, but to 2000 μg/g lead in soil and 1400 μg/g lead in dust from soil at ages 1 through 6 years. Similarly, if the soil is abated at age two years, the correct work sheet is shown in Table 5-5(c). In the work sheet in Table 5-5(c), the child is exposed to 2000 μg/g lead in soil and 1400 μg/g lead in household dust at ages 0 and 1 years, but to 100 μg/g lead in soil and 70 μg/g lead in dust from soil at ages 2 through 6 years.

The worksheets for Tables 5-5(a-c) are combined and shown as columns 2 to 4 in Table 5-5(d). The last 4 columns in Table 5-5(d) summarize the soil lead work sheet entries for a hypothetical child if the soil is abated at ages 3, 4, 5, or 6 years respectively. For example, in the extreme right-hand column, if the soil is abated at age 6 years, he or she is exposed to 2000 μg/g lead in soil from birth through age 5 years, then to 100 μg/g at age 6 years.

The IEUBK Model simulation for this example is run 7 times, each run corresponding to a column in Table 5-5(d) or to a work sheet 5-5(a-c) or analogous work sheets for older children. The results, as annual averages of predicted geometric mean blood lead concentration, are shown in Table 5-6 in exactly the same order as in Table 5-5(d).

Abatement at age 1 reduces blood lead from 16.2 to 5.4 μg/dL in the first year after abatement, a reduction of 10.8 μg/dL or 66.7 percent. The effect at age 2 is a reduction from 18.6 to 6.1 μg/dL, that is 12.5 μg/dL or 67.7 percent. Abatement at age 5 has a reduction of 8.5 μg/dL or 57.8 percent in the first year. It should be noted that blood lead concentrations do not reach the post-abatement quasi-steady state level until two years after the abatement, so that the apparent reduction in blood lead concentration in the first year after abatement will underestimate the effectiveness of abatement.

EXAMPLE 5-5. Historical Exposure Reconstruction for Soil and Dust Lead Concentration and Dietary Lead Intake Around an Unused Lead Smelter

One of the issues that arose in developing validation case studies for the IEUBK model is that many of the earlier data sets were collected at sites where background lead exposure differed greatly from current default values, and where both background exposure and soil/dust exposure were changing substantially during the lifetime of the children in the blood

lead study. It was therefore necessary to construct an historical exposure scenario for the children in the blood lead study. The exposure reconstruction for the 1983 East Helena blood lead study was discussed in the initial validation of the UBK model (U.S. Environmental Protection Agency 1989). In this example, we will discuss the more complicated exposure situation for the 1983 companion study in the Silver Valley of Idaho. We rely heavily on the initial report on Kellogg Revisited (Panhandle District Health Department 1986), the Human Health Risk Assessment (Jacobs Engineering, 1989, for US EPA Region X), the Risk Assessment Data Evaluation Report (US EPA 1990), the House Dust Remediation Report (CH2M Hill 1991 for the Idaho Dept. of Health), the Record of Decision for the Bunker Hill site (U.S. Environmental Protection Agency 1991), and personal communications with Dr. Ian Von Lindern of Terragraphics Inc. (1992-1993).

The narrow east-west Silver Valley was divided initially into three residential areas, Area 1 (Smelterville) about 1.2 to 1.5 km northwest of the smelter complex, Area 2 (Kellogg) about 2.6 to 3.3 km east of the smelter complex, and Area 3 (Pinehurst) about 6 km west of the smelter complex. In subsequent studies this area was extended and subdivided into 5 to 11 areas or zones. A list of zones and distances is attached as Table 5-7. The main distinction is that the Page neighborhood which is only 3 km west of the smelter complex has been distinguished from Pinehurst, and that the Wardner neighborhood about 3 km southeast of the smelter complex has been separated from the Kellogg community. The five areas currently defined are closer in size and population to the "neighborhoods" recommended in Chapter 4.

Silver Valley has a complicated history of lead exposure, including significantly elevated air and dust lead exposures in 1974 and 1975, and a cessation of lead smelting activities after December 1991. Therefore, the exposure history reconstruction in Table 5-8 is a mixture of observed values and interpolated values. The observed values were sometimes recorded as geometric means and sometimes as arithmetic means, and as estimates or interpolations enclosed in brackets. The basis for the dust lead interpolation was not described in more detail in (Jacobs Engineering 1989). The soil lead concentrations were held at the last measured value until a new observed value had been achieved.

Soil and dust lead concentrations were only observed in 1974, 1975, 1983, and 1986-1988. Dust lead concentrations have also been observed in these communities since 1990. There are alternatives to estimating neighborhood soil and dust lead concentrations between actual observations, such as by linear interpolation, that may provide somewhat different estimates than the interpolations used in the human risk assessment study.

TABLE 5-7. NEIGHBORHOOD IDENTIFIERS AND DISTANCE FROM STACK FOR KELLOGG, ID, STUDY

ZONE	APPROXIMATE DISTANCE FROM ZONE CENTER TO Pb SMELTER STACK (Km)	DESCRIPTION
A	1.50	Smelterville, south of old Highway 110 and west of C street
B	1.15	Smelterville, east of C street
C	2.75	Kellogg, north of I-90 and west of Hill street
D	3.25	Kellogg, north of I-90 and east of Hill street
E	2.60	Kellogg, south of I-90 and west of Division street
F	3.30	Kellogg. south of I-90 and east of Division street
G	3.00	Wardner
H	5.70	Pinehurst
I	3.30	Page
J		Smelterville, (1974-75 only)
K		Kellogg/Page, (1974-75 (only)

An alternative assumption is that soil and dust lead concentrations decreased linearly between 1983 and 1986-1988. Thus, in Smelterville the decline in soil lead was 3047 - 2685 = 362 μg/g in 4 years, or 90 μg/g per year, whereas in Kellogg it was 2584 - 1988 = 596 μg/g in 4 years, or about 150 μg/g per year. The dust lead concentrations in Smelterville decreased by 3715 - 1203 = 2512 μg/g in 5 years, or about 250 μg/g per year, whereas the dust lead concentration in Kellogg decreased by 2366 - 1450 = 916 μg/g in 5 years or about 230 μg/g per year. However, the dust lead concentrations in 1990-1992 were still elevated above the Pinehurst concentration. It would be prudent to assume that the dust lead concentration was relatively constant for much of the period around and after 1988. By implication, since soil lead and air lead are sources for dust lead, one might assume that the soil lead and air lead concentrations for 1988-1992 are relatively constant at the 1988 values.

The soil and dust lead values for a Kellogg child born in 1983, assuming a linear decrease of 150 μg/g in soil lead from 2584 μg/g and a linear decrease of 230 μg/g in dust lead from 2366 μg/g, is shown on the worksheet in Table 5-9. In this example we have

TABLE 5-8. OBSERVED AND ESTIMATED AIR, SOIL, AND DUST LEAD CONCENTRATIONS FOR USE IN HISTORICAL EXPOSURE RECONSTRUCTIONS IN SILVER VALLEY COMMUNITIES

YEAR	SMELTERVILLE			KELLOGG			PINEHURST		
	PbA[1,2]	PbS[1,2]	PbD[1,2]	PbA[1,2]	PbS[1,2]	PbD[1,2]	PbA	PbS	PbD
1971	5.7	[6141]	[3530]	8.2			[6.1]		
1972	11.2	[6141]	[6620]	9.6			[6.1]		
1973	16.5	[6141]	[12500]	15.0			[6.1]		
1974	14.3	6141	10583	14.0	2514	6581	6.1	765	2006
1975	8.9	3991	3533	7.4	2586	4573	3.1	508	1749
1976	9.8	[3991]	[6030]	7.5			3.4		
1977	9.1	[3991]	[5670]	6.8			3.6		
1978	5.4	[3991]	[3530]	5.4			2.7		
1979	6.6	[3991]	[4020]	5.9			3.1		
1980	6.2	[3991]	[3780]	5.9			2.2		
1981	4.6	[3991]	[2830]	4.1			1.2		
1982	0.88	[3991]	[3715]	0.28			0.16		
1983	0.20	3047	[3715	0.19	2584	2366	0.14	472	1155
1984	0.12	[3047]	[3715]	0.12			0.09		
1985	0.19	[3047]	[3715]	0.13			0.10		
1986	0.30	[3047]	[3715]	0.19			0.10		
1987	0.36	2685		0.17	1988		0.08		
1988	0.36	[2685]	1203[4]	0.11		1450[4]	0.08		
1989									
1990			1858[3]			1920[3]			1022[3]
1991			1496[3]			1502[3]			1068[3]
1992			978[3]			1227[3]			944[3]

Data Sources:

1. Jacobs Engineering (1989) for data before 1989, Tables 4-5, 4-7, 4-13. PbA values are arithmetic means of lead in air ($\mu g/m^3$), PbS and PbD values not in brackets are geometric means of lead in soil and dust ($\mu g/g$).
2. Jacobs Engineering (1989) for data before 1989. PbS and PbD values in brackets are estimates from Figure 4-16.
3. I. Von Lindern, personal communication. Arithmetic means of dust lead concentrations.
4. Record of Decision, 1991. Tables 5-1, 5-8.

TABLE 5-9. USER-SELECTED ENTRIES FOR IEUBK MODEL WORKSHEET FOR EXAMPLE 5-5, CHILD BORN IN KELLOGG, IDAHO, IN 1983

PARAMETER	YEAR	DEFAULT VALUE	USER SELECTED OPTION	UNITS
DATA ENTRY FOR SOIL (by year)				
Soil lead concentration				μg/g
Age = 0-1 year (0-11 mo)	1983	0	2,584	
1-2 years (12-23 mo)	1984	0	2,434	
2-3 years (24-35 mo)	1985	0	2,284	
3-4 years (36-47 mo)	1986	0	2,134	
4-5 years (48-59 mo)	1987	0	1,984	
5-6 years (60-71 mo)	1988	0	1,834	
6-7 years (72-84 mo)	1989	0	1,834	
DATA ENTRY FOR DUST (by year)				
Dust lead concentration				μg/g
Age = 0-1 year (0-11 mo)	1983	0	2,366	
1-2 years (12-23 mo)	1984	0	2,136	
2-3 years (24-35 mo)	1985	0	1,906	
3-4 years (36-47 mo)	1986	0	1,676	
4-5 years (48-59 mo)	1987	0	1,446	
5-6 years (60-71 mo)	1988	0	1,446	
6-7 years (72-84 mo)	1989	0	1,446	

treated soil and dust lead concentrations as typical values for the community. Model results for the distribution of blood lead concentrations using these inputs would be expected to be more narrow than seen in the actual community due to variability of exposure concentrations within the community.

The dietary lead intake depends on the age of the child and on the year of interest. For a child born in 1983, the dietary lead intake data entry worksheet is shown in Table 5-10, using data from Table 2-1. The two additional dietary exposure scenarios are for children who consume only home-grown vegetables, or only locally-caught fish. From Table 2-3 we calculate a weighted average lead concentration of 5.5 μg/g for leafy and root vegetables grown in Smelterville. The worksheet is shown in Table 5-11. From Table 2-4 we find a

TABLE 5-10. USER-SELECTED ENTRIES FOR IEUBK MODEL WORKSHEET FOR EXAMPLE 5-5, CHILD BORN IN SMELTERVILLE, IN KELLOGG, IDAHO, IN 1983

PARAMETER	DEFAULT VALUE	USER SELECTED OPTION	UNITS
DATA ENTRY FOR DIET (by year)			
Dietary lead intake			
Age = 0-1 year (0-11 mo),	5.53	14.42	μg Pb /day
1-2 years (12-23 mo)	5.78	22.67	
2-3 years (24-35 mo)	6.49	12.34	
3-4 years (36-47 mo)	6.24	9.08	
4-5 years (48-59 mo)	6.01	6.01	
5-6 years (60-71 mo)	6.34	6.34	
6-7 years (72-84 mo)	7.00	7.00	

TABLE 5-11. USER-SELECTED ENTRIES FOR IEUBK MODEL WORKSHEET FOR EXAMPLE 5-5

PARAMETER	DEFAULT VALUE	USER SELECTED OPTION	UNITS
DATA ENTRY FOR ALTERNATE DIET SOURCES (by food class)			
Concentration:			
home-grown fruits	0		μg Pb/g
home-grown vegetables	0	5.5	
fish from fishing	0	0.80	
game animals from hunting	0		
Percent of food class:			
home-grown fruits	0		%
home-grown vegetables	0	36	
fish from fishing	0	50	
game animals from hunting	0		

lead concentration in locally caught fish of 0.80 μg/g, over twice the national average level at that time. The data entry for fish is shown in Table 5-11. The assumed percentages for local vegetables and fish consumption are 36 and 5 percent, respectively.

The results for elevated soil and dust lead plus baseline dietary lead intake show that if locally-grown vegetables and fish are consumed in large amounts, there is a modest increase in blood lead concentration at each age.

We will discuss blood lead estimation for this example in the validation studies that will reported separately from this manual. We have included this example in the Guidance Manual to give the reader some "real world" exposure scenarios and to confront the reader with some of the choices that may need to be made in developing historical exposure scenarios for blood lead studies.

5.3 APPLICATIONS FOR PROBABILITY AND RISK ESTIMATION

EXAMPLE 5-6. Default Parameters

For the default parameters in Example 5-1, the estimated geometric mean blood lead for children of ages 24 to 35 months is 4.2 μg/dL. The user may choose any other age range. If the user next goes into Option 1 from the bottom menu, then "3" from Graphics Selection Menu and selects age range 24-36 months (K), the log-normal probability density should appear on screen. This plot can be printed on a user-specified printer. The user can save the graphics file for additional review using the Multiple Runs Option M with just a single run. No default parameters were changed, except for the GSD, which was changed to 1.42. With GSD = 1.42, there is an estimated 0.68 percent risk that a child with the default exposure scenario will have a blood lead exceeding 10 μg/dL.

A useful alternative display is shown by selecting the Distribution Probability Percent "2" among the plot options. This shows the risk of a blood lead exceedance for any possible blood lead concentration from 0 to 16 μg/dL, not just the level of concern of 10 μg/dL, but the line is too close to zero to be visually distinctive above 12 μg/dL.

EXAMPLE 5-7. Sensitivity of Risk Estimates to User-Selected Geometric Standard Deviation

One way to carry out sensitivity analyses is to carry out each simulation run individually, but to collect the results for different parameters in cumulative output data sets.

The IEUBK model does not currently offer options to do this for any parameters except media concentrations that do not change with age during single simulation run. We will thus fix all of the model parameters at default values, except for the GSD, which in this example will take values from 1.42 to 1.90. After running the model as in the preceding example, we will select "6" in the Graphics Selection Menu. This allows the user to change both the GSD and the blood lead level of concern, while leaving the geometric mean blood lead level at the same value, here 4.2 μg/dL. The results for different GSD values are shown in Table 5-12, for children of ages 24-35 mos.

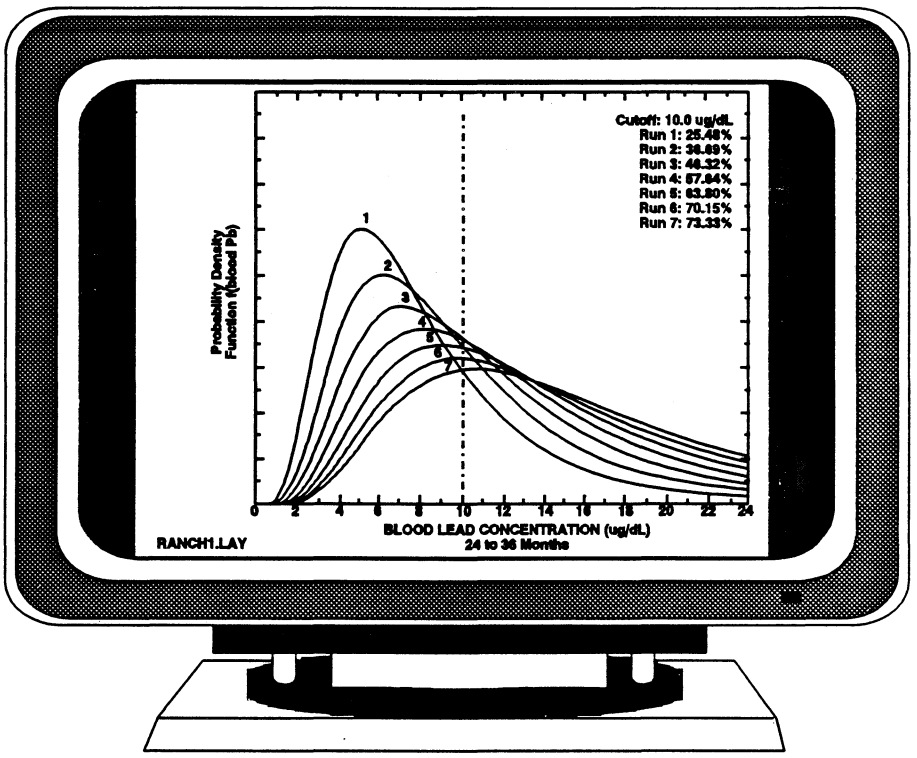
TABLE 5-12. EFFECTS OF GSD ON THE PROBABILITY OF EXCEEDING 10 μg/dL, USING ONLY DEFAULT EXPOSURE PARAMETERS, FOR CHILDREN AGES 24 TO 35 MONTHS

GSD	Probability of Blood Lead > 10 μg/dL
1.42	0.0068
1.50	0.0157
1.60	0.0324
1.70	0.0513
1.80	0.0696
1.90	0.0870

EXAMPLE 5-8. Effects of Dust Lead Concentration on Risk Estimates for Fixed Soil Lead Concentration

In this example, we can use Option "2" on the Computation Menu to assess the effects of different dust lead levels for a fixed soil lead concentration. We will here assume a soil lead concentration of 1,000 μg/g, and dust lead concentrations incremented in the Multiple Runs Analysis. The soil lead concentration is not a default and must be reset to 1,000 μg/g in the Soil/Dust Data Entry Menu (4). We will use 7 levels of dust lead, from 0 to 1,500 μg/g by steps of 250 μg/g. These should be changed in the Multiple Runs Analysis, by entering sub-menus 1 (medium = dust), 2 (range set to 0-1500), and 4 (7 levels of dust, results sent to graphics and results save files). All of the other parameters are set to default values except for a GSD of 1.70 to illustrate the effect of a larger GSD. Selection 3 runs the models.

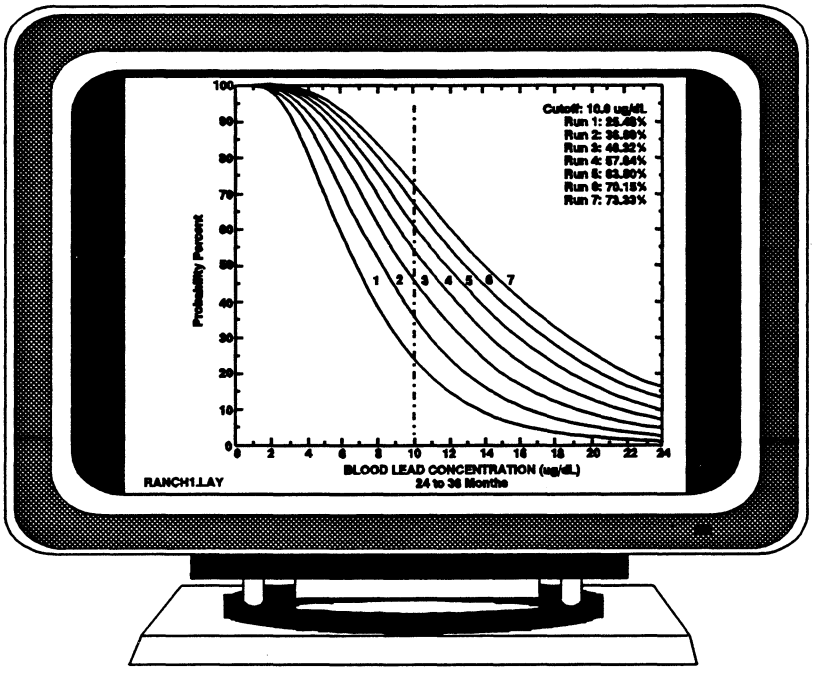
Return to the Output Menu (3), select Plot (2), select Plot Overlay (Density), highlight overlay file, select 24-36 months (K), and the plot will appear on the display. The results are shown in Screen 5-1, which shows the probability density plots for a GSD of 1.70. We are assuming maximum bioavailability (30%). With no lead in dust, the probability that a 2-year-old will exceed 10 μg/dL is estimated as 25 percent. (Run 1), whereas with dust lead concentration of 1,500 μg/g (1.5 times as large as the soil lead concentration) this probability increases to 73 percent. We see that there is substantial sensitivity to the soil-to-dust coefficient and to additional non-soil sources of dust lead in this example.



Screen 5-1. Multiple runs probability density function for soil lead = 1,000 μg/g, dust lead = 0 to 1,500 μg/g, by steps of 250 μg/g (Runs 1 through 7) in Example 5-6.

The cumulative exceedance probability plots (selection 4 in the Graphics Selection Menu) are shown in Screen 5-2. These plots show a clear increase of risk with increasing dust lead level at all blood lead levels of concern, and offer the user a visual display that may help to separate the risk estimates for different dust lead levels.

In order to assess the relationship between geometric mean blood lead and dust lead concentration, the user must set soil lead to 1000 in Option 4 of the Parameter Input Menu

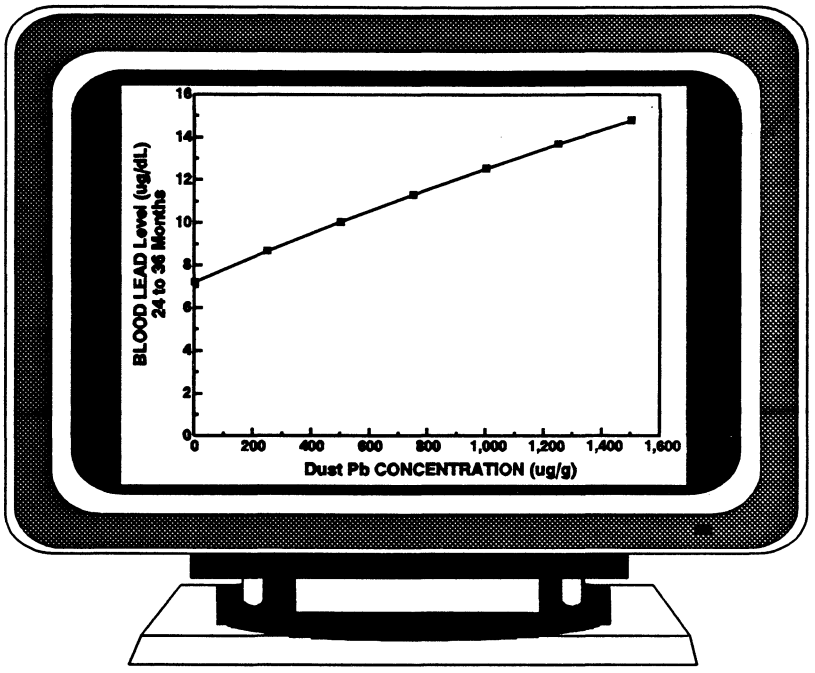


Screen 5-2. Multiple runs probability of exceedance of blood lead levels for soil lead = 1,000 μg/g, dust lead = 0 to 1,500 μg/g, by steps of 250 μg/g (Runs 1 through 7) in Example 5-6.

and then go to Option "2" of the Computation Menu. In Option B, enter sub-menus 1 (medium = dust), 2 (range set to 0-1500), and 4 (7 levels of dust, results sent to graphics and results save files). All of the other parameters are set to default values. Selection 3 runs the models. The results may be plotted immediately, as shown in Screen 5-3, or saved in a *.PBM file for later plotting. Note the slight nonlinearity as dust lead levels exceed 1,000 μg/g, due to saturable absorption effects.

5.4 BATCH MODE INPUT AND STATISTICAL ANALYSES OF OUTPUT

This section demonstrates the use of the batch mode analysis method with input data that are typical of the data available to the user in most environmental lead field studies. Assessment of goodness of fit of predicted and observed blood lead levels (when available) requires a statistical analysis of the data using a variety of mathematical and graphical techniques. Output data from the batch mode runs are in ASCII files that can be loaded into almost any statistical analysis package or spreadsheet program that the user may want to use.



Screen 5-3. Relationship of predicted blood lead to dust lead in Example 5-6.

The IEUBK batch mode output files will require little or no editing before being imported into other programs, unless the missing value code (---) is incompatible with the user's package. We have provided a small special-purpose program called PBSTAT that can be used after the batch mode output file is created, by exiting from the IEUBK model and executing PBSTAT, or by Option "5" in the Batch Mode Menu. PBSTAT is provided as a convenience for the user who may not have or wish to use other programs with the IEUBK output file. The statistical and graphical methods in PBSTAT are demonstrated in the following examples. Additional statistical analyses of the batch mode output data files are not possible using PBSTAT, and must be done with other programs.

EXAMPLE 5-9. Complete Data Set for an Old Mining Community

The input data format for a batch mode input file was described in Section 3.3. The data input file for this example is shown in Table 3-2. This data set was produced by a computer simulation and was edited into the format shown in Table 3-2. These are complete data, i.e., there are no missing values for any of the variables.

Let us suppose that these data represent the data for a sample cohort of children, all of whom were 18 months old at the time of blood lead sampling in late October. Let us assume that the data were collected in the community of "Mountain Pass", an old historic town that has been the site of active lead mining, ore processing, and smelting operations for over 100 years. These operations stopped about 25 years ago, and after a period of declining population the town is once more growing as the center of newly developed tourist and outdoor recreation activities. There is now considerable concern about the potential risk of elevated lead concentrations in soil and in the interior dust of the older houses in Mountain Pass. These children were recruited in the first phase of a long-term prospective study on changes in blood lead concentration in Mountain Pass children during a proposed soil lead abatement project.

The data set contains blood lead concentration in children, soil and dust lead concentration in their houses, in four neighborhoods in Mountain Pass. Air lead concentration were measured by a Total Suspended Particulate (TSP) sampler about ten years ago and were found to be less than 0.2 $\mu g/m^3$, so have not been measured since then. First-draw and partially flushed water lead samples were collected at each house, but have not yet been analyzed. Lead-based paint was measured by a portable X-Ray Fluorescence Spectrophotometer (XRF), but there have been some concerns about the instrument calibration during the unseasonably cold weather in which the measurements were made and the site manager has decided not to use the XRF data until the XRF measurements can be replicated next summer. (Even though this is only a hypothetical example, the reasons why some data may not be available are real, and are all too likely to occur in any real field study). The first model run done by the site manager used this data set "as is", with all of the parameters set to their default values in Table 3-1.

The batch mode run is made from Option 4 in the Computation Menu. The user must identify the input data set, known here as EXAMPLE1.DAT. The user also has the option of renaming the data set before running the batch mode analysis. If the user does not rename the data set, then [name].DAT input file results will be saved in data sets [name].TXT and [name].ASC—in this case, EXAMPLE1.TXT and EXAMPLE1.ASC. The output data file EXAMPLE1.TXT may be viewed from Option "2" of the Batch Mode Menu after the batch run is completed.

Option "5" of the Batch Mode Menu, can be used to examine the differences between observed and predicted blood lead levels using a variety of graphical and statistical techniques. The user must leave the main IEUBK model in order to enter the statistical and

graphical program PBSTAT. Selection 1 in the PBSTAT menu allows the user to load the ASCII file denoted [name].ASC. Selection 2 displays a screen full of statistical information. The information on this screen should be useful for many reports. The table includes the geometric and arithmetic mean blood lead concentrations, as well as the 25th, 50th (median), 75th, and 90th percentiles of observed and predicted blood lead levels. This screen reports paired-sample T-tests for the equality of geometric mean observed and predicted blood lead levels in the neighborhood, which is a test of the equality of the mean logarithms (left side of screen). Tests of the equality of the arithmetic mean blood lead concentration are shown on the right-hand side. You should not expect that the statistical tests will report agreement between observed and predicted values (see Section 1.1.5.3). These tests are used to help diagnose problems.

The two-sample Kolmogorov-Smirnov (denoted K-S) test of the equality of the two distribution functions is also reported. This is based on a very simple statistic, the largest absolute difference between the cumulative distribution of the observed blood lead levels and the cumulative distribution function of the predicted values. We have knowingly violated the assumption that these values are independent, thus the null hypothesis distribution will not give valid significance levels. However, we have found that the K-S statistic, together with the percentiles, provides valuable information about the kinds of discrepancies between the neighborhood-scale blood lead distribution and the distribution of predicted blood lead concentration.

Graphical comparisons of observed and predicted blood lead concentrations are very helpful. If the user exits from the statistics screen and then uses Selection 3 in the PBSTAT selection menu, for graphics and plots, there are a number of choices. Option 1 in the PBSTAT graphics selection menu allows plots of cumulative distribution functions, either singly or combined. Either regular or log-transformed blood lead concentrations may be plotted. The empirical cumulative distribution functions (CDF's) differ substantially. Another useful graphical comparison is in Selection 4 of the Graphing Selection menu, "box and whisker" plots. The boxes show the quartiles of the distribution(s), and the whiskers show the range of non-outlier blood lead concentrations. Outliers, by internal criteria, are shown as isolated data points. Observed and predicted values are highly correlated in the example, as shown by Graphing Selection choice 2. Many other plots may be generated by use of Selection 3.

In this example the model has somewhat over-estimated the observed blood lead concentrations. Any one of several factors could explain the difference between observed

and predicted blood lead concentrations in these children. Are there adequate quality assurance data for both the blood lead and the environmental lead measurements and do they show satisfactory performance during the study? Because the narrative for this scenario stated that blood lead concentrations were collected in late October, which was described as "unseasonably cold", could the children have been spending much less time playing in soils outside? If so, the blood lead data may reflect lower-than-average intake of soil recently, so that the ingestion rates in the model, which are annual averages, are not representative of the atypical conditions under which these blood lead data were collected. Were most of these children placed in some sort of day-care facility? If so, then the children in the day-care facilities could be analyzed as a separate group with appropriate lead concentration data for the facilities. Other possibilities, such as lower bioavailability of soil lead at some houses or in some neighborhoods, should be investigated. In any event, the answers to these questions are going to be found in site-specific data about child behavior, exposure to soil and dust, and on the chemical and physical properties of the soil and dust at the site, and not in further manipulations of model parameters. An analysis of these data, with additional exposure data, is presented as Example 5-11.

EXAMPLE 5-10. Batch Input Data File with Missing Environmental Lead Data

Some environmental data in a data set may be missing because the samples were not collected, were lost or damaged during transportation, storage, and sample preparation for analysis, or were improperly coded and thus not recorded. In any case, the values for missing data in an IEUBK model batch mode input file may be coded by an isolated decimal point where the variable value would otherwise be placed. Examples are given in the data sets EXAMPLE2.DAT and EXAMPLE3.DAT provided on the program disk. Missing values for water lead, air lead, and paint lead are automatically replaced by default values: 4 μg/L for water, 0.1 $\mu g/m^3$ for air, and 0 μg/day for alternative sources. The imputation method for soil and dust lead is different. If soil lead is missing, and dust lead is not missing, then the missing value of soil lead is set to the dust lead value. If dust lead is missing, and soil lead is not missing, then the missing value of dust lead is set to the soil lead value. These cases may be used to estimate or predict blood lead levels. If both soil and dust lead concentrations are missing, then no data are imputed and the blood lead concentration is not calculated for this child. The missing values imputed by the model are earmarked by an asterisk in the [name].TXT output file. The user is responsible for defining an appropriate data imputation process for any site-specific data set that has missing values. The file along with any imputed data should be created before it is submitted to the Batch Mode Option.

One convenient method for imputation of missing dust lead levels is to invoke the Multiple Source menu alternative for dust. The default values in this option (soil-to-dust coefficient of 0.70, air lead contribution of 10 μg/g to house dust) produce a somewhat different set of dust lead estimates and correspondingly different predicted blood lead concentrations.

Note that missing values of blood lead do not affect the prediction of blood lead from environmental lead data, provided that either a soil lead or a dust lead concentration is present, or that the user has imputed values for soil and dust lead calculated by some other method and inserted in place of the missing value.

EXAMPLE 5-11. Lead Exposure in an Old Mining Community Using Site-Specific Information About Ingestion of Soil and Dust

Suppose that the site manager in Example 5-9 has obtained additional information about the children in this sample, and finds that almost all of them have been enrolled in a day care program in this community. Upon visiting the day care facility, the site manager observes that the facility is modern, with easily cleanable floors, entrance surfaces and window sills. She or he observes that the facility appears to be cleaned often, and that the day care facility operators are aware of the hazard of childhood exposure to lead in dust and are making deliberate efforts to reduce the exposure. She or he also learns that most of the children's parents are employed full-time, and that most of these children spend 8 to 10 hours per day at the facility.

Is there now enough information to change the parameters of the IEUBK model so as to possibly provide a closer description of the data? We would not recommend rerunning the IEUBK Model without additional site-specific data. If predicted blood lead concentrations tend to be somewhat larger than those observed, any one or more of the following possibilities could explain the discrepancy:

(i) The soil lead and dust lead concentrations at the day care center may be much lower than the residential lead concentrations, so that a significant part of the child's daily ingestion of soil and dust includes much less lead than if the same quantity were ingested at home;

(ii) The quantity of soil and dust ingested may be smaller than expected because the child spends a great deal of time away from the home in a relatively clean environment, and frequently interacts with adult

caretakers and with other children, thereby reducing both environmental and behavioral magnifiers of soil and dust ingestion;

(iii) The bioavailability of lead in soil and dust at home or elsewhere may be lower than the default values used in the IEUBK Model;

(iv) The children in the sample may represent a non-typical sub-population with respect to ingestion or absorption;

(v) There may be measurement errors in soil lead, dust lead, or blood lead, possibly causing a systematic downward bias in lead measurements.

Any manipulation of the IEUBK Model that reduces lead uptake from a medium would reduce the predicted blood lead concentration and improve the overall fit of the predicted values to the observed values. This does not prove that the manipulation is valid. Lead uptake is the product of ingestion rate and absorption from the medium, so that achieving goodness of fit to the observed values can never prove the correctness of the manipulation of parameters.

We would recommend that some additional site studies be carried out to evaluate these possible causes. These studies include, in the same sequence (i-v):

(i) The soil lead, dust lead, and drinking water lead concentrations at the day care center should be measured;

(ii) The amount of dust in both the residence units and the day care center should be determined by measuring floor dust loadings;

(iii) Methods for child recruitment should be evaluated for possible sampling biases. Socio-demographic factors that may affect soil and dust ingestion should be investigated, including the role of parental awareness and public information programs. Nutritional differences that may affect lead bioavailibility, such as deficiency or repleteness of calcium intake, should be determined where feasible;

(iv) Seasonal biases, biases in sampling locations and in timing of soil and dust sampling studies should be considered as possible measurement errors. QA/QC data for analytical procedures for soil lead, dust lead, blood lead and other media should be reviewed for possible errors, instrument drift or other systematic biases.

For risk assessment applications, it may be preferable to use the default exposure scenario for children who do not spend most of their waking day in a clean environment outside the home. There is no guarantee that other children in this community will not be at

higher risk than the children in the sample. We are not suggesting the use of conservative assumptions about ingestion, but rather, the use of realistic assumptions about a plausible alternative exposure scenario (for example, if the day care facility closes down and is not replaced by a similar facility).

5.5 SOIL LEAD ABATEMENT EXAMPLES

Example 5-12. Use of the Multiple Runs Selection to Estimate Soil Lead Abatement Target Levels when Household Dust is Also Allowed to Vary

One of the more frequent applications of the IEUBK model has been to help determine soil lead concentrations for which abatement may be needed in order to reduce the likelihood of exceeding a blood lead level of concern (LOC) to some user-defined risk of exceedance (ROE) of the LOC at the site. These soil lead target concentrations are site-specific variables and reflect to a greater or lesser degree all of the other parameters that determine childhood blood lead levels after abatement. Effective soil lead abatement will often include household dust abatement, both to remove historical reservoirs of contaminated household dust and to help maintain lower household dust lead concentrations after soil abatement. In this situation, the post-abatement environment must be characterized by a site-specific soil-to-dust coefficient so that the soil lead target concentration is connected to a post-abatement dust lead concentration using the Multiple Source Analysis in the Soil/Dust Data Entry Menu. In this example, we will assume that all of the parameters in the model have been set to default values, but even if the default selections in the Multiple Source Analysis for household dust are invoked, they will not be activated without selecting the Multiple Source option. The following steps are used to illustrate soil target levels for a soil-to-dust coefficient of 0.70 and an air-to-dust coefficient of 100 μg Pb/g dust per μg Pb/m^3 air.

1. From the Main Menu, use Option 1: Parameter Menu, then Option 4: Soil/Dust Data Entry Menu, then tab down to Line 2 (Indoor Dust Pb) and use Option 3: Multiple Source Analysis.

2. The user may select the soil-to-dust coefficient other than 0.70 and the air-to-dust coefficient other than 100, but even if the default values are used the user must enter this menu and then Escape back to the Soil/Dust Entry Menu.

3. Escape (exit) from the Soil/Dust Data Entry Menu to the Parameter Menu, then to the Main Menu. Choose Option 2: Computation Menu, then Option 2: Multiple Runs. This will put the user into the RANGE SELECTION MENU.

4. Set up a range-finding run by using Options 1, 2, and 4 in the Range Selection Menu. In Option 1 (Media), choose Soil and return to the Range Selection Menu. In Option 2 (Range), choose Start = 0 (0 μg/g soil lead) and End = 1500 (1500 μg/g soil lead) and return to the Range Selection Menu. In Option 4 (Output Choices), respond "Yes" to the query "Send to Overlay File", respond "7" to the query "Number of Runs for Range". This will produce output runs at 7 equally spaced levels of soil lead from 0 to 1500 μg/g, namely at 0, 250, 500, 750, 1000, 1250, and 1500 μg/g. The user who is not familiar with this option may also wish to respond "Yes" to the query "Display summary outputs". Return to the Range Selection Menu.

5. Run the Multiple Runs Analysis by selecting Option 3 on the Range Selection Menu. The user should see the message that the data sets RANGE#.LAY and RANGE#.TXT have been saved. The data set RANGE#.LAY is needed to obtain the probability plot values. The data set RANGE#.TXT is needed to document the input parameters for the run.

6. In order evaluate the range-finding runs, exit from the Range Selection Menu to the Computation Menu, then to the Main Menu. Select Option 3: Output Menu, then Option 2: Plot menu, then select the GSD and the blood lead level of concern (LOC). The default values GSD = 1.60 and LOC = 10 μg/dl are used here, so no selection is necessary; otherwise, use Option 6. Then use Option 5: Plot Overlay File (probability density functions). Tab down and select the appropriate RANGE#.LAY file, then select the age range "H", ages 0-84 months, or any other range, as needed. The probability of exceeding blood lead 10 μg/dL for each soil lead concentration from 0 to 1500 μg/g by steps of 250 μg/g is shown in Table 5-13.

TABLE 5-13. RANGE FINDING RUN FOR TARGET SOIL LEAD CONCENTRATION

OVERLAY PLOT	SOIL LEAD CONCENTRATION (μg/g)	PROBABILITY OF EXCEEDING 10 μg/dL, percent
1	0	0.00
2	250	1.99
3	500	12.03
4	750	26.86
5	1000	42.68
6	1250	55.50
7	1500	64.01

7. As a result of the range-finding runs shown in Table 5-13, the soil lead target concentration is between 250 μg/g (ROE = 1.99 %) and 500 μg/g(ROE = 12.03%). In order to narrow the list of possible values, repeat steps 4, 5, and 6 with a smaller range of values. We selected Start = 320 μg/g and End = 420 μg/g in Option 2 (Range) of the Range Selection Menu, and selected 6 runs in Option 4 of the Range Selection menu. Run the Multiple Runs Analysis with Option 3. This produces an output data set RANGE#+1.LAY. Plot the results in RANGE#+1.LAY for soil lead concentrations of 320, 340, 360, 380, 400, and 420 μg/g. The results are shown in Table 5-14.

TABLE 5-14. FOCUSED RUN FOR TARGET SOIL LEAD CONCENTRATION

OVERLAY PLOT	SOIL LEAD CONCENTRATION (μg/g)	PROBABILITY OF EXCEEDING 10 μg/dL, percent
1	320	3.24
2	340	3.45
3	360	3.90
4	380	4.15
5	400	4.70
6	420	5.00

8. Table 5-14 shows that the highest value of 420 μg/g appears to produce ROE = 5.00%. To confirm this, repeat Step 7 with a much smaller range of values. We selected Start = 400 μg/g and End = 430 μg/g in Option 2 (Range) of the Range Selection Menu, and selected 4 runs in Option 4 of the Range Selection menu. Run the Multiple Runs Analysis with Option 3. This produces an output data set RANGE#+2.LAY. Plot the results in RANGE#+2.LAY for soil lead concentrations of 400, 410, 420, and 430 μg/g. The results are shown in Table 5-15. **This procedure has identified a soil lead concentration of 410 μg/g as the target level.**

TABLE 5-15. VERIFICATION RUN FOR TARGET SOIL LEAD CONCENTRATION

OVERLAY PLOT	SOIL LEAD CONCENTRATION (μg/g)	PROBABILITY OF EXCEEDING 10 μg/dL, percent	DUST LEAD CONCENTRATION (μg/g)
1	400	4.70	290
2	410	5.00	297
3	420	5.00	304
4	430	5.32	311

9. The user may wish to view the dust lead concentrations corresponding to this procedure. In order to view RANGE#+2.TXT, return to the Main Menu, then the Computation Menu and select Option 4: Batch Mode. Select Batch Mode Option 2: View TXT File, the RANGE#+2.TXT. The dust lead concentrations are shown in the last column of Table 5-15.

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APPENDIX A: HOW TO CALCULATE THE GEOMETRIC STANDARD DEVIATION FROM BLOOD LEAD DATA, IF YOU MUST

A.1 A DIRECT METHOD FOR CALCULATING THE GEOMETRIC STANDARD DEVIATION

One of the simplest approaches to calculating a GSD from a sample of blood lead and environmental lead data is based on the idea that children with similar environmental lead exposures will have similar geometric mean blood lead levels. For children of a given age with similar soil lead (denoted PbS), dust lead (denoted PbD), and other lead exposures, we can reasonably characterize the variability in blood lead level (denoted GSD) calculated with respect to the actual geometric mean blood lead level of this group of children (denoted GMB) without modelling blood lead levels. The procedure shown here is the simplest procedure we have found, but even with this procedure, the user must be prepared to do a great deal of statistical calculation. We will illustrate how an empirical GSD may be calculated from data after we describe the procedure:

STEP 1: Divide the data set into subgroups, where each group has children of a given age, with soil lead levels in a given interval, dust lead levels in a given interval, and with distinct levels of other important variables. Each such group corresponds to a "box" or cell of soil and dust lead levels, and levels of other variables if used.

STEP 2: From each individual blood lead (denoted PbB) in each cell, calculate ln(PbB), where ln denotes the natural logarithm.

STEP 3: Within each cell, calculate the mean and the standard deviation of the ln(PbB) values. Then, for that cell,

GMB = exp(mean of ln(PbB) values within the cell)
GSD = exp(standard deviation of ln(PbB) values within the cell)

where exp denotes the process of calculating the exponential function of the indicated quantity. Exponential and natural logarithm functions are available in most statistical packages for microcomputers and on most scientific calculators.

STEP 4: Calculate the inter-individual GSD for this neighborhood by finding the median or middle value of the GSD values in the sample. The median is found by ordering the GSD values from all cells from smallest to

largest. If the number of GSD values is odd, the median is the middle value; if sample size is an even number, find the average of the two middle values. Since the number of observations in each box or cell is different, each GSD should be counted a number of times according to the number of degrees of freedom (cell count minus one) for that GSD.

STEP 5: Users with some statistical background may wish to examine the within-cell GSD's for patterns based on the data, such as by plotting GSD against GMB or against the within-cell value of age, PbS, PbD, or other stratifying variables.

STEP 6: Users with more statistical background may wish to use other approaches to calculating a "typical" GSD, such as by calculating a mean or pooled variance of the within-cell variances of ln(PbB). We would caution such users that the data should be carefully evaluated for outliers, either in raw PbB values or in the calculated GSD. One convenient approach for visual detection of outliers is a normal probability of within-cell variances after a variance-stabilizing transformation such as the cube root of the within-cell variance of ln(PbB).

EXAMPLE: In a sample of 166 children from the Midvale, Utah study of 1989 (Bornschein et al., 1990), we found that the estimation of blood lead levels could be considerably improved by determining whether or not the children lived in houses in which paint had recently been removed. There is substantial evidence that inadequately controlled lead paint abatement may increase blood levels in resident young children by 2 to 4 ug/dL on average in the first 6 to 12 months after paint removal (Rabinowitz et al., 1984; Marcus et al., 1991; Menton et al., 1993). Interviews with the family provided such information for 162 of the 166 children, which was used as an additional stratifying variable.

The worksheet for determining subgroups are shown in Table A-1. Each table gives the blood leads of children of a given age, divided by whether or not there was recent paint removal in the residence. Within each table, the children are divided according as the PbS and PbD values at their residence. Each cell in the table corresponds to intervals of 250 ppm of PbS and 250 ppm of PbD. The soil lead levels were averages of non-missing values of perimeter, bare area, play area, and garden soils. It should be noted that data for most of the cells are not available with such detailed sub-division of the data set, and that at higher soil and dust lead concentrations, there is usually only one observation per cell. There was only one case in which two children from the same family had the same age, in years, and analyses without this duplication would produce very similar results. Otherwise, all blood lead levels (denoted PbB) within each cell come from different families. This is believed to

TABLE A-1. CELLS OF BLOOD LEAD LEVELS IN 165 MIDVALE CHILDREN, BY PAINT REMOVAL STATUS, AGE, AND INTERVALS OF 250 μg/g IN SOIL AND DUST LEAD[1]

Paint Removal	Age	Soil Pb	Dust Pb	Blood Lead (μg/dL) Smallest →→Largest					
.	0	375	375	5.5	.	.	.	.	.
.	2	.	625	6.	.	.	.	.	.
.	2	375	125	4.	.	.	.	.	.
.	3	625	625	3.	.	.	.	.	.
.	4	125	125	6.5	.	.	.	.	.
0	0	125	.	3.	6.	.	.	.	.
0	0	125	125	1.	.	.	.	.	.
0	0	125	375	0.5	.	.	.	.	.
0	0	375	125	3.	4.5	.	.	.	.
0	0	375	375	5.5	.	.	.	.	.
0	0	375	1125	3.	7.	.	.	.	.
0	0	375	1375	3.5	.	.	.	.	.
0	0	1125	875	13.5	.	.	.	.	.
0	1	.	625	5.5	.	.	.	.	.
0	1	125	375	2.5	3.	.	.	.	.
0	1	375	375	4.	5.5	7.	.	.	.
0	1	375	625	4.5	.	.	.	.	.
0	1	375	875	3.5	.	.	.	.	.
0	1	625	375	3.	7.	8.	10.	.	.
0	1	625	625	3.5	6.	6.	.	.	.
0	1	875	625	3.	.	.	.	.	.
0	1	875	1125	6.	.	.	.	.	.
0	1	1125	875	1.	10.5	.	.	.	.
0	1	1375	1125	6.	.	.	.	.	.
0	1	1625	625	3.	.	.	.	.	.
0	2	.	375	4.	6.	.	.	.	.

TABLE A-1 (cont'd). CELLS OF BLOOD LEAD LEVELS IN 165 MIDVALE CHILDREN, BY PAINT REMOVAL STATUS, AGE, AND INTERVALS OF 250 μg/g IN SOIL AND DUST LEAD[1]

Paint Removal	Age	Soil Pb	Dust Pb	Blood Lead (μg/dL) Smallest →→Largest					
0	2	.	625	7.	.	.	.	.	.
0	2	125	.	5.	.	.	.	.	.
0	2	125	125	2.5	5.5	5.5	8.	12.	.
0	2	125	625	6.	.	.	.	.	.
0	2	375	375	1.5	.	.	.	.	.
0	2	375	1125	4.5	.	.	.	.	.
0	2	625	375	14.5	.	.	.	.	.
0	2	625	625	4.	7.	11.5	.	.	.
0	2	875	1125	5.5	.	.	.	.	.
0	2	1125	.	13.	.	.	.	.	.
0	2	1125	625	9.5	.	.	.	.	.
0	2	1125	875	19.	.	.	.	.	.
0	3	.	625	5.	.	.	.	.	.
0	3	125	125	2.5	.	.	.	.	.
0	3	125	375	2.	7.5	.	.	.	.
0	3	375	125	6.5	.	.	.	.	.
0	3	375	375	3.	4.	.	.	.	.
0	3	375	1375	13.	.	.	.	.	.
0	3	1125	625	16.5	.	.	.	.	.
0	3	1375	1125	5.	.	.	.	.	.
0	4	.	375	2.	.	.	.	.	.
0	4	125	125	4.	7.5	.	.	.	.
0	4	125	375	5.5	6.	.	.	.	.
0	4	375	.	2.	.	.	.	.	.
0	4	375	625	1.5	7.	.	.	.	.

TABLE A-1 (cont'd). CELLS OF BLOOD LEAD LEVELS IN 165 MIDVALE CHILDREN, BY PAINT REMOVAL STATUS, AGE, AND INTERVALS OF 250 μg/g IN SOIL AND DUST LEAD[1]

Paint Removal	Age	Soil Pb	Dust Pb	Blood Lead (μg/dL) Smallest →→Largest					
0	4	625	375	5.	.	.	.	.	.
0	4	875	625	7.5	.	.	.	.	.
0	4	1125	2375	5.	.	.	.	.	.
0	4	2125	875	8.	.	.	.	.	.
0	5	125	125	2.	4.5	8.5	.	.	.
0	5	125	375	2.5	3.5	10.	.	.	.
0	5	375	375	4.	6.	.	.	.	.
0	5	625	375	5.	.	.	.	.	.
0	5	625	625	4.	.	.	.	.	.
0	5	625	1375	4.5	.	.	.	.	.
0	5	1125	875	13.5	.	.	.	.	.
1	0	125	125	3.	16.5	.	.	.	.
1	0	125	375	0.5	1.5	3.5	5..	6.	.
1	0	375	375	8.5	.	.	.	.	.
1	0	375	875	5.	.	.	.	.	.
1	1	.	375	8.	22.5	.	.	.	.
1	1	125	125	5.5	.	.	.	.	.
1	1	125	375	5.5	.	.	.	.	.
1	1	375	375	3.5	.	.	.	.	.
1	1	375	625	5.5	.	.	.	.	.
1	1	375	875	16.5	.	.	.	.	.
1	1	625	125	2.5	.	.	.	.	.
1	1	625	375	9.	9.	.	.	.	.
1	1	875	625	6.	.	.	.	.	.
1	1	1125	1375	5.5	.	.	.	.	.

TABLE A-1 (cont'd). CELLS OF BLOOD LEAD LEVELS IN 165 MIDVALE CHILDREN, BY PAINT REMOVAL STATUS, AGE, AND INTERVALS OF 250 μg/g IN SOIL AND DUST LEAD[1]

Paint Removal	Age	Soil Pb	Dust Pb	Blood Lead (μg/dL) Smallest →→Largest					
1	2	.	.	8.5	.	.	.	.	
1	2	125	125	3.	4.	4.5	5.5	.	.
1	2	125	375	2.5	3.5	5.	5.	5.5	19.5
1	2	375	.	6.	.	.	.	.	.
1	2	375	375	3.	10.	.	.	.	.
1	2	375	625	8.5	.	.	.	.	.
1	2	625	625	6.5	.	.	.	.	.
1	2	1875	625	10.5	.	.	.	.	.
1	3	.	.	8.5	.	.	.	.	.
1	3	.	625	4.	.	.	.	.	.
1	3	125	375	4.5	.	.	.	.	.
1	3	375	625	5.5	5.5	8.	.	.	.
1	3	375	875	4.	.	.	.	.	.
1	3	625	875	2.	.	.	.	.	.
1	3	875	3625	2.	.	.	.	.	.
1	3	1625	1375	15.5	.	.	.	.	.
1	3	1875	625	7.5	.	.	.	.	.
1	4	.	375	3.5	18.	.	.	.	.
1	4	.	625	3.5	.	.	.	.	.
1	4	125	125	4.5	5.	5.	5.	5.	.
1	4	125	375	2.	3.5	4.	8.	.	.
1	4	375	.	7.	.	.	.	.	.
1	4	875	625	9.	.	.	.	.	.
1	4	875	1125	7.5	.	.	.	.	.
1	4	1625	1375	9.5	.	.	.	.	.

TABLE A-1 (cont'd). CELLS OF BLOOD LEAD LEVELS IN 165 MIDVALE CHILDREN, BY PAINT REMOVAL STATUS, AGE, AND INTERVALS OF 250 μg/g IN SOIL AND DUST LEAD[1]

Paint Removal	Age	Soil Pb	Dust Pb	Blood Lead (μg/dL) Smallest →→Largest					
1	4	3125	1625	13.	.	.	.	.	.
1	5	.	.	4.5	.	.	.	.	.
1	5	125	125	4.	5.	.	.	.	.
1	5	125	375	4.	7.5	.	.	.	.
1	5	375	375	1.5	.	.	.	.	.
1	5	625	375	6.5	.	.	.	.	.
1	5	1875	625	5.5	.	.	.	.	.

[1]An isolated decimal point denotes a missing value.

give a much more valid estimate of variability than within-family GSD's for children of different ages, but similar genetic and non-lead environmental factors and similar family behavior patterns.

The statistics for GMB and GSD were calculated as described in Step 3, for each cell where enough data were available (at least 2 PbB values in order to calculate GSD). The results are shown in Table A-2. The PbS and PbD values are the cell midpoints, and provide convenient plot points. Some of the GSD values are very high, as for the cell whose two values are PbB = 1.5 and 10 μg/dL.

The distribution of GSD values for all cells is shown in Table A-3, in the form of a "stem-and-leaf" plot (Tukey, 1977). No weighting scheme has been applied. Many users would prefer a weighted GSD where the number of observations in each cell is taken into account. This can be done by counting each GSD estimate as representing the number of degrees of freedom (denoted DF) in the GSD estimate. In this application, DF = N − 1, where N is the number of PbB values in the cell. A DF-weighted stem-and-leaf plot is shown in Table A-4. In the unweighted case, the median GSD = 1.694 may be taken as a representative value for this community. In the weighted DF case, a somewhat larger median GSD = 1.768 may be used.

TABLE A-2. GEOMETRIC MEAN AND GEOMETRIC STANDARD DEVIATION OF BLOOD LEADS IN CELLS OR GROUPS, BY PAINT REMOVAL STATUS, AGE, AND INTERVALS OF 250 μg/g IN SOIL AND DUST LEAD[1]

Paint Removal	Age (Years)	Soil Lead (μg/g)	Dust Lead (μg/g)	N	Geometric Mean Blood Lead (μg/dL)	GSD
.	0	375	375	1	5.5	.
.	2	.	625	1	6.	.
.	2	375	125	1	4.	.
.	3	625	625	1	3.	.
.	4	125	125	1	6.5	.
0	0	125	.	2	4.243	1.633
0	0	125	125	1	1.	.
0	0	125	375	1	0.5	.
0	0	375	125	2	3.674	1.332
0	0	375	375	1	5.5	.
0	0	375	1125	2	4.583	1.821
0	0	375	1375	1	3.5	.
0	0	1125	875	1	13.5	.
0	1	.	625	1	5.5	.
0	1	125	375	2	2.739	1.138
0	1	375	375	3	5.360	1.324
0	1	375	625	1	4.5	.
0	1	375	875	1	3.5	.
0	1	625	375	4	6.402	1.693
0	1	625	625	3	5.013	1.365
0	1	875	625	1	3.	.
0	1	875	1125	1	6.	.
0	1	1125	875	2	3.240	5.273
0	1	1375	1125	1	6.	.

TABLE A-2 (cont'd). GEOMETRIC MEAN AND GEOMETRIC STANDARD DEVIATION OF BLOOD LEADS IN CELLS OR GROUPS, BY PAINT REMOVAL STATUS, AGE, AND INTERVALS OF 250 μg/g IN SOIL AND DUST LEAD[1]

Paint Removal	Age (Years)	Soil Lead (μg/g)	Dust Lead (μg/g)	N	Geometric Mean Blood Lead (μg/dL)	GSD
0	1	1625	625	1	3.	.
0	2	.	375	2	4.899	1.332
0	2	.	625	1	7.	.
0	2	125	.	1	5.	.
0	2	125	125	5	5.055	2.013
0	2	125	625	1	6.	.
0	2	375	375	1	1.5	.
0	2	375	1125	1	4.5	.
0	2	625	375	1	14.5	.
0	2	625	625	3	6.854	1.696
0	2	875	1125	1	5.5	.
0	2	1125	.	1	13.	.
0	2	1125	625	1	9.5	.
0	2	1125	875	1	19.	.
0	3	.	625	1	5.	.
0	3	125	125	1	2.5	.
0	3	125	375	2	3.873	2.546
0	3	375	125	1	6.5	.
0	3	375	375	3	4.762	1.768
0	3	375	1375	1	13.	.
0	3	1125	625	1	16.5	.
0	3	1375	1125	1	5.	.
0	4	.	375	1	2.	.

TABLE A-2 (cont'd). GEOMETRIC MEAN AND GEOMETRIC STANDARD DEVIATION OF BLOOD LEADS IN CELLS OR GROUPS, BY PAINT REMOVAL STATUS, AGE, AND INTERVALS OF 250 μg/g IN SOIL AND DUST LEAD[1]

Paint Removal	Age (Years)	Soil Lead (μg/g)	Dust Lead (μg/g)	N	Geometric Mean Blood Lead (μg/dL)	GSD
0	4	125	125	2	5.477	1.560
0	4	125	375	2	5.745	1.063
0	4	375	.	1	2.	.
0	4	375	625	2	3.240	2.972
0	4	625	375	1	5.	.
0	4	875	625	1	7.5	.
0	4	1125	2375	1	5.	.
0	4	2125	875	1	8.	.
0	5	125	125	3	4.245	2.065
0	5	125	375	3	4.440	2.061
0	5	375	375	2	4.899	1.332
0	5	625	375	1	5.	.
0	5	625	625	1	4.	.
0	5	625	1375	1	4.5	.
0	5	1125	875	1	13.5	.
1	0	125	125	2	3.	16.5
1	0	125	375	5	0.5	1.5
1	0	375	375	1	8.5	.
1	0	375	875	1	5.	.
1	1	.	375	2	8.	22.5
1	1	125	125	1	5.5	.
1	1	125	375	1	5.5	.
1	1	375	375	1	3.5	.

TABLE A-2 (cont'd). GEOMETRIC MEAN AND GEOMETRIC STANDARD DEVIATION OF BLOOD LEADS IN CELLS OR GROUPS, BY PAINT REMOVAL STATUS, AGE, AND INTERVALS OF 250 μg/g IN SOIL AND DUST LEAD[1]

Paint Removal	Age (Years)	Soil Lead (μg/g)	Dust Lead (μg/g)	N	Geometric Mean Blood Lead (μg/dL)	GSD
1	1	375	625	1	5.5	.
1	1	375	875	1	16.5	.
1	1	625	125	1	2.5	.
1	1	625	375	1	9.	9.
1	1	875	625	2	6.	.
1	1	1125	1375	1	5.5	.
1	2	.	.	1	8.5	.
1	2	125	125	4	3.	4.
1	2	125	375	6	2.5	3.5
1	2	375	.	1	6.	.
1	2	375	375	2	3.	10.
1	2	375	625	1	8.5	.
1	2	625	625	1	6.5	.
1	2	1875	625	1	10.5	.
1	3	.	.	1	8.5	.
1	3	.	625	1	4.	.
1	3	125	375	1	4.5	.
1	3	375	625	3	5.5	5.5
1	3	375	875	1	4.	.
1	3	625	875	1	2.	.
1	3	875	3625	1	2.	.
1	3	1625	1375	1	15.5	.
1	3	1875	625	1	7.5	.

TABLE A-2 (cont'd). GEOMETRIC MEAN AND GEOMETRIC STANDARD DEVIATION OF BLOOD LEADS IN CELLS OR GROUPS, BY PAINT REMOVAL STATUS, AGE, AND INTERVALS OF 250 μg/g IN SOIL AND DUST LEAD[1]

Paint Removal	Age (Years)	Soil Lead (μg/g)	Dust Lead (μg/g)	N	Geometric Mean Blood Lead (μg/dL)	GSD
1	4	.	375	2	3.5	18.
1	4	.	625	1	3.5	.
1	4	125	125	5	4.5	5.
1	4	125	375	4	2.	3.5
1	4	375	.	1	7.	.
1	4	875	625	1	9.	.
1	4	875	1125	1	7.5	.
1	4	1625	1375	1	9.5	.
1	4	3125	1625	1	13.	.
1	5	.	.	1	4.5	.
1	5	125	125	2	4.	5.
1	5	125	375	2	4.	7.5
1	5	375	375	1	1.5	.
1	5	625	375	1	6.5	.
1	5	1875	625	1	5.5	.

A.2 A MORE SOPHISTICATED STATISTICAL METHOD FOR ESTIMATING THE GEOMETRIC STANDARD DEVIATION

The GSD actually represents the residual variability in the logarithm of the predicted blood lead level. A direct regression method that is an overly simplified approximation to the IEUBK model at steady state exposure may be useful in deriving a residual GSD from a blood lead and environmental lead study. The method is based on the concepts that: (1) the IEUBK model at low to moderate steady-state exposure yields predicted blood leads that are

TABLE A-3. STEM AND LEAF PLOT OF GEOMETRIC STANDARD DEVIATION FOR MIDVALE CHILDREN[1,2]

MINIMUM:	1.048	
LOWER QUARTILE:	1.332	
MEDIAN:	1.694	
UPPER QUARTILE:	2.071	
MAXIMUM:	5.273	
1		0011
1	H	22333333
1		55
1	M	6667
1		88
2	H	00000
2		3
2		5
2		7
2		9
OUTSIDE VALUES		
3		13
5		2

[1]N = 32 groups, unweighted.
[2]76 groups with missing values excluded from plot.

approximately linear functions of PbS and PbD, with age-dependent regression coefficients; (2) the linear model should be fitted in a logarithmic form so as to estimate relative variability. In order to use the model, it is necessary to create indicator variables for the age of the child in the study. These are:

TABLE A-4. STEM AND LEAF PLOT OF GEOMETRIC STANDARD DEVIATION FOR MIDVALE CHILDREN[1] (Weighted by Degrees of Freedom)

MINIMUM:	1.048	
LOWER QUARTILE:	1.332	
MEDIAN:	1.768	
UPPER QUARTILE:	2.061	
MAXIMUM:	5.273	
1		0000011
1	H	2222233333333
1		55
1	M	66666677
1		8888
2	H	00000000000000
2		3
2		5
2		7777
2		9
OUTSIDE VALUES		
3		13
5		2

[1]N = 58 groups, weighted by degrees of freedom.

AGE0 = 1 if the child is age 0 to 11 months; AGE0 = 0 if not;
AGE1 = 1 if the child is age 12 to 23 months; AGE1 = 0 if not;
AGE2 = 1 if the child is age 24 to 35 months; AGE2 = 0 if not;
AGE3 = 1 if the child is age 36 to 47 months; AGE3 = 0 if not;
AGE4 = 1 if the child is age 48 to 59 months; AGE4 = 0 if not;

AGE6 = 1 if the child is age 72 to 83 months; AGE6 = 0 if not;

and so on. Then the model that may be fitted, using all of the children in the data set for which observed or imputed PbS and PbD values are available, using a nonlinear regression program for parameter estimation, is given by

$$\begin{aligned}\ln(PbB) = \ln(&A0*AGE0 + A1*AGE1 + A2*AGE2 + A3*AGE3 + \ldots \\ &+ PbS * (B0*AGE0 + B1*AGE1 + B2*AGE2 + B3*AGE3 + \ldots) + \\ &+ PbD * (C0*AGE0 + C1*AGE1 + C2*AGE2 + C3*AGE3 + \ldots) + \\ &+ X * (D0*AGE0 + D1*AGE1 + D2*AGE2 + D3*AGE3 + \ldots))\end{aligned}$$

Here, X represents other predictive covariates for blood lead. In the Midvale example, X = RMVPAINT = 1 if paint has recently been removed from the premises, and X = 0 if not. In other applications, it may be useful to use water lead or air lead levels as an additional predictor. X may be omitted if necessary. In many applications, the regression parameters may be set equal for some ages. For example, if blood leads stabilize for ages 3 to 5 years, we may set A3 = A4 = A5, B3 = B4 = B5, C3 = C4 = C5, etc. Since the age-dependence of soil and dust lead exposure may differ somewhat from one site to another, depending on climate or other factors, no general prescription for how to carry out such analyses may be given.

When a non-linear regression model is fitted to the data by use of a program that estimates non-linear parameters, it is then possible to calculate the residual standard deviation S for the model, so that

S = standard deviation of ln(observed PbB / predicted PbB)

GSD = exp(S).

For the Midvale example described in this Appendix, we find that for N = 143 children with no missing data for PbD, PbS, or RMVPAINT, S = 0.5701 on the natural log scale, thus GSD = 1.768. The approximate relative standard error of S^2 is $(2 / (N - p))^{0.5}$, where p is the number of nonlinear parameters estimated from the data. With p = 12 parameters (ages 2 to 5 years were grouped), we have $(2 / (143 - 12))^{0.5} = 0.1236$ relative standard deviation for the variance. An approximate 95% confidence interval for the true value of S^2 has a lower bound $(1 - 2 * (2 / (N - p))^{0.5})$, and an upper bound $(1 + 2 * (2 / (N - p))^{0.5})$, times S^2. For Midvale, the limits are

$$(1 - 2 * 0.1236) * (0.5701)^2 = 0.2447$$

$$(1 + 2 * 0.1236) * (0.5701)^2 = 0.4053$$

Thus the lower and upper bounds for S are 0.4947 to 0.6366, and for GSD = exp(S) the confidence limits are 1.640 to 1.890.

APPENDIX B: SUMMARY OF REVISIONS TO LEAD UPTAKE BIOKINETIC MODEL SOFTWARE VERSIONS

TABLE B-1. SUMMARY OF REVISIONS TO LEAD UPTAKE/BIOKINETIC MODEL SOFTWARE FROM LEAD 0.2 TO LEAD 0.4

Item	Lead 0.2 (September, 1989)	Lead 0.4 (September, 1990)
GI-tract absorption model	Default is linear "passive" model.	Default is non-linear "active-passive" model
Drinking water defaults	Composite = 9 μg/L First flush = 0 μg/L Flushed = 9 μg/L Fountain = 0 μg/L % First flush = 0 % Flushed = 0 % Fountain = 0	Composite = 4 μg/L First flush = 4 μg/L Flushed = 1 μg/L Fountain = 10 μg/L % First flush = 50 % Flushed = 35% % Fountain = 15% (New defaults were provided EPA/ODW)
Diet defaults	Dietary lead intakes are based on FDA surveys completed in 1986. Default values range from 22-34 μg/day for ages 0-7.	Dietary lead intakes are based on FDA surveys completed in 1988. Default values range from 5.8-7.5 μg/day for ages 0-7.
Probability density function	P(x) = (1/(2.51)(GSD))¡ exp((-1/2)((lnx-lnGM)/ lnGS D)2)	P(x) = (1/(2.51)(x)(lnGSD))¡ exp((-1/2)((lnx-lnGM)/ lnGSD)2)
Plot of probability density function	Ordinate of "Bell-shaped plot" labelled "probability".	Ordinate of "bell-shaped plot" labelled "probability density function f(blood lead)" numbers removed from ordinate. Probability is computed as the integral of this function over a specified ranged. This is graphically illustrated in the "S-shaped" probability percent plot.
Calculation of blood lead in newborn (BPbn)	Fixed at 6.4 μg/dL: BPbn=BPbm ¡ k, where BPbm is the maternal blood lead (7.5 μg/dL) and k is a constant (0.85).	User option: 1) As in Lead 0.2 and option to select maternal blood lead. 2) "Fetal" model, in which maternal blood lead is calculated based on user-defined exposure data and a maternal biokinetic model, and newborn blood lead is calculated from biokinetic model.
Soil/Dust primary data entry screen	Menu includes "Change GI Absorption Method"	Menu revised to "Change GI Method/Bioavailability". If "yes" is selected, a window containing the following message appears over the secondary data entry screen: "Bioavailability of soil lead may vary depending on the lead source. For example, lead from mine wastes may have a lower bioavailability than lead from smelters. Differences in bioavailability are thought to reflect differences in gastrointestinal absorption of specific lead species and particle sizes, which vary depending on the source. The following data entry screen allows the user to make adjustments in the gastrointestinal absorption coefficients to account for site-specific information on bioavailability.

TABLE B-2. SUMMARY OF REVISIONS TO LEAD UPTAKE BIOKINETIC MODEL SOFTWARE FROM LEAD 0.4 TO LEAD 0.5

Parameter or Feature	Lead 0.4 (September, 1990)	Lead 0.5 (December, 1990)
(Non-linear GI Absorption Model	Volume of GI-tract calculated, VGI = (VGI)/(GF); where VGI is the adult GI-tract volume (liters) and GF is the age-dependent allometric scaling factor (GF < 1 for children). Default value for Km, 100 μg/L.	Volume of GI-tract calculated, VGI = (VGI)(GF). Default value for Km, 100 mg/L.
Age Range Selection	Menu specified selection.	User designated option allows user to specify any designed age range from 1-7 years.
Multiple Runs	Multiple model runs are made manually; i.e., the user specifies input for each run, and saves output in Results Out file.	Allows user to input a range of lead values for one medium (air, diet, drinking water, dust or soil), and make a series of model runs in which lead levels in the specified medium are varied over the specified range.
X-axis Scaling	Set by program.	Allows user to set scaling of X-axis of probability density function and probability percent graphs manually.
Overlay Graph Files	Not available; graphs of individual model runs can be displayed and/or printed.	Allows user to save graph output (i.e., probability density function or probability percent graphs) from multiple runs to an file and print output of multiple runs on a single graph.
Text Files	Data from individual model runs can be saved to a file.	Allows user to save the data output of individual or multiple model runs, in user specified ASCI text files; these files can be reviewed and printed in Lead and/or imported into a word or processing program after exiting from Lead.
Blood vs. Media Concentration: Model Runs (Graph Output)	Not available.	Allows user to input a range of lead values for one primary medium (air, diet, drinking water, dust or soil), and produce a series of model runs in which lead levels in the specified medium are varied over the specified range. The output of each run is captured in an X-Y plot of mean blood lead vs. medium lead.
Blood vs. Media Concentration: Find	Not available.	Calculates a lead level in the user-specified medium that is associated with a specified mean blood lead.

TABLE B-3. SUMMARY OF REVISIONS TO LEAD UPTAKE BIOKINETIC MODEL SOFTWARE FROM LEAD 0.5 TO LEAD 0.99d

Parameter or Feature	Lead 0.5 (December, 1990)	Lead 0.99d (January, 1994)
Batch Mode Model Runs	Not available.	Accepts a properly formatted ASCII text file (*.DAT) containing data on lead exposure and blood lead levels for a sample population, and calculates predicted blood lead levels for each individual. The output is saved as a *.TXT file that can be viewed within Lead or imported into a text editor (e.g., word processor), and as a *.ASC file that can be imported into PBSTAT for selected statistical analysis and graphic display.
PBSTAT	Not available.	Accepts the output of batch mode operations (i.e., *.ASC files) and delivers statistical and graphic output selected by the user from a menu. PBSTAT can be accessed from the main menu of Lead, or externally with a DOS command (PBSTAT). The printer options in PBSTAT are the same as those in PBPLOT.
PBPLOT	Not available.	Produces graph prints from Lead. It is accessed with a DOS command (PBPLOT). PBPLOT performs the same functions as "Graphics Selection Menu" in Lead, however, it produces graph prints at much higher resolutions (e.g. HP Plotter and PostScript printer graphs). PBPLOT accepts *.LAY and *.PBM files produced with Lead.
Main Menu		Restructured.
Model Iteration Period	One month with no user option.	One day with user option.
"Fetal" Model	Maternal blood lead is calculated based on user-defined exposure data and a maternal biokinetic model, and newborn blood lead (BPbn) is calculated from a biokinetic model.	Not available.
Soil Intake	Default value is 100 mg/day for all ages.	Default values are: age (yr) — soil intake (mg/day) 0-1 — 85 1-2 — 135 2-3 — 135 3-4 — 135 4-5 — 100 5-6 — 90 6-7 — 85
View/Print Data File	User must exit Lead and import *.TXT data files into a text editor (e.g., word processor) to view or print data.	Allows the user to view and print *.TXT data files within Lead.

TABLE B-3 (cont'd). SUMMARY OF REVISIONS TO LEAD UPTAKE BIOKINETIC MODEL SOFTWARE FROM LEAD 0.5 TO LEAD 0.99d

Parameter or Feature	Lead 0.5 (December, 1990)	Lead 0.99d (January, 1994)
Contribution of soil lead to indoor dust lead	Default value function is 0.28 μg Pb/g dust per μg Pb/g of soil.	Default value function is 0.70 μg Pb/g dust per μg Pb/g of soil.
Outdoor air lead concentration	Default value is 0.2 $\mu g/m^3$.	Default value is 0.1 $\mu g/m^3$.
Dietary lead intake	Default values were based on a preliminary analysis of 1988 FDA survey data.	Default values are based on a more detailed analysis of FDA 1988-90 data.
Editing of default biokinetic parameters	Coding error resulted in changes to RECSUM time constants (e.g., TPLUR) not being accepted, as a result the UBM appeared to be insensitive to changes in TPLUR.	Coding error corrected.
Euler Algorithm	Forward Euler algorithm calculates the increase compartmental lead mass over the iteration interval as the total lead inflow to the compartment, minus the total lead outflow at the beginning of the interval.	Backward Euler algorithm calculates the increase compartmental lead mass over the iteration interval as the total lead inflow to the compartment, minus the total lead outflow at the end of the interval.
Tissue Pb and Excretory Transfer Coefficients		Revised.
Non-linear GI Absorption Model	"Non-integrated" approach: Saturable absorption coefficients are calculated for each medium (soil, diet, drinking water, etc.) based on intakes from each medium, and are used to calculate media-specific uptakes which are summed to yield total uptakes.	"Integrated" approach: Intakes from all media are considered in the calculation of the saturable absorption coefficients for each medium (via SATURATION(t).

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