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LIST OF ABBREVIATIONS

Abbreviation	Description
AM	Arithmetic mean
ANOVA	Analysis of variance
CalOSHA	California Occupation Safety and Health Agency
CCIA	Connecticut Construction Industries Association
CDC	Centers for Disease Control and Prevention
CONLIS	Construction Lead Intake Simulation
ConnDOT	Connecticut Department of Transportation
CRISP	Connecticut Road Industry Surveillance Project
CT	Connecticut
CV	Coefficient of variation
DHS	Department of Health Services
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
GM	Geometric mean
GSD	Geometric standard deviation
HEPA	High efficiency particulate air
IH	Industrial Hygienist
LEV	Local exhaust ventilation
LHPP	Lead Health Protection Program
LOAEL	Lowest observable adverse effect level
MMAD	Mass median aerodynamic diameter
MRP	Medical removal protection
NHANES	National Health and Nutrition Examination Survey
NIOSH	National Institute for Occupational Safety and Health
NOAEL	No observable adverse effect level
OEL	Occupational exposure limit
OSHA	Occupational Safety and Health Administration
PBPK	Physiologically based pharmaco-kinetic
PBZ	Personal breathing zone
PDF	Prevented Dose Factor
PEL	Permissible exposure limit
PPE	Personal protective equipment
RCRA	Resource Conservation and Recovery Act
RPE	Relative Preventive Effect
SSPC	Steel Structures Painting Council
TWA	Time weighted average
U.S.	United States

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ABSTRACT

OSHA's most recent lead in construction standard projected that a 4-fold reduction in air-lead concentration during certain work activities (i.e. from a typical value of 200 $\mu g\ m^{-3}$ to 50 $\mu g\ m^{-3}$) would avoid substantial illness among workers. However, the effectiveness of lead health protection programs that address requirements under this standard has remained largely unknown until the research presented in this project. This research characterizes the sources and pathways of airborne lead exposure during bridgework, develops an exploratory model and applies the model toward an analysis of data collected during a large-scale lead health protection intervention. Over 30 different tasks were identified that produce elevated levels of lead in the air (average values range from less than 30 $\mu g\ m^{-3}$ to almost 10000 $\mu g\ m^{-3}$). Blood lead levels among almost 2000 painting, ironwork, general craft and professional workers enrolled in a model lead health protection program designed to monitor and prevent workers from absorbing lead during these high-exposure tasks were summarized for years 1992 – 1995. For blasters and ironworkers, CRISP, which stands for Connecticut Road Industry Surveillance Project, maintained substantially lower blood lead levels in 1994 than levels found among workers with the same job title who conducted work outside of Connecticut during the same year. We incorporated the characteristics of bridgework that generates airborne lead, the components of CRISP and a previously published mass balance bio-kinetic model into a model named CONLIS, for CONstruction Lead Intake Simulation in order to derive lead dose from both environmental and biological measurements. We tested, validated and developed software to run the model and to systematically explore the influences on lead intake among workers from exposure and preventive techniques deployed during abrasive blasting activities. Our initial investigation found that a 100-fold preventive effect from Connecticut's lead health protection program. We also used the model to establish and test a simplified predictive model and to simulate conditions for planning programs and managing and exposure. Two scenarios illustrate that future production rates (abrasive blast time per month) would be restricted to 30% of the original production rate when workers are allowed to reach the limit of exposure. CONLIS represents an approach that could have a broad range of potential applications for effectively protecting workers.

PREFACE

Occupational exposures to air contaminants originating from the performance of tasks can cause severe adverse health effects among the worker population. To anticipate and control these exposures, the mechanisms that produce and prevent pollutant intake among workers need to be understood. Construction workers comprise a population at relatively high risk for lead poisoning because lead and lead-containing compounds are common in certain construction materials, particularly paint. OSHA's most recent lead in construction standard projected that a 4-fold reduction in air-lead concentration during certain work activities (i.e. from a typical value of 200 $\mu g\ m^{-3}$ to 50 $\mu g\ m^{-3}$) would avoid substantial illness among workers. The agency estimated that full compliance with the standard would avert 227,000 acute cases annually and 4000 chronic cases of adverse health effect among 940,000 construction workers. However, the effectiveness of lead health protection programs that address requirements under this standard has remained largely unknown until the research presented in this project. This research characterizes the sources and pathways of airborne lead exposure during bridgework, develops an exploratory model and applies the model toward an analysis of data collected during a large-scale lead health protection intervention. In conjunction with exploring indicators of prevention, the dynamic model for estimating lead intake that is developed as part of this project is calibrated and tested. The model is evaluated with respect to how accurately it predicts lead absorbed during daily intake in a chamber study and during a month of work-related exposure.

The original motivation for this investigation emerged from a NIOSH demonstration project in Connecticut that sought to prevent lead poisoning among bridge workers during an intense effort to rehabilitate the State's bridge infrastructure. Chapter 2 characterizes the structure and execution of lead-related bridgework, the mechanisms of generation, resuspension, transport and removal and the lead concentrations associated with specific tasks. Over 30 different tasks were identified that produce elevated levels of lead in the air (average values range from less than 30 $\mu g\ m^{-3}$ to almost 10000 $\mu g\ m^{-3}$). The variability in each summary estimate is presented in Chapter 2.

A model lead health protection program designed to monitor and prevent workers from absorbing lead during these high-exposure tasks is characterized in Chapter 3. Blood lead levels among almost 2000 painting, ironwork, general craft and professional workers enrolled in the Connecticut demonstration were summarized for each year of the project. CRISP, which stands for Connecticut Road Industry Surveillance Project, began as a voluntary program in 1992, became mandatory in 1993 and continued through 1995. Blood lead levels from both ironwork and painting crews declined during the course of the project. CRISP-enrolled blasters and ironworkers were found to have substantially lower blood lead levels in 1994 than levels found among workers with the same job title who conducted work outside of Connecticut during the same year. This assessment suggested that the components of CRISP strongly influenced bridge workers' blood lead levels. We therefore designed a work-factor blood-lead model that combines the bridgework system, components of Connecticut's lead health protection program and a previously published mass balance bio-kinetic model in order to derive lead dose from both environmental and biological measurements. We developed software to run the model and to systematically explore the influences on lead intake among workers from exposure and preventive techniques deployed during abrasive blasting activities. The components of the model core and its dynamic behavior are described in Chapter 4.

The model developed in this project, named CONLIS, for CONstruction Lead Intake Simulation, was used to systematically investigate the impacts of bridgework that disturbed lead paint during two large bridge projects conducted from 1994 through 1995 and the preventive effects of Connecticut's lead health protection program among 195 bridge workers.

Chapter 5 presents the detailed assessment of the preventive effect of the CRISP intervention using CONLIS. Environmental exposure profiles and blood lead measurements were first converted into two separate estimates of dose. One module of CONLIS calculates dose based on environmental factors derived from work related time-activity data (e.g., personal breathing zone, PBZ, lead concentration profiles). A second dose estimate is derived from measured blood leads and employs a pharmaco-kinetic model originally developed by Bert and colleagues (1989). An initial estimate of personal protection for each of two Connecticut bridge projects was found by dividing absorbed lead derived from the PBZ exposure profiles and that derived from blood lead measurements. A 100-fold reduction between the first and second dose estimates was found in both bridge-project sub populations, which indicates substantial protective effect, probably attributable to respiratory protection; however the effect of other protective measures such as workplace hygiene need to be further explored.

The last part of Chapter 5 illustrates in two exposure scenarios how the predictive model can be deployed for program planning and exposure management. For a defined sequence of abrasive blasting activity, the model generates a probability distribution of blood lead levels. Scenarios demonstrate that variability in blood lead levels is due to the stochastic nature of both breathing zone lead concentrations and protective measures. Results reveal that future production rates (abrasive blast time per month) would be restricted to 30% of the original production rate when workers are allowed to reach the limit of exposure.

The research presented in this project has provided an initial understanding of the impacts of a worker protection program on lead intake among bridge construction workers. Although the influences on lead intake were intentionally simplified, the results and insights apply to a range of hazardous work conditions. The development and validation of the CONLIS model represents an important result of this research. It was demonstrated that CONLIS accurately predicts absorbed doses for two different bridge projects. The research suggests that CONLIS is useful for exploring the influences of changes in breathing zone lead and worker protection measures during the planning and management stages of a lead-related bridge project.

Field measurements from the CRISP demonstration calibrated CONLIS. CONLIS simulations demonstrate that exposures can be controlled in construction environments and blood lead levels below OSHA's baseline can be maintained. Unlike models that assume a constant air concentration value, the dynamic response of CONLIS is especially suited for variable exposure conditions. To my knowledge, the research presented here represents the first time this technique has been applied to an exposure control intervention in an occupational setting. CONLIS represents an approach that could have a broad range of potential applications for managing other occupational exposure-control systems. The techniques and tools developed here apply to the management of a multitude of toxic agents found in the workplace that require task-based monitoring and personal protective measures.

Significant findings

The research presented in this project has culminated in the development of a new exploratory model designed to prevent occupational exposures to lead. To build this model, my investigation began by characterizing lead exposures during bridgework operations. A systematic review of 12 bridge projects that collected personal breathing zone lead concentration during bridge rehabilitation and repair tasks provided a profile of exposure. Parsing samples by sampling time, working environment, task execution practice and tool usage revealed new influences on airborne lead concentration. The analysis demonstrated that lead removal work produces multiple sources of airborne lead and that work performed in tightly enclosed structures produces the highest airborne lead concentrations and the need for a high degree of worker protection.

Then, we examined the effectiveness of a lead health protection program that was conducted in Connecticut call the Connecticut Road Industry Surveillance Project (CRISP). We conducted multiple comparisons of average and peak blood lead levels among the entire CRISP enrolled workforce noting that there was an overall reduction in blood lead among workers over time. As well, blood lead between two groups of blasters, one from the CRISP program and the other from blasters outside the CRISP program were much lower among CRISP enrollees suggesting that these workers were substantially more protected than workers protected under the OSHA regulation alone.

Encouraged by these findings, we investigated further the mechanisms of protection. To date, very few evaluations of worker protection programs could be found in the published literature and among these, none provided a model for linking environmental measurements of exposure, protection and absorbed dose among workers. As a consequence, the relationships between worker protection and absorbed lead remain largely unknown. In an effort to examine these relationships, an exploratory model was developed as part of this project. There are four specific aims addressed in this research.

Specific Aim 1: To use the blood lead data from half of the cohort involved in the Connecticut intervention program to estimate, using the Physiologically Based Pharmaco-Kinetic (PBPK) model of (Bert et al. 1989), recent lead exposure (i.e. the cumulative lead intake from work over the past 30 day period).

This exploratory tool is a lead-flow simulation model named CONLIS (CONstruction Lead Intake Simulation) that simulates lead intake from the workplace and converts it to a level of lead in the blood of a worker. One of the unique features of CONLIS is that it can estimate dose from two types of measurements. CONLIS combines work methods, task exposure rates and air concentration to establish a measure of anticipated dose. Absorbed dose is derived from two measures of blood lead in individual workers and a physiologically based pharmaco-kinetic model published by Bert et al (1989).

The analytical solution of the Bert model equations incorporated into CONLIS was compared to Bert's numeric model and then to experimental observations published by Rabinowitz et al. (1976). Then, predictions from CONLIS using data from a NIOSH field study of bridge worker exposures during a bridge rehabilitation project were compared to blood lead levels among exposed workers. Good agreement was observed between predictions and measurement of lead in workers' blood.

Specific Aim 2: To develop an understanding, using regression methods, of the predictive value of various task, personal and environmental variables on cumulative lead intake as estimated in specific aim one.

Subsequently, we deployed CONLIS in further exploratory analyses of the effectiveness of the CRISP Lead Health Protection Program (LHPP) intervention. Dose estimates were examined for factors that affect exposure among abrasive blast crews. The impact of program year, inhaled air concentration, the frequency of production, breathing rate, initial body burden of lead, body weight and preventive effects introduced by the CRISP LHPP were examined systematically. An initial estimation of intake fractions revealed that two major bridge projects during the CRISP intervention each had a 100-fold difference between a measure of dose without regard to respiratory protection and absorbed dose among crews of 12 bridge workers. This difference provided an initial estimate of reduced lead intake attributable to worker protection techniques. A comparison of the proportion of occurrences among workers of excess dose from 1994 and 1995 provided additional evidence that exposure control was affected by project year and improved over time. The fraction of workers who would have experienced excess lead but did not also provided an estimate of differential benefit among workers grouped by job title. Blasters benefited substantially from protective measures over the two-year period regardless of their employer whereas estimates from other groups were not as strong or consistent.

An estimate of the average reduction from worker protection measures of lead taken in by workers (i.e. dose fraction) was derived from one half of the CRISP field data collected in 1995.

Specific Aim 3: To attempt to validate the regression model using the other half of the data from the Connecticut intervention program cohort.

This new value was multiplied to estimates of anticipated dose contained in the second half of the 1995 data set to predict absorbed dose. Regression analysis revealed that predictions of lead dose levels for the study group as a whole compared reasonably well to absorbed dose derived from blood lead measurements. When a random sample of the study population derived the dose fraction, project-averaged model predictions compared well to observations.

Specific Aim 4: Explore the implications of the regression model for identifying:

a) cost-effective surveillance requirements for ongoing exposure control programs including the potential deficiencies in the Connecticut data set; and
b) efficacious control strategies

We also used CONLIS to explore in hypothetical scenarios how excess blood lead can be avoided and how alternative methods of protection can be evaluated. For a defined sequence of abrasive blasting activity, the model generates a distribution of blood lead levels. Simulations were performed for two alternate conditions. Scenarios demonstrate that variability in blood lead levels is due to the stochastic nature of both breathing zone lead concentrations and protective measures. Results reveal that future rates of abrasive blasting would be reduced to 30% of the original production rate when workers are allowed to reach the limit of exposure.

The impact of the LHPP on the bridgework workforce and preventive effect of specific techniques remain unresolved. CONLIS simulations provide a way to begin systematic investigation of impacts from specific lead paint removal activity and worker protection techniques on worker intake rates.

For bridge projects involving many crews, multiple containment structures, a variety of equipment and a variable work routine the monitoring and control of exposures can require substantial effort. To address this problem, this project derived a dose fraction estimated from task-based and biological measurements of lead accumulated over time. This fraction was further refined by an assessment of influences represented by contractor, program year, exposure intensity and job title variables. The program-wide dose fraction that provided an adequate metric for exploring relationships between abrasive blast activity, worker protection and blood lead levels may not be a sensitive enough metric for estimating exposures at much lower airborne lead concentrations or when exposure events are less frequent. Under these conditions a more detailed characterization of concentration and events may be required.

To thoroughly characterize the effects of exposure events, CONLIS could be used to produce a work-factor input from area or personal breathing zone concentration, dose fractions (i.e. reduced dose from worker protection practices and equipment) and a blood lead response for a typical worker. For a broader range of working conditions, such an investigation would determine the relative increase or decrease in lead intake, absorption and blood lead as a function of production and worker protection influences.

For example, one could calculate the impact on the likelihood of worker poisoning from environmental regulations that require tighter enclosures. As well, one could explore the impact of technological advances in enclosures that enable workers to clean surfaces every day instead of taking one to four days to dismantle, move and set up enclosures (e.g., rolling enclosures along the I-beams underneath a bridge). One could also calculate the effects of increasing the per hour cleaning rate from bigger and more powerful blast guns and more effective removal of visually impairing airborne debris while generating the more lingering and respirable particles.

CONLIS could be used to generate a table of predicted blood lead levels from a broad range of lead intake values and initial blood lead levels, an approach used for other toxic exposures. For example, Navy deep-sea repetitive diving tables (NOAA 2003) are used to avoid nitrogen toxicity. These tables allow the diver to monitor the rate of nitrogen inhalation for various dive conditions. This method avoids an invasive and potentially expensive regimen of frequent biological nitrogen monitoring.

CONLIS could be used to plan and implement exposure control systems in other hazardous occupational settings as well as in the broader context of episodic exposures to toxic agents. Such a tool could be useful too for industrial hygienists and engineers who are responsible for characterizing and mitigating immediate hazards and for continuously monitoring workplace conditions.

By combining a future CRISP-like program with modern control theory a systematic method could be constructed using a feedback and adjustment regimen. This would be similar to CRISP in principle but a much different system in practice. A combined program would apply CONLIS as a system state observer. This program enhancement could substantially condense the time and effort needed to demonstrate the optimum control of blood lead levels for an entire bridge workforce (Ogata 1990).

Translation of findings

The research presented in this project has provided an initial understanding of the impacts of a worker protection program on lead intake among construction workers. Although the influences on lead intake were intentionally simplified, the results and insights apply to a range of hazardous work conditions. The development and validation of the CONLIS model represents an important result of this research. It was demonstrated that CONLIS accurately predicts absorbed doses for two difference bridge projects and long-term blood lead levels within the bounds of baseline and full compliance levels projected by OSHA for this workforce.

Unlike models that assume a constant air concentration value, this dynamic model is especially suited for variable exposure conditions. To my knowledge, the research presented here represents the first time this technique has been applied to an exposure control intervention in an occupational setting.

CONLIS represents an approach that could have a broad range of potential applications for managing other occupational exposure-control systems. Because of the potential benefits of avoiding hazardous working conditions, ineffective control techniques and costly delays, investigations into other applications may be worthwhile.

CHAPTER 1 INTRODUCTION

1.1 Background

In the 1970s, state health surveillance registries in the U.S. began to link high blood lead levels among workers to lead exposures at construction sites. Since that time, evidence has mounted that construction workers are at high risk for lead poisoning. Several studies have reported that workers who removed leaded paint in an enclosed structure meant to prevent environmental contamination (an EPA requirement) incurred severely elevated blood lead levels in the range of 50 to 100 $\mu g\ dl^{-1}$ (Fischbein et al. 1984; Waller et al. 1992; Schirmer 1990; Osorio and Melius 1995; Rabin et al. 1994).

Construction workers comprise a population at relatively high risk for lead poisoning because lead and lead-containing compounds are common in certain construction materials, particularly paint. Regular replacement of paint on lead-painted structures is necessary, since the paint oxidizes, which can lead to corrosion of these structures if left untreated. Lead-containing particles, either from oxidation or generated by replacement activities, become entrained in the air. Although it has for some time been standard practice to equip construction workers with respiratory protection, the protection is not perfect and a fraction of these suspended particles is inhaled or ingested. It is thought that this exposure is actually responsible for causing many health problems among these workers. OSHA estimated that a 4-fold reduction in air-lead concentration (i.e. from a typical 200 to 50 $\mu g\ m^{-3}$) during certain construction work would avoid 227,000 acute cases annually and 4000 chronic cases of adverse health affect among 940,000 construction workers in the United States (OSHA 1993).

1.1.1 Lead uptake and transport

Lead enters the body principally through the lungs and the digestive tract. Lead distributes through the body via the bloodstream. Once lead enters the bloodstream, it spreads rapidly into liver, kidney, bone, spleen, lung, heart and skeletal muscle tissue. The primary elimination route is through the kidneys, but secondary elimination routes include the feces, sweat, and accumulation in hair and nails.

The amount of lead deposited in the lungs and subsequently absorbed into the blood depends on several factors. Deposition rate depends on the shape and the size distribution of particles, as well as an individual's breathing rate (volume of air inhaled per unit time). Clearance rates depend on the region of deposition (i.e. within or outside of the ciliated region) and on particle solubility. In the ciliated regions of the lung, particles are carried to the pharynx rapidly (within a few hours) or slowly (within a day), swallowed and potentially absorbed through the gastrointestinal tract. In the alveolar region, clearance half-life of lead in vapor form is approximately 10 hours and occurs by transport to the ciliated region, to lymph or blood or to the pulmonary tissue (Castellino et al. 1995; Dinman 1991). However, other investigators have observed that 44-60% of inhaled submicron particles reaches the alveoli and only about 1-2% is cleared after 72 hours (Booker et al. 1969). At nominal breathing rates, adult lungs are estimated to absorb 35% of inhaled lead mass from ambient air (Hursh et al. 1969). No specific corresponding estimate has been derived for lead in construction environments. However, there is also no evidence that we know of to suggest that it would greatly differ from this figure.

Degree of lead intake through the digestive tract depends on the subject's age, eating, and hygiene habits (i.e. skin cleanliness and hand to mouth activity), and the chemical form of the lead compound ingested. As well, some inhaled particles cleared by the upward propelling action of the ciliated regions of the lungs may be ingested. A study conducted on adult human volunteers revealed that about 8-12% of lead ingested with food was absorbed. However, lead ingestion under fasting conditions increased the absorbed fraction to $35.0 \pm 13\%$ (Hursh et al. 1969).

Lead moves through and is deposited or eliminated from the body at different rates, depending on the type of tissue. Lead initially concentrates in the bloodstream. The ratio of lead found in blood cells to the lead in the peripheral blood fluid varies according to the dose and the time elapsed from absorption. However, most (94-99%) is bound to the erythrocytes. A pulse dose of lead will have a half-life of about 30 days in the bloodstream, during which it deposits in other tissues or is eliminated from the body. Uptake and release time constants for other tissues are much slower than for blood. Correspondingly smaller amounts of recent lead intake are typically found in other tissues. Once released from blood, the highest levels of lead distributed to the soft tissue are found in the kidney and liver. Less lead mass is found in the lungs, spleen, heart, skeletal muscles and brain. Bone tissue, which exhibits slow uptake, acts as a sink for lead (i.e., it tends to stay there). The same can be said for hair and nails. The high affinity and incorporation into the bone matrix causes lead to accumulate in and release slowly from these tissues. Lead substitutes for calcium and becomes part of the hydroxyapatite crystal during bone remodeling. Autopsy studies revealed that among non-occupationally exposed young men, 5% of the lead in the body came from soft tissues and 95% from bone. These proportions were similar in occupationally exposed man (Barry 1975; Castellino et al. 1995).

1.1.2 Health effects and mechanisms of lead toxicity

Lead is a well-known toxic agent. Animal and cell system studies have found a host of physiologic effects. Specifically, lead is known to impair cellular function. When the human body takes up lead, the element rapidly forms highly stable complexes with nucleophilic functional groups and can induce generation of oxygen radicals. This means that lead can interfere with cell membrane transport systems, receptors and structural proteins, high affinity binding proteins, calcium balance, enzymatic systems and mitochondria structure and function (Castellino et al. 1995). The consequences include reduced red blood cell survival, disturbances in blood pressure regulation (inhibition of cell uptake of potassium), interference with smooth muscle contractility, nerve cell death and chronic disruption in nerve stimuli transmission.

Chronic overexposure to lead in humans can result in severe damage to the blood-forming, nervous, urinary and reproductive systems. Specifically, severe health effects such as peripheral neuropathy and kidney damage at a blood lead level of 40 $\mu g\ dl^{-1}$ and other renal effects such as decreased vitamin D metabolite levels at 30 $\mu g\ dl^{-1}$ have been observed among workers who are chronically exposed to lead (Kim et al. 1996). Studies have also shown a positive association between blood pressure and lead in blood; this has been observed in men with levels as low as 7 $\mu g\ dl^{-1}$ with no evidence of a threshold (Schwartz 1988). Acute exposures (rapid change in blood lead levels over 2-4 weeks) can produce fatigue, disturbed sleep and constipation (Marino et al. 1989). More severe acute exposure produces abdominal colic, anemia, kidney disease, peripheral neuritis and encephalopathy (Castellino et al. 1995).

Even though an argument can be made that repeated short-term spikes in exposure are best detected by measuring lead in blood, the toxic action in body tissue could pose special problems in the context of construction work. For example, during bridgework, several tasks have been known to produce extremely high airborne lead concentrations near workers (Sussell et al. 1992) that could result in acute exposure. Subtle symptoms such as loss of grip strength (motor weakness) or fatigue from short-term exposures (Levy et al. 1983) could present some additional risks of injury during work with hand tools in high places.

Nevertheless, since the preponderance of recent lead intake is concentrated in the bloodstream and the fact that blood-lead can be easily and consistently measured, blood lead level is the best surrogate measure for determining the incidence of mild adverse effects from acute inhalation exposures (Castellino et al. 1995).

1.1.2.1 Blood lead levels measured in construction workers

Even after the passage of the OSHA lead in construction standard, a substantial proportion of construction workers continue to have blood lead levels high enough to be associated with adverse health effects. A 1994-1996 survey revealed that almost 13% of Iowa and Illinois construction workers had blood lead levels above 10 $\mu g\ dl^{-1}$ (geometric mean equals 5 $\mu g\ dl^{-1}$) and, in Maryland, 50% of construction workers surveyed in a cross-sectional study had blood lead levels of 7 $\mu g\ dl^{-1}$ or more (Reynolds et al. 1999; Sokas et al. 1997). Reynolds et al. (1999), in a study of ironworkers who worked on a previously deleaded bridge, found a geometric mean of 27.2 $\mu g\ dl^{-1}$ and a range from 6.3 to 50 $\mu g\ dl^{-1}$ among blood lead levels of 44 workers prior to intervention. Forst (1997) and colleagues examined members of a local iron workers union for the prevalence of blood lead levels that reached or exceeded 25 $\mu g\ dl^{-1}$. These investigators found that 11% of the ironworkers tested had blood lead level of 25 $\mu g\ dl^{-1}$ or more. In another study of ironworkers Levin et al., (1997) found that 26% had blood lead level of 20 $\mu g\ dl^{-1}$ or more.

In contrast, the NHANES results reported for 1988-1991 found that 95 percent of U.S. adults have blood lead levels less than 10 $\mu g\ dl^{-1}$ and 95 percent of U.S. males have blood lead levels less than 11 μg dl^{-1}. Results for a later NHANES study in 1991-1994 show that the geometric mean blood lead level for adults 20-69 years of age is less than 4 μg dl^{-1} (Pirkle et al. 1994; CDC 1997). The most recent NHANES study presented a geometric mean of 1.75 μg dl^{-1} and 95% confidence intervals of (1.67 – 1.83) in the adult population tested from 1999-2000 (CDC 2003).

These results suggest that the geometric mean blood lead for the U.S. population has decreased 10-fold over the last decade, while that for workers has increased or stayed level, revealing a growing gap between exposures for construction workers with respect to the general population.

1.1.2.2 Permissible exposure standards

Most of the lead in the environment to which people are exposed is the result of industrial activity. Since we largely control the generation of the pollutant, and with lead's toxicity well documented, the question arises as to why we tolerate any level of exposure? Why do we not ban the use of lead altogether? The answer is that lead is such a useful substance that we are not yet willing to do without it. As is true for many toxic substances, exposures are tied to industrial production and use and we've decided as a society to tolerate exposures because the use confers benefits. For example, lead is used in the production of lead shot, bullets and lead battery components. Lead arsenate has been used in insecticides, glazes, lead borate in the production of plastics, roof coverings, pipes and wires (Castellino et al. 1995). In fact, overall production of both primary and recycled lead is increasing. Although specific uses for lead change over time (for example, we no longer use leaded gasoline in the U.S.), the decrease in lead use in obsolete applications is more than offset by new or expanded industrial uses such as in computer monitors and circuit boards (COEH 2003). World consumption of lead has increased from over 2,600,000 tons per year in the 1960s to over 5,500,000 tons per year in the 1990s (Castellino et al. 1995). Increased consumption means that effective monitoring and control strategies are becoming even more critical than in previous years.

Consequently, this raises some important questions. Is there a "safe" level of exposure below which there is no measurable health effect and which would therefore be a logical place to set the standard? Also, if there is no safe level or if achieving such a "safe" level is not feasible, what price are we willing to pay in terms of health consequences by choosing a particular "acceptable" exposure level? If deemed necessary, can we justify a higher acceptable threshold for subgroups of the population such as construction workers? Finally, is extra monitoring and control enough to protect the health of these workers so that they don't suffer more than the general public?

1.1.2.2.1 Is there a safe level of exposure? PEL, OEL, NOAEL and LOAEL

In the workplace, an occupational exposure limit (OEL) for an air contaminant is defined as the maximum "admissible" or "acceptable" concentration in the workplace air. OELs are institutional limits that serve as guidelines and are set based on a substance's toxicity and physico-chemical characteristics. All OELs assume that the exposed persons are healthy adult workers, although in some cases the OELs should also protect "sensitive subgroups". For example, exposure limits may not be valid for pregnant women and nursing mothers. For OELs, the average exposure time is normally 8 hours per day and is set under the assumption that a worker can be exposed to a substance for 250 days per year over a working life of 40 years (NIOSH 1992b). In the workplace, OELs can be set by adopting recommended exposure limits (set by NIOSH), which take into consideration practical factors such as monitoring detection limits and analytical methods (Paustenbach 1997). An extension of the OEL, namely, the permissible exposure limit (PEL) is a regulatory limit that takes into account economic and technical feasibility. For this reason, PELs are often higher than OELs and considerably higher than a community reference exposure level. In a community setting, a reference exposure level (set by U.S. EPA) is a concentration level at or below which no adverse health effects are anticipated for a specified exposure duration (Alexeeff et al. 2002). Reference exposure levels are designed to protect the most sensitive individual in the population, since they include margins of safety beyond the level at which adverse health effects occur in healthy subjects.

For some chemicals, there may be no lower exposure limit for which the onset of adverse health effects has been observed (NOAEL). In such cases, a "safe level" is determined by applying a set of adjustment factors to the lowest exposure level in which adverse effects have been observed. The lowest observed adverse effect level (LOAEL) is an elevation in the severity or frequency of an adverse health effect in an exposed compared to an unexposed group of animals or humans. In the absence of an observed NOAEL, adjusting the LOAEL downward derives an estimated NOAEL. A recent study that examined the relative magnitudes of LOAEL and NOAEL for mild adverse effects from acute inhalation exposures found that 95% of these relationships had a ratio of 6 to 1 or less (Alexeeff et al. 2002). This study only examined mild adverse effects, so the typical adjustment factor may be different for other levels of health effect severity. Applying another adjustment factor to the estimated NOAEL that accounts for extrapolation from animals to humans and variability within the human population derives a reference exposure level. This adjustment factor can range from 1 to 10 (Dourson et al. 2001; Alexeeff et al. 2002). Finally, converting the reference exposure level for a continuous exposure to one that accounts for the intermittent exposure during work hours derives a health-based OEL.

To illustrate, we use an "aggregate" model developed in California to quantitatively relate exposures from ambient air lead concentrations to blood lead levels. The aggregate model was developed to relate lead taken in from the airborne pathway both directly through inhalation and indirectly through other media impacted by airborne lead, such as soil and household dust. For current levels of lead in ambient air, the steady-state blood lead to air lead ratio for adults is approximately 1.8 micrograms per deciliter per 1 microgram per cubic meter (OEHHA 1997). Therefore, an average air concentration of lead that corresponds to a blood lead level of 10 $\mu g\ dl^{-1}$ (the observed level corresponding to increased incidence of hypertension) would be 5.6 $\mu g\ m^{-3}$. A derived NOAEL would be 0.9 $\mu g\ m^{-3}$ when an adjustment factor of 6 is applied. Then, the reference exposure level is estimated by applying an adjustment factor of 3 to the NOAEL (the adjustment factor used for other heavy metals) to get 0.3 $\mu g\ m^{-3}$ (Dourson et al. 2001). This level reflects 24 hours of exposure for 7 days a week. So, an equivalent OEL is determined by adjusting the reference exposure level by the expected 4.2-fold lower occupational exposure time (Paustenbach 1997). The result is an OEL of 1.3 $\mu g\ m^{-3}$. The resultant blood lead level from average occupational exposure at the OEL would be 2 $\mu g\ dl^{-1}$. This blood lead level is plausible since it is above the geometric mean background blood lead level currently measured among the general adult population (CDC 2003).

1.1.2.2.2 *Discrepancy between exposure standards*

OSHA's lead in construction standard has set an 8-hour permissible exposure limit at 50 $\mu g\ m^{-3}$ for lead in the air. Under full compliance, the Agency estimated that workers' blood lead levels are expected to remain below 25 $\mu g\ dl^{-1}$, and the annual average blood lead levels will range from 5.0 to 12.8 $\mu g\ m^{-3}$ depending on the specific routine of work activity. OSHA claims that blood lead levels in this range will decrease the expected annual incidence of several mild adverse health endpoints as well as long-term effects from those expected at this range of occupational baseline blood lead levels.

In comparison, the ambient air quality standard is set at 1.5 $\mu g\ m^{-3}$, averaged over three months in the U.S. federal standard and averaged over 30 days in California. Existing studies indicate a consistent association between ambient concentrations of lead in the air and subsequently measured blood lead levels in the general population. Using the aggregate model, blood-lead levels of 2.7 $\mu g\ dl^{-1}$and below would be expected in the general population when ambient air levels remain in full compliance with federal or state standards. This is an order of magnitude less than OSHA's expected upper bound of 25 $\mu g\ dl^{-1}$ for construction workers. So, how is this discrepancy justified?

The discrepancy between what is tolerated in the general population and what is considered acceptable for workers is determined through a regulatory impact analysis, which involves both technological and economic feasibility (cost-benefit analysis) (OSHA 1993). The rationale for such an analysis is in part based on a general belief that workers have a choice about risking exposure to hazardous conditions. At the same time, it is also rationalized that they are adequately compensated for taking that risk (Rock 1995). In theory, there could be much less of a difference between the expected average blood lead levels among workers and the background levels of lead in the blood of the general population. Close monitoring of exposures and rapid initiation of corrective action could avoid blood lead level elevation among workers. However, recall that recent studies among construction workers in several states have found higher levels than expected under full compliance with the OSHA standard. So why, with the technological ability to monitor and control exposures in the workplace, might this be so? The issue reduces to time and money. Unless motivated through tangible evidence that a device or change in routine will increase productivity or reduce the cost of production, contractors are not likely to fully comply with the OSHA standard. Even a heavily promoted Special Emphasis Program (SEP) (a regulatory tool used by OSHA), which allowed OSHA to randomly inspect bridge construction sites for violations, didn't compel contractors to avoid incurring fines (McAllister 2003). Two recent intervention studies described in the next section highlight some of the benefits and barriers to full compliance among bridgework contractors.

1.1.2.3 Current Monitoring and Control Practice

OSHA has had to design a strategy for the construction industry that differs from that of general industry. This difference is due to unique challenges characteristic of construction work including its episodic nature, that it often involves hard physical labor, and is conducted under extreme weather conditions and extremes in surrounding conditions such as heavy traffic or confined spaces. These issues, which are problems endemic for construction and not unique to lead, tend to impede the establishment of effective environmental monitoring, medical surveillance, biologic monitoring, medical removal protection (MRP), training, and hygiene. For example, efforts to implement an effective and well-organized health and safety program are impaired by the fact that most construction work is sporadic and workers are not tied to a single employer. The only work-related institution with which construction workers are most commonly affiliated is a labor or trade union; however, only 75% of the U.S. construction workforce is unionized. Frequent relocation also hampers continuity of health care, individual health changes are not caught early, and the causes of these changes are difficult to track and therefore to prevent (Ringen et al. 1995).

Under current OSHA requirements and as part of an industrial hygiene program in general, workplaces are evaluated for lead hazards. The lead concentration is monitored in the breathing zone of workers and in the general work area, compared against defined acceptable levels (i.e. 50 $\mu g\ m^{-3}$ for breathing zone air averaged over 8 hours) and controls are initiated or adjusted as needed. Controls are implemented to reduce source emissions, the residence time of the pollutant in the work environment, and the consumption of contaminated food, beverages and cigarettes. Protective clothing and respiratory protection provides barriers between the worker and the toxicant. Work surfaces are cleaned and the worker is provided with wash facilities. The level of lead in the worker's body is measured and compared to defined acceptable levels. Early symptoms and signs of adverse health effects are monitored and treated. Provisions are made for ensuring that the worker is protected physically and financially if the worker is removed from the job to prevent further lead exposure and permit a decline in the blood lead level. Workers and the public are informed about the hazard, and workers are trained about ways to minimize exposure. All activities of this program are recorded.

A statewide effort to implement a worker protection program that included OSHA's requirements occurred when, in the early 1990s, Connecticut established a lead health protection program for bridge workers (Maurer et al. 1995b). Both painting and ironwork contractors who engaged in lead-related work as part of bridge maintenance and demolition projects were targeted. An intensive air and biological monitoring program was pursued. Requirements were written into contract specifications and pass-through costs were established for aspects of a prescribed lead health protection program (LHPP). A comparison study examined workplace conditions with and without the benefit of the LHPP and the promulgation of OSHA's lead in construction standard. Investigators found that 2 out of 16 exposure reduction techniques specified under general worker health and safety regulations were implemented on jobs executed before the LHPP (Hammond et al. 1994). After requiring the LHPP at Connecticut job sites, 12 out of 16 techniques were implemented 100% of the time, and the remaining 4 were usually implemented. Blood lead levels were lower among workers from job sites with exposure control techniques in place than among workers without these controls. However, many other methods were also instigated as part of the LHPP in Connecticut and the relative impact of these methods on either air or blood lead levels was not evaluated. Also, the Connecticut program was expensive. Part of the program's success could have been the fact that a substantial Federal grant and State highway funds subsidized it. Thus, adopting a similar program in other states would likely be even more expensive unless similarly subsidized.

Another study examined the level of compliance with the OSHA lead-in-construction standard among painting contractors before and after interventions designed to facilitate compliance. This study cites a lack of resources as a major limitation. In this study an intervention was designed to educate, train and provide technical assistance for the purpose of encouraging residential and commercial painting contractors to establish lead safety programs and comply with the OSHA standard. Requirements were not established in contracts nor were pass-through costs provided to participating employers. Through education and encouragement alone, several contractors implemented components of a lead safety program. However, investigators explained that, for multiple reasons, changes in blood lead levels due to intervention were not feasible to monitor and therefore could not be evaluated. Investigators speculated that adopted aspects of the program were those in which practices were already familiar, accepted in the industry, inexpensive, or those in which cost savings could be realized. For example, housekeeping improvements and the practice of containing debris translated into lower labor costs, decreased contractor liability and improved customer satisfaction. However, investigators found that, in spite of their intervention, contractors fell short in several areas. Among the obstacles were a perceived work disruption or threat to work quality and costs for blood lead testing, special tools and equipment (Materna et al. 2002).

Recent data from State surveillance registries have documented blood lead levels among workers from lead using industries. Several States' lead registries track cases where blood lead levels reach or exceed 25 $\mu g\ dl^{-1}$ among workers. These registries have identified that levels of 25 $\mu g\ dl^{-1}$ and higher appear often among construction workers (Roscoe et al. 2002; CDHS 2002). The OSHA standard was expected to eliminate this problem if full compliance was achieved. The California study cites a lack of resources as a major limitation (Materna et al. 2002). During post study focus group sessions, this study's target population of "motivated contractors" was queried. Group participants listed perceived work disruption, a threat to work quality and costs for blood lead testing, special tools and equipment as obstacles to improving health program practices. The Connecticut study found that contractors had almost all of the LHPP industrial hygiene (IH) controls in place (a condition similar to full compliance with the OSHA standard). Researchers observed that blood lead levels were lower among workers from compliant job sites than among workers without these controls. Many of the barriers cited in the

California study may have been overcome in Connecticut because the intervention that enabled such a successful adoption of industrial hygiene controls was resource intense. For example, the cost to Connecticut for the LHPP during the intervention program was approximately 25% of the cost to paint a bridge. Almost half of the LHPP costs came from frequent air and blood lead monitoring (Castler 1995; Castler 2000; Shatkin et al. 1997). One powerful motivator for improved IH practices in Connecticut may have been the direct evidence of exposure from specific tasks and work routines. Evidence was provided to contractors and their employees through frequent air and biological monitoring. This feedback mechanism was absent from the California intervention.

Ultimately, a strategy to reduce health effects by anticipating problems before they occur and narrowing the gap in time between the discovery of a problem and follow up action is needed. The Connecticut model (named CRISP, which stands for Connecticut Road Industry Surveillance Project) provided the foundation for such a strategy. To exploit the Connecticut experience, a systematic exploration of the information about worker exposures and the protective techniques deployed by CRISP is needed. An exploratory tool used as a repository for valuable field data and a forum for decision-making would also be valuable so that a more efficient monitoring program could be implemented. Such an approach could also allow for investments of time and resources to be built into project budgets and contract specifications, thereby creating a more equitable bidding environment. The research presented in this project seeks to conduct a systematic exploration of the Connecticut demonstration. The objectives of this research are presented next.

1.1.2.4 Objectives of this research

The goal of this project is to provide a better way to monitor and control air pollutant intake in occupational settings that is less reliant on invasive biological measurements. The aim of this research is a better understanding of the relationships among tasks, airborne contaminant exposure patterns, personal protection and contaminant intake in occupational settings. Although many of the findings can be generalized, the focus in this project is on exploring the impacts of bridgework abrasive blasting activity patterns, airborne concentrations of lead, program protective effects and dose absorbed over a month among construction workers enrolled in the Connecticut LHPP. This research identifies new task groups that are associated with task execution patterns. This research also demonstrates that the Connecticut LHPP implemented as a demonstration in the early 1990s substantially reduced lead intake among painting contract crews. Previous evaluation studies did not attempt to directly link task-based lead exposure, contaminant control effects and the amount of lead taken in among workers.

The structure and execution of lead-related bridgework is characterized by physically challenging tasks (which affects worker turnover), challenging work environments, and specialized equipment including that used for personal protection. These factors make measuring the effects of bridgework on lead intake among workers very expensive. To address this problem, a modeling tool is developed that simulates lead absorption from daily episode of abrasive blasting activity. The model, named CONLIS (CONstruction

Lead Intake Simulation) calculates two estimates of lead dose derived from air and blood concentrations of lead measured during bridge projects, respectively. Comparison and reconciliation of these estimates facilitates the systematic exploration of the effects of abrasive blasting activity and worker protection on lead intake.

CONLIS is used to determine the respective impacts of work task, personal and environmental variables in predicting cumulative lead intake, as well as identifying deficiencies in the Connecticut data set. Candidate predictive models are derived from the results of preliminary data exploration. Model predictions are compared with lead intake derived from measured blood lead levels from the Connecticut intervention program cohort. CONLIS is also useful for identifying cost-effective surveillance requirements for ongoing exposure control programs and for constructing efficacious control strategies. The approach used by CONLIS is expected to be applicable to a broad set of workplace air pollutant monitoring and control requirements in industrial hygiene practice.

The research presented in this project relates to broader goals set by NIOSH through its National Occupation Research Agenda to investigate intervention effectiveness. The major goal of the intervention effectiveness research team is to determine whether specific interventions succeed in preventing work-related injury and illness. Important objectives include evaluating the development and implementation of interventions (Goldenhar et al. 2001). Research objectives include: (1) measuring the extent to which the intervention has reduced occupational illnesses or exposure to hazardous conditions; (2) evaluating the effect of the intervention on the social and economic consequences of work injury and illness (e.g., worker compensation, medical and indemnity costs, and quality of life); and (3) evaluating how the intervention has changed workers' knowledge, attitude, or behaviors. This project primarily addresses the first objective.

1.1.2.5 Outline of project

This section provides a synopsis of topics covered in this project. Chapter 1 has provided the context and framework for developing a new approach to monitoring and controlling hazardous air pollutants in the workplace, using lead as an example. Chapters 2 and 3 characterize the sources of lead exposure and the effect of a new approach to protecting workers from lead poisoning during bridgework in Connecticut. Chapter 4 introduces CONLIS, a theoretical work-factor blood lead model. Chapter 5 explores the CRISP LHPP for influences on the amount of lead absorbed by the enrolled workforce and illustrates the utility of the new model. Chapter 6 summarizes the results of this research and presents future research directions. The specific topics discussed in each chapter are presented in the remaining part of this chapter.

Chapter 1 has laid out the overall purpose and need for this research. It has provided some background about the properties and health risks posed by lead. The hazards of lead exposure in the general and occupational environment and the kinetics of lead in the human body have been summarized. Current knowledge has revealed that high blood lead levels continue to occur among workers and the risks of acquiring lead-associated disease among construction workers attributable to lead exposure are considerable. Finally, the broad and specific aims of this research and the contents of each chapter in this project are presented.

Chapter 2 characterizes the sources and mechanisms of lead exposure among construction workers involved in coating and ironwork operations. Lead-related bridge projects conducted over the past decade and published in trade and professional journals or government or publicly available reports are reviewed and almost 1400 task-based personal breathing zone concentrations of lead are abstracted to represent exposures during 25 equipment or tool-based tasks. Variables in project design and execution such as cleanup during abrasive blasting and partially enclosed work influenced elevated air concentrations during specific tasks and activities. These influences, along with those of a lead health protection program for workers, provide the foundation for understanding the dynamics of lead intake among workers in this industry. The review presented in Chapter 2 revealed a need for close personal monitoring and additional worker protection measures while conducting lead-related bridgework.

Chapter 3 discusses the key components of the Connecticut LHPP designed by Maurer (Maurer et al.,1995a), and implemented through Yale University. The demographic characteristics and blood lead levels of five employee groups (almost 2000 workers) were summarized. This chapter discusses the specific components and overall effectiveness of CRISP in maintaining blood lead levels below the target limit set by the Occupational Safety and Health Administration (OSHA) during more than 90 bridge projects from 1991 through 1995. The proportion of blood lead level exceedences above OSHA's medical removal limit of 50 $\mu g\ dl^{-1}$ among the entire workforce declined from 21% to 1% between 1992 and 1995. Peak blood lead levels among two subgroups of potentially highly exposed workers from the CRISP program were significantly higher than levels among workers who conducted similar operations outside of Connecticut. These initial findings along with those from Chapter 2 established that further investigation into the essential components that reduced worker blood lead levels overall would be worthwhile.

Chapter 4 develops a model depicting pathways from a task performed during bridgework to lead intake for an individual worker. This model combines work methods, task exposure rates, air concentration and worker protection components described in Chapters 2 and 3. This type of approach was used for the cost-benefit analysis to simulate long-term blood lead levels in the 1978 General Industry and 1993 Interim Lead in Construction Standards (OSHA 1978; OSHA 1993). Similar models evaluated the impact of particle size and job tenure assumptions on blood lead (Froines et al. 1995). However, none of the previous investigations applied the techniques presented here to explore influences from Connecticut's program and predict lead dose from relatively recent exposures.

The model core is comprised of two modules. The front-end module describes two pathways and the events in time that result in a lead dose rate. The back-end module contains a transfer function for converting dose rate to body burden, representing a previously validated physiologically based pharmaco-kinetic (PBPK) model developed by Bert and colleagues (1989). This module describes lead uptake and kinetics in the human body.

The model, CONLIS, is operated through MATLAB (2000) scripts developed as part of this project to rapidly generate time series predictions of lead in body compartments and, for the purpose of exploration, to generate both an environmental and blood lead dose rate. A finite-width pulse response simulation demonstrates the model's behavior during the initial stages of body compartment loading and release over a 40-day period. Once calibrated for a specific workforce, CONLIS provides the structure for predicting blood-lead levels under a broad range of exposure and control scenarios encountered by bridge workers.

Chapter 5 explores the CRISP LHPP for influences on the amount of lead absorbed by the enrolled workforce. The first of two studies presented in this chapter explores the effect of Connecticut's lead health protection program during 1994 and 1995 on exposures among 195 bridge workers. CONLIS was used to convert environmental and blood lead measurements to two separate estimates of dose. An intake fraction analysis (Bennett et al. 2002) revealed that environmental and blood lead derived dose estimates differ by approximately 100-fold due to respiratory protection. Consistent with findings in Chapter 3, average lead dose for the group as a whole declined over time. An impact analysis (Kleinbaum et al. 1982) of program-year estimated that two-thirds of dose-equivalent exposure exceedences that would have occurred among blasters were prevented. The potential influences of exposure intensity, contractor and job title were examined by analysis of covariance methods described by (Selvin 1995). Interactions were uncovered among exposure intensity, program year and absorbed dose and among job title and program year through these exploratory analyses. These findings guided the decision to use data collected in 1995 in the next study.

The second part of the chapter derives and tests a predictive model against field measurements collected in 1995 of lead absorbed by Connecticut bridge workers. The calibration and validation test was accomplished by splitting the data into two sets established through a random selection process. A key component that represents the influence of removal mechanisms such as task-related respiratory protection was derived. With the addition of this new component the predictive model produced dose values obtained from a new set of environmental variables comparable to those obtained from blood lead measurements.

Using two hypothetical scenarios, the last part of Chapter 5 demonstrates that blood lead levels can be anticipated and alternative methods for achieving them can be evaluated. For a defined sequence of tasks to be performed over a one-month period, CONLIS generates a probability distribution of possible blood lead levels at the end of the period. Variability in possible blood lead levels is due to the stochastic nature of the ambient lead concentrations and respirator penetration values. The 95th percentile of the blood lead distribution with a mean of 20 micrograms per deciliter is specified as the criterion for an acceptable task sequence.

Chapter 6 summarizes the findings of this research. The focus here has been on construction activities and lead exposures and the effects of Connecticut's LHPP. Other potential applications of CONLIS are discussed. For example, CONLIS could also characterize the effects of exposure events more extensively. CONLIS could produce inputs from area or personal breathing zone concentration and explore a range of worker protection fractions and blood lead responses for a typical worker. For a broader range of working conditions, such an investigation would determine the relative increase or decrease in lead intake, absorption and blood lead as a function of production and worker protection influences. One could calculate the impact on the likelihood of worker poisoning from environmental regulations that require tighter enclosures. Impacts of technological advances such as enclosures that enable workers to clean surfaces every day or increasing hourly cleaning rate from bigger and more powerful blast guns could be evaluated as well. The approach to planning and implementing exposure control programs, new understanding and tools developed during this project can be productively applied to other settings as well as in the broader context of episodic exposures to toxic agents.

CHAPTER 2 SOURCES OF LEAD EXPOSURE IN BRIDGE WORKPLACES

2.1 Abstract

Approximately 200,000 lead painted bridges are repaired and rehabilitated at a rate of about 3% per year. In spite of federal regulations, this workplace continues to poison workers. An extensive workplace evaluation is needed so that emission sources and potential exposures to workers can be identified and, where possible, mitigated.

This chapter begins to address this need by characterizing the sources of lead exposure from bridgework that involve the disturbance of leaded paint. The mechanisms of aerosol generation, aerosol transport, and removal and re-suspension of particles that occurs during tasks and activities associated with such work are reviewed. The statistical analysis performed in this chapter used a tiered approach that progressively delineated task-level concentrations of lead produced from different work conditions. Exposure sources, as measured by personal breathing zone (PBZ) lead, relevant modifying factors and control techniques are systematically evaluated. A lognormal analysis of variance (ANOVA) model was chosen to examine air samples with regard to between-project task heterogeneity and variance of airborne lead concentrations.

Over 30 different tasks were characterized during two types of bridge maintenance operations. Task related distributions of airborne lead concentrations showed some evidence of left skewness, resulting in the arithmetic mean of concentrations of lead being greater than the geometric mean. Most tasks generated PBZ lead concentrations above the OSHA 8-hr time weighted average (TWA) permissible exposure limit (PEL) of 50 $\mu g\ m^{-3}$ and were found to vary considerably from influences explored in this study. Also, the task descriptions evolved over time. As air samples were more precisely labeled, it became apparent that a particular tool, piece of equipment or context influenced lead concentrations. As well, when the sampling time became shorter, systematic differences were observed among air samples of the same task.

This review and analysis also uncovered several topics that require further investigation. Not much is known about the particle size distribution produced from paint combustion during bridge component removal and replacement, or the implications of particle charge on contaminant exposure and control. The particular effects on the PBZ air exchange within containment structures of variable design and the implications of potential ingestion pathways at work and respirator performance during bridgework also need further exploration.

2.2 Introduction

According to the National Bridge Inventory, there are more than 200,000 steel highway bridges in service throughout the United States, of which approximately 80 to 90 percent are coated with lead-based paint (Appleman 1997; FHWA 2002). These bridges are refurbished at a rate of about 3% per year (Randall et al. 1998). Special practices and equipment are required to conduct work that involves disturbing leaded paint, so that the environment is protected from lead contamination and workers and the local public are protected from becoming lead poisoned. In spite of federal regulations, numerous cases of lead poisoning occur among the approximately 50,000 workers involved in bridge repair and maintenance (CDHS 2002). OSHA has solicited for more field data and has recently engaged in widespread inspections that were part of a national Special Emphasis Program (SEP) (Dear 1996). However, ultimately an extensive workplace evaluation is needed so that emission sources and potential exposures can be identified and, where possible, mitigated.

Several federal agencies have examined exposures to lead from bridge paint and the efficacy of special practices and equipment, so that bridge maintenance and demolition costs can be managed. Cost analyses of bridgework were presented that included the components of paint removal practice, worker protection and waste treatment and disposal. As well, overall strategies and project decision processes are discussed (Appleman 1997; FHWA 2002; Smith et al. 1994). In its 1993 Lead in Construction Standard, OSHA provided a brief explanation of a few tasks and operations performed on bridges that are presumed to overexpose workers to airborne lead particles (CalOSHA 1993). In its Report to Congress, the National Institute for Occupational Safety and Health (NIOSH) reviewed the health effects of lead exposure and occupational exposure criteria. The agency also discussed state-of-the-art methods, devices and work practices designed to control exposures during commercial paint removal activities (Sussell 1997). These agency reports have broadly identified emission and environmental contamination source, potential exposures to workers and the local public, control technologies and practices and costs. However, a full characterization of the bridge workplace is lacking.

This chapter presents a more complete overview of bridgework as it relates to personal and environmental exposure to lead. The subject is introduced with a brief characterization of the structure and execution of lead-related bridgework. There is a review of the mechanisms of aerosol generation, aerosol transport and removal, and re-suspension that occurs during tasks and activities associated with such work. The body of the chapter uses this context to compile and evaluate the available evidence for potential exposure sources, as measured by PBZ concentrations of lead during the performance of a task. The effect on PBZ lead concentration of modifying factors such as various control techniques is also evaluated.

2.2.1 *Structure and execution of lead-related bridgework*

There are two major types of projects that disturb lead-based paint. One type involves the partial removal of paint, followed by steel component removal, replacement and overcoating. The other includes the full removal and replacement of the structure's protective coating. For convenience, we will refer hereafter to the first type as ironwork operations and the second as coating operations.

2.2.1.1 *Ironwork operations*

Ironwork involves both hot and mechanical methods to remove and replace concrete and steel components, which typically include decks, beams, bolts, rivets and other fasteners, valves, and piping. Post-process cleanup of debris is also included in the ironwork category. Welding, torch cutting and burning are called hot procedures since they heat steel surfaces and typically incinerate paint. Mechanical methods include any procedure where painted surfaces are subjected to mechanical disturbance.

A typical workday includes repeated cycles of cleaning steel, followed by removing and replacing components. Beam removal and replacement may involve either flame cutting with torches or mechanically busting rivets with a rivet buster. In some cases, rivets are burned out using a slice torch. New beams and other replacement components are either welded or bolted in place. In other cases, new holes are drilled or existing holes are enlarged using a reamer (Goldberg et al. 1997; Goldberg et al. 2000).

Paint removal is also part of ironwork. When conducted in an enclosed space, OSHA requires paint surrounding the work surface to be removed before steel is welded, torched or burned (OSHA 1996). Methods commonly used for this purpose include wet and dry blast cleaning, hand and power tool cleaning and chemical stripping. However, chemical stripping and wet blasting are less common techniques partly because they do not completely prepare the surface for recoating. Power tools used for surface preparation and component removal can be either air-powered, with or without vacuum attachments and collection containers, or powered by electricity. When air-powered, these tools also require an air compressor. Such a compressor, without vacuum attachments, must deliver a minimum grit volume per tool of 10 cfm when pressurized to about 90 psi. With vacuum attachments, this requirement increases to 200 cfm per tool (Trimber 1993; Smith & Beitelman 1994).

Paint and steel component removal and replacement may take place in open areas, in existing confined spaces, or within containment structures built to enclose the work area and confine dust and debris. These naturally ventilated containment structures often consist of permeable tarpaulins (tarps) with partially sealed joints. A containment classification system has been developed by the Society for Protective Coatings (formerly the Steel Structures Painting Council or SSPC) and a partially sealed containment is commonly referred to as an SSPC class 5 containment. Other containment systems are described in the section on coating operations.

For both legal and practical reasons, the amount of airborne dust and hazardous waste generated often determines work methods and the level of containment. A relevant law is the federal Resource Conservation and Recovery Act (RCRA), which mandates how waste material must be tested and treated. Under this law, if the leachable lead concentration is 5 parts per million or greater, the material is classified as hazardous waste, which requires special handling and containment (US EPA 1986; Spee, 1987; Goldberg et al. 1997; Smith & Beitelman 1994). State regulation and contractor practices can also influence work methods and containment selection (Appleman 1997).

2.2.1.2 Coating operations

Coating operations are implemented when the ironwork has been completed. Coating operations use mechanical methods to prepare steel surfaces for recoating with new paint. The most common method of surface preparation is by open abrasive blasting with either expendable or recyclable abrasive material. This method requires a compressor, pressurized blast pot, air hoses, blast hoses, blast nozzles, and personal protective equipment for the worker. In addition, when recyclable grit is used, a recycling unit and air dryers or moisture separators are also required. For certain jobs, the blasting nozzle can also be equipped with a vacuum shroud (vacuum blaster) (Smith & Beitelman 1994).

During abrasive blasting, a typical workday includes blasting a structure with abrasive materials such as steel pellets for about four hours, followed by one to two hours of vacuuming. Then, newly settled dust and debris is blown from blasted surfaces, followed by approximately two hours spent applying a primer coat. High-velocity mechanical disturbances are produced during the surface-cleaning phase, which generates a great amount of debris. Debris likely to be classified as hazardous waste requires containment so that paint chips, dust, and used abrasive are prevented from contaminating the nearby environment or exposing the public. For both full and partial removal jobs, depending on the location of work and whether shrouded power tools are used, the level of emission control varies from requiring only ground tarps to requiring negatively pressurized containment structures with filtered exhaust air (Mickelsen 1995; Appleman 1997).

There are six major containment designs used for abrasive-blast cleaning. These designs are referred to as bridge-to-grade, suspended tarpaulin, suspended platform, outrigger and cable, enclosed staging and micro-containment (Appleman 1997). Containment designs and the SSPC classification system that defines the level of emission control are further described in the appendix. Where possible, containment structures are designed so that the used abrasives and debris are directed through chutes or tubes into a barge or hopper. This is done both as a convenient method of disposal for debris and to facilitate recovery and recycling of used grit.

Because the recovery systems in the containment structures are not completely effective (or are absent), additional vacuuming and sometimes mopping the containment floors and walls are required to meet environmental regulations. Blast equipment operation and maintenance, sometimes also called groundwork or support, are conducted outside of containment.

Both ironwork and coating operations can generate substantial amounts of airborne particles. The next section characterizes some mechanisms of aerosol generation, transport, removal and resuspension using common ironwork and coating methods.

2.2.2 Mechanisms of aerosol generation

Although aerosol generation during coating and ironwork operations has not been well studied on bridges, some insight can be gained by understanding the general mechanisms of aerosol generation using hot and mechanical methods. This section outlines those general mechanisms.

2.2.2.1 Hot methods

Several tasks during ironwork involve heating steel components. During these tasks, lead may enter the environment through vaporization or burning of lead-containing compounds such as paint. Many welding and cutting tasks fall into this category. The temperatures of interest in a controlled welding process are typically between 500°C and the melting point of the mild steel (1493°C). Whenever welding or cutting is performed, using either oxy-acetylene torches or an arc welder, the workpiece can be heated to temperatures of 3300°C to 3800°C. The melting and normal vaporization temperatures of lead are, respectively, 520°C and 1750°C. Therefore, this torch cutting and burning heat nearby paint well beyond the temperature at which lead begins to vaporize (INSC 2002; Oxylance Corporation 2002; Smith Equipment 2002).

Although attempts are made to remove lead-containing paint in the immediate vicinity of a welding or cutting operation, experience has shown that some paint residue remains. Brumis and colleagues (2001) found that the method, abrasive blasting, was effective in stripping paint but that insufficient stripping resulted in burnt paint. Goldberg found that a least some paint remained on beams clean by shrouded pneumatic needle guns and rotopeeners prior to torch cutting (Goldberg et al. 2000). Combustion and vapor byproducts resulting from hot processes are a function of the type of coating, rate of ventilation in the combustion zone, flame intensity and fire geometry. In addition to the elemental lead and lead compounds of interest, these byproducts may include high concentrations of unburned hydrocarbons and particulate matter (Persson et al. 1998). With regard to dispersion of vaporized inorganic lead, the vapors rise due to thermal convection and can disperse into the near field of the worker performing the task. These vapors may also condense in the atmosphere to form metallic lead fume that can adhere to soot particles or be transformed into lead oxide. These fine particles are mostly less than one μm in aerodynamic diameter and are therefore respirable (Liu et al. 1996).

2.2.2.2 *Mechanical methods*

2.2.2.2.1 *Blasting*

Lead-containing particles reach high airborne concentrations during high-pressure blasting methods, which removes scale, paint and dirt from surfaces within an enclosure. Blasting involves propelling grit onto a surface at high velocity from a distance of about 1 m. Grit is released through a nozzle under high pressure (e.g. 100 psi). Grit velocity as it leaves the nozzle is around 120 meters per second. The surface clean rate for such operations is defined as the amount of surface area cleaned per unit time, typically expressed in $m^2\ hr^{-1}$. Surface clean rate depends on the specified cleanliness grade (e.g. commercial, near-white or white metal), feed rate, air pressure, type of grit material, and nozzle design. Rates can reach 47 $m^2\ hr^{-1}$ per operator, but a rate of 9 $m^2\ hr^{-1}$is typical (Holt et al. 2001; Settles et al. 1996; Smith & Beitelman 1994). In any case, such an operation results in a large amount of lead being emitted into the enclosure atmosphere.

Lead emission rates from blasting operations have been studied under typical working conditions. Conroy et al., (1995) found an average emission rate of 33 mg s^{-1} with a range of 1.3 – 70 mg s^{-1}. This occurred with two active blasters removing paint containing approximately 3% lead by weight. An average of 28 mg s^{-1}, with specific measurements ranging from 1.2 – 57 mg s^{-1} was observed with four blasters and with paint containing approximately 0.8% lead.

Airborne particles that emit from blasting with steel grit have diameters less than 10 μm as determined by particle counting and volume methods (FHWA 1995). Evidence from the Federal Highway Administration (FHWA) study suggested that a substantial proportion is in the sub-micron range. Particles in this size range can remain suspended for long periods, and pose a significant health risk if inhaled.

2.2.2.2.2 *Grinding, crushing, and drilling*

Liberation of lead due to mechanical disturbance of lead-based paint may occur during ironwork. Equipment such as manual or power scrapers, sanders, chippers, roto-peens, grinders, needle guns, rivet busters, wrenches and drills grind or crush dirt, paint and scale on structures (Goldberg et al. 1997; Goldbert et al. 2000; OSHA 1993; Sussell et al. 1992; Trimber 1993). For example, needle guns and roto-peens use expendable abrasive media disks and clean surfaces at a rate of about 0.9 to 1.4 m^2 per hr (Smith & Beitelman 1994). During this process, particles are propelled into the near field of the worker who is using the tool when local exhaust ventilation (LEV) attachments are absent or ineffective (Olhiser 2002).

Although not specific to bridgework, a few studies of similar mechanical mechanisms have been evaluated in other industries. Liu et al (1995) found that the mass median aerodynamic diameter (MMAD), measured by personal cascade impactor, was 7.2 μm for particles generated during a grinding operation in a brass foundry. These investigators also found that 19.8% of the particle mass generated during a similar operation had a MMAD of 10 μm or less and about 6% had 2 μm or less.

2.2.3 Mechanisms of resuspension

2.2.3.1 Mechanical motion

The simple act of moving around contaminated equipment can resuspend surface dust into the air. The operation and maintenance of blast, dust-collection and cleaning equipment, handling of containment structures, surface painting and groundwork during painting operations can cause resuspension. Additionally, lead becomes airborne when grit is recycled, filters are changed and when surfaces are blown down, swept, or vacuumed. Surface dust can be propelled into the near field of the worker performing any of these tasks.

2.2.3.2 High pressure release of air or other media

Recently cleaned surfaces may subsequently collect dust that settles out of the air. This settled lead dust may resuspend when new coatings are spray-applied, due to the pneumatic action of the sprayer. For example, conventional spray systems commonly used for applying zinc-rich coatings use streams of compressed air to atomize the paint and propel it through the air onto the steel part. The force exerted by such a sprayer is more than sufficient to blow the settled lead-containing dust from the workpiece and resuspend it into the atmosphere. Similarly, air discharges from other pneumatically driven tools, blow-off from repeated blast cleaning, or from airless spray paint systems can resuspend nearby surface dust (Goldberg et al. 2000; Olhiser 2002).

Each of these mechanisms can produce airborne particles with characteristics that affect how lead remains in the air and, if inhaled, how it deposits in the lung and absorbs into the bloodstream. Mechanical methods can cause particles to acquire an electrostatic charge, which affects whether they remain suspended or adhere to surfaces. Methods involving combustion or vaporization and condensation can initially form particles below 0.1 μm. As these particles coagulate, they can subsequently form particles in the range 0.2 to 1 μm, which tend to remain suspended in the air (Hinds 1982). The next section expands on these phenomena, describing the transport and removal mechanisms of airborne particles during ironwork and coating operations.

2.2.4 Airborne lead transport and removal mechanisms

During abrasive blasting, removed paint breaks up into particles or adheres to particles of grit and becomes airborne. Air currents transport suspended particles. Airborne particles within a containment structure can escape through leaks, be captured by filters, be attracted onto surfaces by electrostatic forces, or settle by gravity. Blasting produces clouds of particles that can travel through openings, and visible plumes have been observed several hundred feet downwind of a leaky containment structure before depositing (Mickelsen 1995; Randall et al. 1998; Sussell et al. 1992). Contact with surfaces inside the containment structure can create a bond so that the debris clings tenaciously to materials such as tarps, tools clothing or skin. When dehumidifiers are used to delay flash rusting on newly cleaned steel, the conditions become even more favorable for material adhesion through static electricity (Adams 1986; Olhiser 2002).

Mechanical ventilation systems are often employed to exhaust this airborne dust and debris. These systems also dilute airborne dust that can reduce visibility and the airborne concentration of lead for the worker. Some data are available to indicate the amount of ventilation required to substantially reduce to amount of airborne debris for a given containment volume. A study by Mickelsen (1995) specifically demonstrated the efficacy of mechanical ventilation for removing these airborne particles under different conditions. One large containment structure maintained a volume of 5600 m^3, with an airflow rate of 680 $m^3 min^{-1}$ and velocity at the face of exhaust vents of 1700 $m\ min^{-1}$. After blasting had ceased, the relative dust concentration took approximately 17 minutes to achieve a 90% reduction in particle concentration a value that is close to the theoretical prediction for a well-mixed space with removal by ventilation alone (Nazaroff et al. 2001). A smaller enclosure (volume = 85 m^3) with an airflow rate of 168 $m^3 min^{-1}$ and velocity at the face of exhaust vents of 34 $m\ min^{-1}$ reduced the relative dust concentration by 90% in approximately one minute (Mickelsen 1995).

Containment structures are ventilated using one or more dust collection systems that can have a manufacturer's rated air-pulling capacity of 850 $m^3 min^{-1}$. However, field performance of dust collection systems can deviate substantially from the manufacturer's rated airflow rates and high efficiency particulate air (HEPA) filtration (Mickelsen 1995; Seavey et al. 1996). SSPC Guide 6 suggests target exhaust vent face velocity rates of 30 $m\ min^{-1}$ for cross draft and 18 $m\ min^{-1}$ for down draft air movement through a small containment during abrasive blast operations (Appleman 1997).

In the remainder of this chapter, industrial hygiene and engineering evaluations from 15 bridge projects are examined. We focus on the influence of project tasks on personal breathing zone lead concentrations of bridge workers. These influences, along with those of a lead health protection program for bridge workers (examined in Chapters 3 and 5), provide a better understanding of the dynamics of lead exposure in construction.

2.3 Methods

Several methods were used to study bridgework and characterize lead exposure. We interviewed subject matter experts and visited an ongoing bridge project. We obtained publicly available records from a Department of Transportation and a federally funded demonstration project. As well, we conducted a systematic literature review and retrieved relevant industrial hygiene and engineering studies.

2.3.1 Study selection criteria

Numerous unpublished reports containing industrial hygiene evaluations were available for review from 58 bridge projects performed during the Connecticut Road Industry Surveillance project (CRISP). To increase the chances that there would be adequate data to analyze the review was restricted to those projects that had at least five monthly evaluations and provided some information on the time spent conducting abrasive blasting, ironwork or mechanical disturbance activities. Where more than one study was conducted during a bridge project, the study that provided the greatest number of air samples was selected. Information about potential influences of nearby work, equipment, materials and the environment on personal breathing zone lead concentration during the performance of tasks was also obtained through my review of industrial hygiene reports pertaining to these projects and interviews we conducted with industry experts.

To augment the Connecticut information, a literature search was conducted of industrial hygiene and engineering evaluations relating to other bridge projects of the past ten years. This search focused on studies that reported personal breathing zone (PBZ) concentrations of lead. Data were gathered by conducting a hand search of the Society of Protective Coatings and Linings trade journal and the American Industrial Hygiene Association journal, along with an online electronic search of other professional journals and available government reports. Data from these studies have been included for evaluation if they met the following additional criteria:

1) The study contained task-based samples that were collected from bridge projects conducted during the period 1991 and 2001;
2) Data were gathered by trained personnel, collected in the personal breathing zone of the worker performing the task outside of personal protective equipment, more than one air sample was reported and the sampling duration was recorded;
3) The distribution of air lead concentration sample values was reported or could be calculated;
4) Data were collected and analyzed using accepted methods. For example, samples collected on 37 mm mixed cellulose, using portable air sampling pumps at a flow rate of 2 liters min^{-1} and analyzed using the National Institute of Occupational Safety and Health (NIOSH) method 7082 (NIOSH);
5) The study was part of an on-site industrial hygiene or engineering evaluation of production processes and existing controls;
6) Data were from one or more projects with typical production processes and state-of-the-art engineering and work practice controls;
7) Annotations accompany data describing the conditions under which the sampling was conducted (task(s) performed and whether the task was conducted in an open or enclosed environment).

We conducted a systematic review of all available project evaluations found in peer reviewed literature. The purpose was to identify factors that affect lead levels in air, because differences existed between projects that might significantly impact these levels. For example, substantial differences existed between projects in the surface paint lead content. As well, state or local regulations sometimes prescribe the method chosen to prepare surfaces; for example requiring that "hot" (e.g. torch cutting and welding) work be conducted in an enclosure. It would not be possible to examine these factors by restricting the study to one project or a single state.

2.3.2 Statistical methods

Air sampling data were summarized by descriptive statistics. A tiered approach was used to examine the task-based air sampling data. Starting with five broadly defined activities (i.e. surface preparation, component removal and replacement, cleanup, surface coating and equipment handling) samples were progressively subdivided into multiple tasks within each activity. The relationship between sample duration and airborne lead concentration was examined using least-squares regression. We tested air lead concentration distributions for normality and lognormality using the Shapiro-Wilks and Shapiro-Francia methods. When the data was best characterized as lognormal, we performed a lognormal transformation prior to conducting a one-way analysis of variance (used to test for group homogeneity) and Bartlett's test for equal variance (STATA 1997). In rare cases, one or two unusually low concentration values appeared in the data set. Professional judgment was used to determine whether to include the value in the summary statistics; where a value was excluded, it is acknowledged in a table footnote.

2.4 Results

While my initial idea was to include as many projects as possible, it became clear that some winnowing of the data was necessary to perform a successful analysis. For one thing, this study was limited to those Connecticut projects that extended beyond an initial startup time so that we could capture routine and stable conditions. It was also restricted to the Connecticut projects that had more than a few air samples. Among these, monthly summaries that did not include some indication of daily routines were rejected because it was less clear how representative these air samples were of the underlying project conditions. However, some project evaluations were included from the peer-reviewed literature where sparse but adequate data on air concentration during specific tasks was available.

One hundred three bridge projects were identified in Connecticut Department of Transportation project logs as lead-related and scheduled to start between January 1991 and December 1995. Five or more monthly industrial hygiene reports were available for twenty-eight of these projects. Seventeen of those projects were rejected because reports provided sparse air sampling data or did not provide daily account of blast cleaning or ironwork tasks. Eleven evaluations met the inclusion criteria.

Additionally, eighteen potentially relevant project evaluations were found in the archived literature and available government reports. Four studies provided enough information for inclusion in my review (Conroy et al. 1995; Goldberg et al. 1997;Goldberg et al. 2000; Sussell et al. 1992; Randall et al. 1998). Six studies were rejected because not enough information was provided to determine the sampling duration or a measure of variance (Maurer et al. 1993; Mickelsen 1995; Mickelsen et al. 1995; Mickelsen et al. 1997; Sussell et al. 1992; Valenti et al. 1998). Six other studies were rejected because no information was provided on personal breathing zone lead outside personal protective equipment as the measure of exposure (Reynolds et al. 1997; Reynolds et al. 1999; Forst et al. 1997; Sokas et al. 1997; Levin et al. 1997; Brumis et al. 2001). Three studies provided overlapping air sample results on worker cohorts contained in the Connecticut project reports (Cannon et al. 1996; Hammond et al. 1994; Ewers et al. 1993).

In total, 2353 potentially relevant air samples extracted from project evaluations met the inclusion criteria. Of this number, 1425 were included in the analysis. We did not include air samples that were labeled as an 8-hr TWA, that involved more than one task or a job title, or that were collected inside hoods, helmets or capes. A few unusually low or insufficiently labeled samples were also excluded.

Sample results were rejected if they were labeled with a job title but not a specific task or activity. Also, sample results were rejected when more than one task-based sample was summarized as an 8-hr time weighted average. However, when sampling times indicated that one sample was taken over an entire shift and labeled as a single task or activity, it was included. Summary results that did not present enough information to determine a measure of variance among samples or did not report the sampling duration were rejected. The variance of aggregated task-based samples provides some indication of the influence of working conditions. The amount of time over which a single sample has been collected determines whether sample results for a particular task can be combined. Finally, air samples taken inside hoods, helmets or capes were not comparable to personal breathing zone air samples outside personal protective equipment. In the end, 61% of the air samples taken during industrial hygiene evaluations were judged to be relevant for the purpose of this study.

2.4.1 Bridge characteristics

Tables 2.1a and b list the characteristics of fifteen bridge projects conducted as part of CRISP (Table 2.1a) and in other states (Table 2.1b). Fifty-two structures were included in these projects. Most were girder designs, located outside of major metropolitan areas, and constructed between 1957 and 1965. Bridge structures ranged in total length from 80 m to 6401 m. Most were coated with paint having a lead content by weight of approximately 20%. However, lead content on bridge structures ranged from less than

1% on project 11 to over 70% on project 10. Most projects conducted some enclosed work although only limited information was provided about containment structures.

2.4.2 Project activities

Table 2.2a displays the distributions from PBZ lead samples taken during the 11 projects conducted under CRISP and divided into 6 project activity categories. There were 343 air samples classified as a surface preparation activity. Component removal and replacement activities produced 130 air samples. Work area cleanup activities provided 174 air samples. Coating activities produced 83 air samples and equipment-handling activities provided 456 samples. Twelve air samples were labeled as inspection and carpentry and classified here as 'other duties'. Substantial variability is present in each activity group where almost all of the geometric standard deviations (GSD) exceed 5.0. As well, Shapiro Wilk p-values were less than 0.05 for almost all groups, indicating that these data are neither normally nor log-normally distributed.

Air samples were further divided into 13 sub-activities based on the mechanisms of particle generation or resuspension described in the introduction. Summaries appear in Table 2.2b. Surface-preparation was subdivided into abrasive blasting and power-tool cleaning. This subdivision reduced a combined GSD of almost 9.0 to two GSD values of 7.2 and 4.4. Component removal and replacement was subdivided into component removal, heating processes and mechanical processes producing a mechanical process GSD that is one half that observed in the broader activity group (i.e. 6.1 to 3.2). Cleanup was divided into general cleanup, cleanup with hand tools and cleanup with power tools. The resulting GSD of the air lead concentrations included in the subdivision labeled 'cleanup with power tools' is larger than the GSD for the combined group labeled 'cleanup'. Equipment handling was subdivided into setup, containment handling and groundwork. Similarly, the subdivision labeled 'groundwork' has a larger GSD than the combined group labeled 'equipment handling'. All other sub-divisions resulted in less variability than their parent group. Shapiro Wilk p-values were greater than 0.05 for log transformed data from about half of the 13 subgroups suggests that the data do not significantly differ from a normal distribution. Bartlett's test for equal variance was reasonably satisfied (p-values mostly >0.05).

The tool, equipment or process largely identified further subdivisions of air samples grouped by task. Concentration distributions from each group are summarized in Tables 2.3a-e. However, two analyses were conducted on the Connecticut project concentrations prior to summarizing the task-based distributions produced from all projects.

Table 2.2c displays the distribution of task-based sample duration. Most tasks contain concentrations measured over a wide range of sampling times. A linear decrease in air concentration with increasing sampling duration is significant among air concentrations produced by abrasive blasting, needle gunning, recycling operation and painting tasks. This suggests that a lesser proportion of time was spent performing the actual task as sampling time increased. This possibility was evident in the pool of samples taken during abrasive blasting. Most task samples were taken over a period of 4 to 6 hours while a few were taken over a period of 30 – 75 minutes. The latter measurements tended to show higher results than the former, suggesting that longer sampling time represent proportionately less time performing the actual task. However, the opposite relationship is observed among a few concrete chipping air samples (N=4).

Task-based concentration distributions were examined for normality and log normality (Table 2.2d). Shapiro Wilk p-values were greater than 0.05 for log transformed data from most of the subgroups, indicating that the data do not significantly differ from a normal distribution.

2.4.3 Task based personal breathing zone lead concentrations

PBZ lead concentration distributions from Connecticut (CT) and non- Connecticut bridge projects are displayed in Tables 2.3a-e, which are referred to as projects 1-11 and 12-15 respectively. Pertinent air samples were derived from multiple projects, spanning several days in each instance, and were taken from a number of workers. On any given day, air samples were taken mostly over 4-7 hour-long periods to measure the concentration of lead in the PBZ produced by a particular task. Each table displays the results for tasks that pertain to a specific lead-related activity. In many cases, a particular technology, context, or tool further subdivides a particular task.

2.4.3.1 Surface preparation

Surface preparation tasks (Table 2.3a) were evaluated in the PBZ of workers during eleven CT and three non- CT bridge projects. The abrasive blasting method was evaluated on twelve projects. Evaluators (field technicians) specified air samples taken during abrasive blasting as to whether LEV attachments were used on tools. We further stratified this task by two additional factors, namely, the class of containment structure and the percentage weight of lead in the paint. Project 11 had substantially lower lead content (1%) relative to the other CT projects (15% - 34%). When stratified by lead content, project 11 exhibits a 4-fold lower estimate from projects 4 –10 in all measures of central tendency. Information about lead content in the paint during projects 4 and 5 was not available so separate distribution estimates were examined by including and excluding air samples from these two projects. No substantial change occurred when samples from projects 4 and 5 were removed. The geometric mean air concentration from Project 3 open abrasive blasting samples, which comprises the highest average lead content (i.e. 34%), is 3-fold higher than the geometric mean from projects 4 – 10. With the exception of project 11, geometric mean PBZ lead concentration during open abrasive blasting varied from 2000 – 11000 $\mu g\ m^{-3}$. The arithmetic mean (AM) typically varied from 9000 – 14000 $\mu g\ m^{-3}$, but individual measurements have reached almost 200,000 $\mu g\ m^{-3}$. Variability among Connecticut abrasive blasting air concentration drops considerably only when parsed into individual projects. Compared with open abrasive blasting, vacuum blasting reduces concentrations by at least an order of magnitude.

These data indicate that concentrations during vacuum blasting still exceed 50 μg m^{-3} but tend to stay below 500 μg m^{-3}.

Eight projects evaluated concentrations produced during the use of power tools. Some project evaluators further stratified power tool use by the presence or absence of a LEV and the use of a particular type of tool. Two projects assessed power tool cleaning without vacuum attachments (projects 9 and 13). Substantial differences among concentration distributions may be due in part to the type of tool used (e.g. needle gun versus grinder or scaler), or the lead content in the paint (e.g. 18% on project 9 versus 39.1% on project 13). Nevertheless, these data suggest that concentrations produced from power tool use without LEV attachments may exceed 5000 μg m^{-3} and that, under similar conditions, power tools equipped with vacuum attachments reduce the mean PBZ lead concentration by at least an order of magnitude.

2.4.3.2 Component removal and replacement

Component removal and replacement tasks (Table 2.3b) were evaluated on five CT and one non-CT bridge projects. Evaluators obtained air samples during seven component removal and replacement tasks, involving methods that either combust or pulverize surface paint. Evaluators subdivided combustion tasks into welding, torch cutting, and burning. We further separated out air samples produced by torch cutting from two projects that either had a much lower lead content in the paint or used an abrasive-blasting method of surface preparation prior to torch cutting. This yields a 4-fold lower AM for projects 2 and 11 compared with the AM for projects 1,8 and 9. Project 13 produced a two-fold higher AM compared to project group 1,8 and 9. Project 13 involved twice the lead content in the paint (39% versus 20%) and samples were collected during one third the amount of time compared to those collected on projects 1,8 and 9 (133 versus 413 minutes). It is possible that one or both factors influenced the observed differences in distribution estimates.

PBZ lead concentrations during burning were evaluated on CT projects 1 and 9 and on project 13 from New York. Concentrations were 20-fold greater in New York. However, there are several differences between the CT and New York projects. Sampling times from the New York project were one fifth those taken from CT projects, work in New York was conducted in an enclosed space and, as noted above, the lead content in the paint was substantially higher on the New York bridge (project 13).

PBZ concentrations produced by welding were evaluated on five CT projects. Concentrations produced during welding can reach levels observed during torch cutting, but typically only reach levels 4-fold lower than during the latter (AM = 150 μg m^{-3} versus 650 μg m^{-3}).

PBZ concentrations generated by mechanical methods were reported separately by project evaluators as drilling, rivet busting, reaming and bolting up. Drilling was evaluated during five bridge projects and mostly produced air concentrations below 20 $\mu g\ m^{-3}$. Rivet busting, reaming and bolting up were only evaluated during one New York project. Rivet busting was further subdivided according to the level of enclosure, as the AM was twice as high when this work was conducted in an enclosed area (AM = 200 $\mu g\ m^{-3}$ versus 420 $\mu g\ m^{-3}$).

2.4.3.3 Cleanup

Cleanup tasks (Table 2.3c) were evaluated on Connecticut bridges during projects 2-11. Many of the PBZ lead concentrations were delineated by the tool used to conduct the task, the level of enclosure or the simultaneous performance of nearby tasks. Vacuuming conducted during abrasive blasting produced 70-fold greater AM air concentrations compared to the AM produced from the same task conducted after abrasive blasting.

Three projects evaluated air concentrations produced during 'blow- down' (a post-blasting cleaning step where the cleaned surface is dusted with an air hose). When combined, there was substantial heterogeneity in air concentrations among projects, as indicated by a large F-test result and small p-value. We explored bridge attributes that could be used to delineate this task into more homogeneous groups, and found that the total length of bridge structures included in the project potentially influences air concentrations during this task. One smaller project (6) produced ten-fold larger AM during blow- down compared to two larger projects (9 and 11).

2.4.3.4 Surface coating

Surface coating tasks (Table 2.3d) were evaluated during seven Connecticut projects. When coating is stratified on sequence, prime coatings produced five times higher airborne lead concentrations than those produced during the application of mid or top coats. In fact, prime coating produced PBZ concentrations in excess of 500 $\mu g\ m^{-3}$.

2.4.3.5 Equipment handling

Ten CT and two non-CT projects evaluated equipment handling tasks (Table 2.3e). On six projects (4, 7-11), evaluators used 'groundwork' to label PBZ concentrations during any work conducted outside the containment structure. On other occasions, evaluators delineated groundwork into equipment 'operations' and 'maintenance'. This refinement produced a two to four-fold higher AM than tasks simply labeled groundwork. 'Maintenance' produced a similar AM to groundwork, but substantially higher AM than 'operations'. An even greater refinement of operations revealed that three times higher concentrations were produced while tending recyclers, separators or air handlers than during grit pot tending. The AM concentration produced during filter changing is at least ten-fold higher than from samples simply labeled equipment maintenance.

PBZ concentrations produced during 'support' on coating operations, which is essentially the same as groundwork, were of the same order of magnitude as those produced by groundwork and containment handling. However, PBZ concentrations produced during 'support' on ironwork operations were much lower (below 50 $\mu g\ m^{-3}$).

Eight projects evaluated PBZ concentrations produced during containment structure handling and nine projects evaluated setup. Concentrations during setup are similar in magnitude to those produced during pot tending. Containment handling produced substantially different concentrations among projects, so we further stratified this task on percentage lead content in the paint and found at least five-fold lower measures of central tendency from project 11 compared to the aggregate results from seven other projects.

Tasks with only one or two air samples during CT and non-CT bridge projects are displayed in Table 2.4.

2.5 Discussion

This chapter augments the information synthesized by OSHA, NIOSH, the Transportation Research Board, US Army Corps of Engineers and the FHWA (Appleman 1997; FHWA 2002; OSHA 1993; Smith & Beitelman 1994; Sussell 1997). The study here presented characterizes the sources of lead exposure from bridgework that involves the disturbance of leaded paint. Integral to this study, we have examined in detail the methods, devices and work practices designed to control exposures during ironwork and paint removal operations.

Group differences were examined using a one-way log normal analysis of variance model. This fixed-effects model examined how task and sub-activity groupings affect mean PBZ concentration variances within each group. The assumption of equal variances required to use the comparison procedure was rarely violated at the task level. The tiered approach that progressively grouped task-level concentrations based on different work conditions has substantially extended the list provided in the 1993 OSHA standard (OSHA 1993). This augmented list can further guide decisions about initial worker protection under similar conditions.

2.5.1 Findings and Interpretation

Multiple work-related factors influenced PBZ concentrations of lead during bridgework. Also, the definition of what constitutes a task evolved over time. As air samples were more precisely labeled, it became apparent that a particular tool, piece of equipment or context seemed to influence lead air concentrations. As well, when the sampling time became shorter, differences were observed between concentration distributions for the same task.

Sometimes identifying what constitutes a task was not straightforward. There were several examples where a job assignment needed to be further subdivided into different duties which each displayed a unique distribution of PBZ concentrations. The larger aggregate data were homogenous if the task's means and variances were not statistically significantly different. For instance, we subdivided air samples grouped under the label 'groundwork' into more refined categories 'equipment maintenance' and 'operation' and then further subdivided into 'filter changing' and 'monitoring recycling equipment'. When so parsed, these tasks produced substantially different distribution of PBZ concentrations. When painting was monitored and labeled as a second or third rather than first coat of paint application, the resulting air concentrations were systematically different because the first paint application blows the residual lead particles off the surface. To cite still another example, there was a noticeable difference of result between subdivisions when vacuuming was subdivided between vacuuming 'during blasting' (in containment) versus 'after blasting' (outside containment).

In a workplace when there are dozens of tools that seem to aerosolize lead by a similar mechanism, it is tempting to treat them as one task. Welding, torch cutting and burning (e.g. using a slice lance); for example have been treated in this manner in the OSHA Lead in Construction Standard. However, we observed that welding produced distinctly different PBZ concentrations than burning and torch cutting, which suggests that a composite of samples from workers using these three tools can lead to biased estimates of PBZ lead concentrations. The same could be true for the combination of tasks known as 'power tool cleaning'. Unfortunately, we could not evaluate this possibility given the large variation in sampling time among the data included in this study because differences in sampling time potentially represent lead concentration averaged over both task and non-task intervals. Therefore, the potential influence of different power tools and burning tasks on PBZ lead concentrations could not be evaluated due to insufficient data.

A 3-fold larger AM was observed among PBZ concentrations for workers tending recyclers compared to workers tending grit pots which contained either fresh grit or grit that has been cleaned (recycled). This finding is consistent with the circumstance that recyclers handle contaminated grit, which is a prolific source of lead dust. Specifically, bulk samples of contaminated steel grit collected during a coating operation on a steel tank have been shown to contain 10-fold more lead than cleaned grit (Sussel et al. 1992).

As mentioned above, welding produced considerably lower (one half) PBZ concentrations than produced by burning or torch cutting. One possible explanation for this difference is the operating temperature of each process. Controlled welding operates between the melting and vaporization temperature (i.e. flash point) of lead and therefore may not actually cause paint to combust. Torch cutting operates at much higher temperatures, which can easily vaporize lead. An alternate possibility is that the amount of painted surface area involved in welding is typically much less than for torch cutting.

In any case, these findings suggest that there is a substantial difference between welding and torch cutting processes. They should be classified as different tasks when describing lead exposure.

Air concentrations from painting that occurred on the same day following the blast cleaning process (i.e., primer application) differed substantially from coating applications that occurred some later time (e.g. mid and top coating). It is possible that high-pressure spray painting activity itself resuspends nearby surface dust during prime coat applications. Just prior to priming, clean steel is 'blown down' to remove dust, grit and debris. Surfaces are then inspected and primed at the end of the day. This means that steel is painted quite soon after it has been abrasively blasted so dust can resettle alongside the freshly blown- down steel surface. It is also possible that carrying and blowing grit away from the work area resuspends nearby surface dust while applying the prime coat. To avoid having the residual airborne dusts settle and bind into the primer coat, crews often blow and carry grit and debris farther away from the work area. This movement resuspends the finer and denser particles from the blasted substrates (Olhiser 2002).

Cleanup is also a task that seems to be affected by activity occurring in other areas of the workspace. Vacuuming during abrasive blasting produced much higher PBZ concentrations than were produced by the same task conducted after abrasive blasting had ceased. Theoretically, a crew could finish sooner by removing debris and grit during blasting activity so that it does not build up as the work progresses in which case more surface area could be blasted before the end of the day. If so, these findings impose a potential constraint on production rates.

Another activity that could impose tension between reduction of PBZ contamination and production rates is surface preparation. Abrasive blasting typically cleans to commercial or near-white levels at 9.3 to 13.6 m^2 hr^{-1}, whereas power tools clean at a rate of 0.9 to 1.4 m^2 hr^{-1}. Obviously, a slower clean rate could severely extend the time and cost of surface preparation on bridge projects. Alternatively, power tools are better when it comes to controlling lead containing dust because of their slower removal rate. Indeed, this study indicates that air concentrations are often reduced by orders of magnitude when cleaning is performed using power tools instead of open abrasive blasting. Power tools are particularly effective at limiting airborne dust when used with LEV attachments. This reduction has been observed in at least one other study of power tool paint removal activities (Croteau et al. 2002). However, there remain some questions about how easily power tools can be fitted and operated with these attachments. All tools can be retrofitted with vacuum attachments, and most new tools come with manufacturer-installed kits. To operate them properly, though, the vacuum shroud has to be flush to the surface or most of the capture efficiency is lost. Vacuum tools generally work well for small projects, but become difficult to operate for extended periods because the attachments and additional hosing make the original tool much heavier and more cumbersome (Olhiser 2002).

Despite generating great quantities of dust, surfaces cleaned by abrasive blasting are freer of lead than those cleaned by power tools. This could, in part, explain the relatively low concentrations produced from torch cutting on project 2. Higher PBZ lead concentrations produced by welding, torch cutting or burning suggests that prior cleaning with power tools may have been incomplete. Brumis and Goldberg have suggested that this is due to the configuration of the beams, which obscure or covered parts of painted surfaces and reduce their accessibility to the paint-stripping tool. Goldberg observed that red lead primer was at times visible on about 10 percent of the steel surfaces after paint removal. He observed that, over time, the primer had penetrated into the profile of the steel plate. He estimated that at least some paint remained on the steel about 75 percent of the time. Brumis compared air concentrations produced from torch cutting on partially stripped and unstripped steel. Samples taken inside a welder's helmet were 670 $\mu g\ m^{-3}$ versus 30,000 $\mu g\ m^{-3}$ respectively (Goldberg et al. 2000; Brumis et al. 2001).

Enclosing work areas may influence PBZ concentration produced from component removal and replacement work. Concentrations produced by torch cutting were quite different between Connecticut projects and project 13, which was conducted in New York. On project 13, rivet busting was done within a 9 m by 14 m containment structure. Goldberg found that the dust and debris that was generated during this task was easily resuspended by the vibrating action and air exhausted from the pneumatic tools (Goldberg et al. 2000). This effect along with the absence of significant natural ventilation provides some insight toward reasons for the observed difference.

It was surprising to see elevated PBZ concentrations during Setup, which generally does not disturb paint. One possible reason may have been surface dust from deteriorated paint. Lead loading on wipe samples during scaffold setup averaged five to ten thousand micrograms per square foot on some projects (Olhiser 2002). In a report of lead poisoning among ironworkers, Reynolds noted that ironworkers could have been poisoned by the visible orange dust on the surfaces of beams exposed once a bridge deck was removed (Reynolds et al. 1997). It is also possible that tetra-ethyl lead particles from past auto emissions were present in sufficient quantity to cause blood lead levels to increase prior to any disturbance of the paint.

Many potential influences on air concentrations produced by bridge renovation activity were explored in this study and considerable insight has been gained from this analysis. However, in many instances, substantial variability persisted (i.e. $GSD \geq 4.5$) (Rock 1995). Some variability is likely to be due to the fluctuation in the inherent mechanisms of particle generation during a task. Large variability between monitoring periods could come from factors that we have already identified such as the amount of blasted area, lead content of the paint, other workers' performing tasks nearby and variations in ventilation rates near the task. However, large GSDs could also reflect unmeasured influences on PBZ concentrations. Several potential sources of unmeasured influences on task-based airborne lead concentration are discussed in the next two sections.

2.5.2 Study limitations

Bridge projects evaluated in this study were limited to more common techniques deployed during ironwork and coating operations. Less common methods of paint removal include chemical stripping and wet blasting. There are also many other materials in use for conducting paint and component removal and replacement activities. Project-wide influences on some tasks could not be explored since evaluations were only available from one project. Therefore, inter-project influences are limited to the particular practices, technology and environments represented by the 15 projects included in this review. Many air samples were collected over several hours. When airborne lead concentrations were extremely high, this collection practice may have overloaded filters and limited the air sampling data used in this study in another way.

Air concentrations may be even higher during blasting than reported. Ewers et al. (1993) pointed out that the recommended NIOSH filter load of 2 milligrams of dust was exceeded after 15 minutes of sampling during a blasting task. Sampling often ran for 2 or more hours, so it is possible that overloaded cassettes could have reduced the airflow through the filters. If field technicians did not check flow rates and reported the rate set at the beginning of the sample, this reduction could cause air concentrations to be underestimated. A rough estimate of visibility extinction from dust that is generated during blasting suggests this possibility. We can further support this possibility by employing Hind's equation for visual extinction (Hinds 1982), $L_v = 3.9 \times 0.4 / C$, where L_v (m) is the visual range and C (g m^{-3}) is the mass concentration for respirable dust particles. Using this formula, an estimated lead concentration for respirable particles of approximately 1 g m^{-3}could extinguish an object 1.6 m away. This is the typical distance between a blaster and the surface to be blast cleaned. Randall sampled both respirable dust and airborne lead concentrations during a bridge rehabilitation project in New York (Randall et al. 1998). If Randall's findings are used to convert respirable dust to lead concentration, then a rough estimate of ~72,000-143,000 μg m^{-3} of lead when there is 20% lead content in the paint would reach visibility extinction during a blasting episode. Interestingly enough, air concentrations of this magnitude were occasionally observed among bridge projects with similar lead content (i.e., about 20%) in the paint. Sometimes blasting commences until the blaster no longer can see the work piece. Then, when enough dust has cleared, blasting resumes (Olhiser 2002). This pattern would result in a series of PBZ lead concentrations during short periods of time that reach or exceed 200,000 μg m^{-3}, which may not be reflected in longer term air samples. Two hundred thousand per cubic meter is 4 times the maximum limit for the type of respirators blasters typically use during this type of activity. It is much more likely that workers could inhale acutely toxic levels of lead if peak levels of this magnitude are reached.

The bridge project workplace could benefit from further investigation in several areas. The next section highlights some gaps in current knowledge.

2.5.3 Further research needs

Several topics warrant further investigation. Not much is known about the particle size distribution produced from paint combustion during bridge component removal and replacement, or the implications of particle charge on contaminant exposure and control. The particular effects on the PBZ air exchange within containment structures of various designs warrant further investigation. Finally, the implications of potential ingestion pathways at work and respirator performance during bridgework need further exploration.

2.5.3.1 Particle size distribution

The study presented here examined airborne lead concentration produced by hot and mechanical methods. There is evidence from studies of similar processes that hot and mechanical methods generate characteristically different particle size distributions. Air concentrations of the same order of magnitude as those produced by abrasive blasting with recyclable and expendable grit have been measured in the breathing zone of welders and torch cutters (Goldberg et al. 2000). However, particles travel through and deposit in the lungs differently depending on their size and shape and breathing pattern (Castellino et al. 1995). In a modeling study, Esmen et al. (2002) found that particles in the size range of fume particles could deposit in the lungs up to 10 times the mass of dust particles. If, as implied, equivalent air concentrations from hot compared to mechanical processes can pose a much greater hazard to the worker, particle size and composition relative to lead concentration merits further investigation.

2.5.3.2 Containment characteristics and ventilation

Studies that examined differences between PBZ and area concentrations in homes and occupational environments indicate that area concentrations are not the same as PBZ levels (Wallace 1996). For example, Mickelsen (1995) reported that there was a considerable difference between the area and PBZ concentration of lead among workers who performed blast-cleaning tasks. When the concentration reaches steady state (C_∞) it is equal to the generation rate (G) divided by the PBZ ventilation rate (β) plus G divided by the area ventilation rate (Q). However, Conroy (1995) argued that air concentration quickly becomes uniform throughout a containment structure because of the high velocity action of abrasive blast cleaning. In that case $\beta >> Q$ so $C_\infty \approx G/Q$.

Most project evaluations included in the present analysis provided limited information about the characteristics of enclosures and ventilation. It is possible that the air exchange rate and particle dispersion characteristics within enclosures could impact PBZ lead concentrations during the performance of enclosed tasks. Further research is needed to examine the effects of containment characteristics and ventilation on the air exchange in PBZs of enclosed workers.

2.5.3.3 Particle charge and other transformations

Charged particles tenaciously cling to paint removal containment materials. Clear or white plastic tarps inside the containment provide a vivid contrast to the red particles that cover the walls of the containment. This loading is tough to remove, often requiring mops and vacuums (Olhiser 2002). There is ample reason to study improved methods for cleaning such surfaces, as well as investigating possible ways of avoiding buildup and reducing adhesion.

Possible physiological effects from inhaling these transformed particles have also been scantily studied. In theory, charged particles and polarized molecules (which can easily acquire a charge) would be expected to deposit and clear differently in the respiratory tracts of workers. One study of acid ions revealed that considerable mass is deposited in the upper respiratory tract when a polar substance is inhaled (Frederick et al. 1998). However, there is limited information about these effects on respiratory tract deposition, absorption and clearance of non-water soluble, charged or oxidized lead particles.

2.5.3.4 *Ingestion and take-home lead*

Decontamination units that contained showers were located either on site or a few miles away during almost all of the projects included in this study. During Connecticut projects, blast and air cleaning equipment, respirators, decontamination units and lunch trailers were monitored for lead contamination. Lead dust loading of around 53800 - 75300 $\mu g\ m^{-2}$ prior to cleaning respirators and other surfaces were recorded. Loading of more than 75300 $\mu g\ m^{-2}$ was found on workers prior to washing their hands or showering at the end of the day (Cannon et al. 1996). Often, a 15 to 20-fold decrease was recorded from cleaned surfaces and washed hands. An evaluation of skin wipes of blasters after being buddy-vacuumed detected residual lead of about 500 µg. (Olhiser 2002). Vehicles used by work site personnel also contained lead (Piacitelli et al. 1995). These potential sources of exposure and the pathway toward lead intake need further examination.

2.5.3.5 *What about personal protective equipment (PPE)?*

This study has examined PBZ concentrations produced from several tasks and workplace conditions during ironwork and coating operations. Most task-based air concentrations of lead were above acceptable limits set by OSHA. Industrial hygiene evaluations reported that workers wore respiratory protection and underwent blood lead testing. Several studies have attempted to examine air concentrations of lead inside welding helmets, blast hoods and blast helmets (Brumis et al. 2001; Conroy et al. 1995; Liu et al. 1995). Only a few have examined the degree of protection afforded by these devices (Sussell et al. 1992; Feletto). Others have examined the efficacy of powered air purifying and negative pressure respirators (Myers et al. 1986). Further study is needed to examine the efficiency of respiratory protection on reducing inhaled lead concentrations.

2.5.4 Summary

We have described two bridge maintenance operations in this chapter. Over 30 different tasks were performed during these operations that sometimes generated PBZ lead concentrations above the OSHA 8-hr TWA PEL of 50 $\mu g\ m^{-3}$. We found that task-based concentrations could vary considerably due to several factors. Namely, the lead paint content on the bridge, whether the task is carried out in an enclosure, whether a cleaning tool has a vacuum attachment, whether other lead disturbing tasks were carried out nearby, or the method employed for cleaning a surface play a role in determining exposure to lead. An understanding of how these factors impact lead exposure in construction work is a prerequisite to formulating an effective control strategy in this type of setting.

Another essential piece of the puzzle would address lead intake among exposed workers. So far no information has been presented about lead intake among bridge crews. In industrial settings, a job title may be an adequate indicator of a worker's long-term exposure and a stationary process may be an easy target for source control. However, in construction, a job title can be a poor indicator of many workers' long-term exposure. This is particularly true for titles such as 'laborer' or 'foreman'. In any case, task-based air sampling along with regular bio- monitoring is needed to characterize long-term lead exposure and lead intake and construct an adequate control system.

Most of the task-based PBZ concentrations and important accompanying information was gathered in Connecticut during a comprehensive demonstration project to prevent lead poisoning during an intense effort to rehabilitate the state's bridge infrastructure. A medical monitoring program accompanied industrial hygiene evaluations. Chapter 3 describes CRISP overall along with workforce exposures as determined from frequent measurements of blood lead concentration. The effectiveness of the CRISP intervention will be examined by making comparisons between the peak blood lead levels of CRISP workers and workers who conducted similar projects without the CRISP lead health protection program.

Table 2.1a: Connecticut bridge and rehabilitation project characteristics

Bridge code	Evaluator	Eval period	# bridges	Year built (rehab)	Bridge type	Total length in m (surface area m^2)	% lead content	Operation	Enclosure	Town (s)
1	Enviromed	4/94 - 10/94	4	1958	girder	167	15	ironwork	none	Montville
2	Enviromed	12/94 - 4/95	1	1961	girder	80		ironwork	suspended tarp (class 5)	Old Lyme
3	Leighton	7/95 - 6/96	2	1961	girder	831	34	coating	enclosed non specific	Seymour
4	Leighton	10/94 - 7/95	5	1958 (1990), 1964	girder	384		coating	enclosed non specific	Stonington, Groton, Plainfield
5	Enviro - science	9/95 - 3/96	5	1958	girder	198		coating	enclosed non specific	Old and East Lyme, Plainfield
6	Leighton	7/94 - 11/94	5	1957 (1989), 1965	1 box girder, all others girder	366*	29	coating	enclosed non specific, box girder	New Haven, Branford, Milford, Wallingford
7	Enviromed	4/95 - 6/95	7	1965	1 girder & floor beam, 6 girder	274	23	coating	bridge to grade, mobil trailer	New Haven
8	Enviromed	6/94 - 11/94	2	1958	girder	134	20	ironwork & coating	bridge to grade, mobil trailer	Fairfield
9	Leighton	1/94 - 12/95	1	1938 (1992)	thru - Arch	1048	18	ironwork & coating	enclosed not specified, side containment (e.g.handrail)	Middletown and Portland
10	Enviromed	7/95 - 9/95	9	1965	girder	809	20 (70 max)	coating	enclosed non specific	Waterbury, Naugatuck
11	Enviromed	1/93 - 12/95	4	1943 (1975), 1973	truss deck	3219 (278,700)	1.0 (<0.1 - 18)	ironwork & coating	bridge to grade, ridged suspended platform, enclosed staging, mini	New London, Groton

* estimated from Connecticut DOT records - one bridge structure was not able to be located in the database; the 'eval period' is the earliest and latest date (month and year) in which project evaluation reports were available.

Table 2.1b: Bridge and rehabilitation project characteristics outside of Connecticut

Bridge code	Evaluator	Eval period	# bridges	Year built (rehab)	Bridge type	Total length in m (surface area m^2)	% lead content	Operation	Enclosure	State	Town (s)	References
12	NIOSH	1991	1	1963	through - truss	529 (131,000)	alkyd primer (red lead)	coating	suspended tarp (class 5)	KY	Covington	Sussell et al (1992)
13	NYU	1993 - 1994	2	1908	suspension	2831	39 (61 max)	ironwork	suspended tarp (class 5)	NY	New York City	Goldberg (1997, 2000)
14	USEPA	1992	2	-	rolled beam	(3711)	20	coating	bridge to grade	NY	Western New York	Randell et al (1998)
15	UNIV ILL, Chic	1991 - 1992	2	-	Bascule	(254,400) **	<1.0 - 3.0	coating	enclosed non specific	Ill	Chicago	Conroy et al (1995)

m = meters, ; ** used ton/square feet conversion factor given in Appleman 1997 pg 23 and then converted to square meters; m, meters; CT. Connecticut; the 'eval period' is the earliest and latest date (year) in which the project evaluation was published.

Table 2.2a: Summary of personal breathing zone lead concentration grouped by bridge activity

		Air concentration (µg m^{-3})						Shapiro-Wilk normal		Log-normal	
Activity	N	AM sample duration (min)	AM (SD)	MIN	MAX	GM (GSD)	N sub groups	W-statistic	p-value of Z	W-statistic	p-value of Z
Surface preparation	343	379	6758 (15800)	3.0	184701	1266 (9.0)	2	0.41	0.00	0.98	0.00
Component removal and replacement	130	354	184 (380)	1.7	2324	42.0 (6.1)	3	0.51	0.00	0.97	0.01
Cleanup	174	341	905 (1833)	7.0	11842	217 (5.5)	3	0.53	0.00	0.98	0.00
Handing equipment and supplies	456	347	538 (5625)	1.2	112060	23.4 (5.8)	3	0.06	0.00	0.92	0.00
Coating application	83	270	128 (261)	3.0	1979	41.9 (4.5)	1	0.48	0.00	0.98	0.24
Other duties	12	303	130 (255)	2.0	881	20.7 (8.1)	1	0.58	0.00	0.89	0.12

µg , micrograms; m, meters; N, number of air samples, AM, arithmetic mean; SD, standard deviation; GM, geometric mean; GSD, geometric standard deviation.

Table 2.2b Summary of air samples divided into 13 sub-activities based on mechanisms of particle generation or resuspension

		Air concentration (μg m^{-3})						Shapiro-Wilk normal		log normal		ANOVA between tools			
Activity category	N samples	AM sample duration (minutes)	AM (SD)	MIN	MAX	GM (GSD)	N tasks	W-statistic	p-value of Z	W-statistic	p-value of Z	btw grp (F)	p-value	equal variance test	p-value
abrasive blasting	309	371	7487 (16487)	3.0	184701	1796 (7.1)	1	0.43	0.00	0.98	0.00	-	-	-	-
power tool cleaning	34	306	137 (209)	4.3	869	52.8 (4.4)	6	0.63	0.00	0.97	0.49	5.60	0.00	5.15	0.16
component removal	2		13.1 (8.4)	7.2	19.0	11.7 (2.0)	1	-	-	-	-	-	-	-	-
heating component removal, replacement	104	350	224 (415)	1.7	2324	58.7 (6.0)	3	0.56	0.00	0.98	0.08	4.46	0.01	4.18	0.12
mechanical component removal, replacement	24	373	22.6 (34.0)	2.6	148	10 (3.2)	4	0.62	0.00	0.92	0.06	1.39	0.28	1.68	0.64
cleanup	11	343	486 (1171)	8.0	4006	128 (4.8)	1	0.42	0.00	0.93	0.44				
cleanup with hand tools	21	271	368 (825)	8.3	3873	133 (4.0)	3	0.41	0.00	0.98	0.93	3.16	0.07	4.96	0.08
cleanup with power tools	142	352	1017 (1965)	7.0	11843	243 (5.7)	2	0.55	0.00	0.98	0.01	0.26	0.61	5.76	0.02
setup	150	293	71.0 (217)	1.3	2122	17.9 (4.2)	1	0.31	0.00	0.95	0.00	-	-	-	-
containment handling	52	345	53.9 (108)	1.2	511	14.1 (5.0)	1	0.53	0.00	0.94	0.01	-	-	-	-
Groundwork	254	366	913 (7521)	1.2	112060	30.3 (6.8)	6	0.09	0.00	0.92	0.00	12.29	0.00	10.61	0.06
painting	83	271	128 (261)	3.0	1979	41.9 (4.5)	1	0.48	0.00	0.98	0.24	14.19	0.00	7.61	0.02
misc duties	12	303	130 (255)	2.0	881	20.7 (8.1)	2	0.58	0.00	0.89	0.12	0.58	0.46	4.94	0.03

μg , micrograms; m, meters; N, number air samples, AM, arithmetic mean; SD, standard deviation; GM, geometric mean; GSD, geometric standard deviation.

Table 2.2c: Relationship between PBZ lead concentrations taken during Connecticut bridge projects and sample duration

		Sampling duration (minutes)				Trend of arithmetic air concentration versus sampling duration					
Task	N	AM	SD	MIN	MAX	Slope ($\mu g\ m^{-3}\ min^{-1}$)	LCL	UCL	intercept	LCL	UCL
Abrasive blasting	289	371	191	40	833	-11.3	-21.39	-1.23	11768	7564	15971
Vac blast	5	339	141	134	481	0.34	-0.71	1.39	39.8	-341	420
Needle gunning	7	275	161	68	495	-0.04	-0.07	-0.01	22.8	12.4	32.7
Grinding	8	295	124	162	464	-1.11	-3.08	0.87	530	-95.5	1156
Power tool cleaning	7	335	212	60	605	0.30	-0.01	0.60	-0.71	-118	117
Welding	42	353	135	120	540	-0.01	-0.89	0.87	168	-159	496
Torch cutting	13	356	147	64	510	-1.91	-4.79	0.98	1145	40.3	2250
Burning	23	341	129	140	490	0.41	-0.66	1.47	137	-249	523
Drilling	12	325	111	163	490	-0.11	-0.26	0.03	56.6	6.5	107
Chip concrete	4	498	56.7	450	580	1.19	0.44	1.95	-549	-929	-170
Blowdown	19	215	150	50	480	-0.20	-4.27	3.87	681	-373	1739
Vacuuming	104	377	166	36	770	1.89	-0.37	4.15	380	-549	1309
Shoveling	8	262	125	111	480	0.31	-0.45	1.08	60.4	-159	280
Sweeping	6	271	92.6	162	435	0.73	-3.02	4.49	174	-891	1239
Waste transfer	5	285	174	150	581	-0.06	-0.47	0.35	70.0	-63.8	204
Cleanup	10	343	218	90	754	-1.24	-5.70	3.21	961	-822	2743
Set up	138	293	177	56	625	-0.02	-0.23	0.20	81.1	7.3	155
Containment handling	40	345	219	48	813	0.14	-0.04	0.31	21.3	-49.1	91.8
Groundwork/support	129	380	176	65	800	0.26	-3.02	3.54	371	-1000	1743
Pot tending	28	461	143	89	695	-0.06	-0.28	0.16	74.6	-29.9	179
Filter changing	13	223	149	61	527	-42.04	-175.73	91.65	21239	-14148	56627
Equipment operation	27	286	167	31	555	0.24	-0.41	0.89	58.0	-152	268
Equipment maintenance	10	351	194	76	628	1.47	-6.26	9.19	331	-2617	3279
Recycler/separator	22	350	151	30	630	-0.87	-1.49	-0.25	423	187	658
Painting	75	270	154	65	660	-0.44	-0.84	-0.05	260	137	384
Inspection	7	256	190	30	504	-0.67	-2.38	1.05	391	-142	924

N, number of air samples, AM, arithmetic mean; SD, standard deviation; LCL, lower confidence limit; UCL, upper confidence limit; slope, slope of the regression line; intercept, starting values of sampling duration and airborne lead concentration. Sanding (319 minutes) Peening (221 minutes) N=1 samples each and rivet busting N=2 ranges from 409 to 422 minutes and carpentry N=2 ranged from 380 to 555 minutes.

Table 2.2d. Tests for normality and log normality among Task-based concentration distributions

			swilk normal		swilk log normal	
tasks/duties	Other factors	Total N	W	p-value	W	p-value
Abrasive blasting	enclosed, class 5	9	0.81	0.03	0.94	0.56
Abrasive blasting	enclosed, class 3	300	0.43	0.00	0.98	0.00
Abrasive blasting	vacuum attachment	5*	0.97	0.85	0.80	0.08
Needle gunning	vacuum attachment	7	0.90	0.35	0.40	0.68
Grinding		12	0.75	0.00	0.94	0.54
Power tool cleaning		4	-	-	-	-
Welding		48	0.44	0.00	0.99	0.90
Torch cutting		28	0.62	0.00	0.96	0.31
Burning		25	0.74	0.00	0.91	0.04
Drilling		13	0.68	0.00	0.89	0.11
Blowdown	enclosed	20	0.51	0.00	0.90	0.04
Vacuuming	enclosed, during blasting	31	0.79	0.00	0.94	0.06
Shoveling	enclosed	9	0.46	0.00	0.94	0.61
Vacuuming	enclosed	10	0.69	0.00	0.87	0.09
Sweeping	enclosed	7	0.83	0.08	0.88	0.21
Set up		150	0.31	0.00	0.95	0.00
Containment handling		52	0.53	0.00	0.94	0.01
Support	during coating operation	75	0.19	0.00	0.92	0.00
Groundwork	during coating operation	55	0.13	0.00	0.84	0.00
Pot tending		29	0.59	0.00	0.94	0.08
Filter changing		13	0.44	0.00	0.95	0.57
Equipment operation		34	0.47	0.00	0.93	0.03
Equipment maintenance		12	0.49	0.00	0.85	0.04
Recycler/separator		22	0.48	0.00	0.96	0.42
Painting	enclosed, 1st coat	26	0.81	0.00	0.96	0.49
Painting	enclosed, 2nd or 3rd coat	19	0.82	0.00	0.93	0.16
Coating		38	0.40	0.00	0.98	0.77
Inspection		10	0.63	0.00	0.89	0.19
Chipping concrete		7	0.53	0.00	0.85	0.12
Waste transfer		5*	0.83	0.12	0.95	0.73
Support	during ironwork	12	0.88	0.09	0.96	0.75
Power tool cleaning	no attachment	4	-	-	-	-
Cleanup	enclosed, during blasting	5*	0.90	0.40	0.93	0.57
Cleanup		6*	0.51	0.00	0.83	0.11
Vacuuming		81	0.49	0.00	0.99	0.66

* used sfrancia test for smaller sample size; groundwork during ironwork N=2, roto-peen N=1, component removal N=2, sanding with vacuum attachment N=1, welding new steel N=3; carpentry N=2; air powered wrench N=2; air powered jacking N=2; rivet busting N=2 not included

Table 2.3a: Summary of personal breathing zone lead from surface preparation tasks evaluated during Connecticut and non-Connecticut bridge projects

						Air concentration ($\mu g\ m^{-3}$)				ANOVA			
Project code(s)	Task	Other factors	bridge attribute	N	Sample duration (minutes)	AM (SD)	MIN	MAX	GM (GSD)	Btw grp (F)	p-value	Equal variance test	p-value
2	Abrasive blasting	enclosed, class 5		9	288	8937 (10692)	155	30020	3229 (6.14)	-	-	-	-
12	Abrasive blasting	enclosed, class 5		8	273	13671 (9430)	3690	29400	10624 (2.22)	-	-	-	-
3*	Abrasive blasting	enclosed, class 3	%lead content	14	520	11330 (11832)	1668	41290	7187 (2.66)	-	-	-	-
11*	Abrasive blasting	enclosed, class 3	%lead content	80	310	1740 (2480)	5	10000	515 (6.14)	-	-	-	-
4 - 10**	Abrasive blasting	enclosed, class 3	%lead content	206	409	9347 (19385)	3	184702	2392 (7.10)	1.16	0.33	11.35	0.08
9	Abrasive blasting	vacuum attachment		5	339	155 (94.0)	22	280	118 (2.71)	-	-	-	-
1, 9	Needle gunning	vacuum attachment		7	275	12.0 (7.7)	4	25	10.1 (1.92)	1.19	0.33	-	-
13	Scaling	no attachment		11	75.0	989 (774)	168	2743	722 (2.40)	-	-	-	-
13	Grinding	no attachment		19	121	503 (1221)	28	5509	202 (3.20)	-	-	-	-
1,2,9	Grinding			12	295	257 (305)	4	869	118 (4.46)	1.72	0.23	0.93	0.63
2,10,11	Power tool cleaning			4	138	46.4 (28.5)	14	82	38.7 (2.12)	2.15	0.43	-	-
9	Power tool cleaning	no attachment		4	483	129 (104)	52	276	101 (2.20)	-	-	-	-

extremely low value excluded < 0.05 ug m^{-3}, ** excluded projects with no record of lead content and found no detectable difference - see text.
N, number of air samples; AM, arithmetic mean; SD, standard deviation; GM, geometric mean; GSD, geometric standard deviation;
µg, microgram; m, meter.

Table 2.3b: Summary of personal breathing zone lead from component removal and replacement tasks evaluated on Connecticut and non-Connecticut bridge projects

						Air concentration ($\mu g\ m^{-3}$)				ANOVA			
Project code(s)	Task	Other factors	Bridge attribute	N	Sample duration (minutes)	AM (SD)	MIN	MAX	GM (GSD)	btw grp (F)	p-value	equal variance test	p-value
1,2,8,9,11	Welding			48	354	153 (340)	1.7	2120	42.7 (5.2)	1.37	0.26	2.75	0.60
13	Torch cutting			21	133	1158 (983)	63	3746	737 (3.0)	-	-	-	-
13	Torch cutting	enclosed class 5		31	188	1539 (1493)	69	5800	975 (2.8)	-	-	-	-
1,8,9	Torch cutting		%lead content, prep method	10	413	651 (772)	19	2324	309 (4.2)	2.31	0.17	0.03	0.99
2,11	Torch cutting		%lead content, prep method	18	290	156 (381)	2	1390	23.6 (6.5)	0.26	0.62	0.62	0.43
1,9	Burning			25	341	267 (298)	5.5	1417	137 (4.2)	0.38	0.54	0.31	0.58
13	Burning			6	56	6850 (3650)	1500	12000	5755 (2.1)	-	-	-	-
13	Rivet busting	enclosed and encapsulated		18	139	420 (346)	45	1100	287 (2.6)	-	-	-	-
13	Rivet busting	encapsulated		37	171	178 (250)	6	1430	95.0 (3.3)	-	-	-	-
13	Rivet busting			22	174	258 (322)	10	1200	131 (3.5)	-	-	-	-
13	Reaming			6	133	31.0 (28.0)	7	84	23.0 (2.3)	-	-	-	-
13	Bolting up			11	221	57.0 (82.0)	7	286	29.0 (3.2)	-	-	-	-
13	Drilling			4	315	8.0 (4.0)	6	14	7.0 (1.5)	-	-	-	-
1,2,9,11	Drilling			13	325	19.4 (25.2)	3	77.6	10.3 (3.0)	0.92	0.47	4.88	0.09

N, number of air samples; AM, arithmetic mean; SD, standard deviation; GM, geometric mean; GSD, geometric standard deviation; µg, microgram; m, meter

Table 2.3c: Summary of personal breathing zone lead from cleanup tasks evaluated during Connecticut bridge projects

						Air concentration ($\mu g\ m^{-3}$)				ANOVA			
Project code(s)	Task	Other factors	Bridge attribute	N	Sample duration (minutes)	AM (SD)	MIN	MAX	GM (GSD)	btw grp (F)	p-value	equal variance test	p-value
9,11	Blowdown	enclosed	project size (based on total length/surface area)	16	231	237 (243)	64.4	958	172 (2.1)	3.77	0.07	2.46	0.12
6	Blowdown	enclosed	project size (based on total length/surface area)	4	154	2143 (2116)	233.6	5170.0	1319 (3.6)	-	-	-	-
9,11	Vacuuming	enclosed		10	268	31.9 (24.2)	13.0	94.0	26.8 (1.8)	0.09	0.77	1.97	0.16
11	Cleanup	enclosed, during blasting		5	378	127 (123)	8.0	320.0	68.7 (4.3)	-	-	-	-
10,11	Cleanup			6	319	786 (1579)	41.9	4005.9	215 (4.8)	0.37	0.58	-	-
2,3,6,9,11	Vacuuming	enclosed, during blasting		31	393	2362 (2978)	11.9	11842.9	692 (6.9)	4.42	0.01	7.05	0.07
11	Shoveling	enclosed		8	262	626 (1315)	37.1	3872.9	202 (3.9)	-	-	-	-
11	Sweeping	enclosed		3	271	491 (236)	218.6	646.9	441 (1.8)	-	-	-	-
4,5,6,7,8,10, 11	Vacuuming			81	382	716 (1486)	7.0	9799.0	204 (4.9)	3.28	0.01	1.72	0.94
9	Waste transfer			3	285	57.0 (55.2)	20.3	120.5	42.1 (2.5)	-	-	-	-

N, number of air samples; AM, arithmetic mean; SD, standard deviation; GM, geometric mean; GSD, geometric standard deviation; μg, microgram; m, meter; ANOVA, analysis of variance.

Table2. 3d: Summary of personal breathing zone lead from coating tasks evaluated during Connecticut bridge projects

					Air concentration ($\mu g\ m^{-3}$)						ANOVA	
Project code(s)	Tasks	Other factors	N	Sample duration (minutes)	AM (SD)	MIN	MAX	GM (GSD)	btw grp (F)	p-value	equal variance test	p-value
3,4,6,9	Painting	enclosed, 1st coat	26	252	191 (206)	3	688	95.5 (3.9)	1.40	0.27	3.17	0.37
3,9	Painting	enclosed, 2nd or 3rd coat	19	347	15.9 (13.5)	4	54.8	11.7 (2.2)	0.27	0.61	1.53	0.22
4,5,6,7,9,11	Coating		39	253	140 (331)	3.1	1979	46.1 (4.3)	3.00	0.02	3.36	0.65

N, number of air samples; AM, arithmetic mean; SD, standard deviation; GM, geometric mean; GSD, geometric standard deviation; µg, microgram; m, meter.

Table 2.3e: Summary of personal breathing zone lead concentration from equipment handling tasks evaluated during Connecticut bridge projects

						Air concentration ($\mu g\ m^{-3}$)				ANOVA			
Project code(s)	Task	Task performed (during)	bridge attribute	N	Sample duration (minutes)	AM (SD)	MIN	MAX	GM (GSD)	btw grp (F)	p-value	equal variance test	p-value
2 - 11	Set up			149	317	71.1 (218)	0.9	2122	17.6 (4.3)	2.53	0.01	25.59	0.00
11*	Containment handling		%lead content	23	350	13.3 (18.0)	1.2	64	6.4 (3.3)	-	-	-	-
3,4,5,6,7,9,10	Containment handling		%lead content	28	342	218 (683)	4.1	3636	37.1 (5.8)	1.13	0.38	8.05	0.09
3,4,6,9,11	Support	coating		75	398	306 (1482)	4.3	12449	40.1 (4.7)	0.48	0.75	4.30	0.23
9	Support	ironwork		12	422	17.4 (11.8)	4.5	41.5	14.0 (2.0)	-	-	-	-
12	Groundwork	coating		10	396	703 (2115)	5.0	6720	26.9 (9.6)	-	-	-	-
4,7,8,9,10,11	Groundwork	coating		55	334	684 (4762)	0.1	35348	12.9 (6.5)	1.29	0.29	1.57	0.82
15	Equipment operation			12	480 - 600	-	14	1400	-	-	-	-	-
4,5,9,10,11	Equipment operation			36	286	153 (364)	1.5	1830	30.4 (5.4)	0.95	0.45	11.86	0.01
3,4,8,9,10	Recycler operation			22	350	117 (240)	4.3	1121	38.1 (4.6)	1.72	0.19	3.32	0.35
3,4,6,9	Pot tending			33	461	39.4 (73.1)	0.7	353	11.4 (5.1)	1.93	0.15	4.35	0.23
15	Equipment maintenance			5	480 - 600	-	13	1900	-	-	-	-	-
4,6,8,9,11	Equipment maintenance			12	351	626	4	5136	38.2	0.86	0.53	4.04	0.13
10,11	Filter changing			13	223	11871	40	112060	1032	0.63	0.44	0.29	0.59

N, number of air samples; AM, arithmetic mean; SD, standard deviation; GM, geometric mean; GSD, geometric standard deviation; µg, microgram; m, meter.
* one extremely low value was exclude < 0.05 ug m^{-3}

Table 2.4: Summary of airborne lead concentrations from tasks examined by one or two samples

Project code(s)	Task	Other factors	N	Sample duration (minutes)	Air concentration ($\mu g\ m^{-3}$) MIN	MAX
11	Rivet busting		2	416	32.5	51.5
9	Wrench	air powered	2	-	0.8	0.8
1	Jacking	air powered	2	-	2.6	7.2
1	Component removal		2	-	7.2	19
8	Groundwork	during ironwork	2	400	1.3	1.6
11	Sanding	vacuum attachment	1	319	9	9
7	Rotopeen		1	221	9.6	9.6
3,9	Carpentry		2	468	7	7.5
14	Abrasive blast	3-sided enclosure	2	235	100	800
14	Needle gun	with attachment	2	235	<4.2	<4.2
13	Cleanup	during ironwork	2	235	8.00	291

N, number of air samples; µg, microgram; m, meter.

CHAPTER 3 EFFECT OF CONNECTICUT HEALTH PROTECTION MODEL [1]

3.1 Abstract

In 1990, Yale University, the Connecticut Departments of Health Services and of Transportation, the Connecticut Construction Industries Association, and the state's construction trade unions created the Connecticut Road Industry Surveillance Project (CRISP). This project was intended to demonstrate that lead poisoning could be prevented in construction workers involved in bridge maintenance and rehabilitation. Two key features of CRISP, were a centralized medical monitoring system and contract-specified lead health protection program. The implementation of CRISP produced data pertaining to 90 bridge projects from 1991-1995 and approximately 2000 workers. In this chapter we summarize these data and evaluate the efficacy of the CRISP program. Specifically, the characteristics of the workforce and their blood lead levels are evaluated. The distribution of peak lead concentrations in blood for CRISP workers classified into 5 groups are compared to that from workers outside of Connecticut. This evaluation determined that the demonstration project was instrumental in lowering bridge worker blood lead levels. After 1992, only the painting contract employees experienced peak blood lead levels with $\leq 2\%$ exceeding 50 $\mu g\ dl^{-1}$. Compared to similar workers in other states, Connecticut workers had significantly lower peak blood lead levels.

3.2 Introduction

In the U.S., there are an estimated 90,000 bridges with lead containing paint on steel structures (OSHA 1993). In general, bridge maintenance work that disturbs lead paint entails torch cutting, grinding steel components, and removing and replacing paint. Workers involved in bridge repair have been among the commonly seen occupational groups with severely elevated blood lead levels (O'Donnell 1997). This is problematic because chronic overexposure can result in severe damage to blood-forming, nervous, urinary and reproductive systems and accumulation in bone tissue resulting in lead releases back into the bloodstream for many years (Barry 1975),(Hodgkins et al. 1991). Severe health effects such as peripheral neuropathy and kidney damage above a blood lead level of 40 $\mu g\ dl^{-1}$ and other renal effects such as decreased vitamin D metabolite levels at 30 $\mu g\ dl^{-1}$ have been observed among workers who are chronically exposed to lead (Kim et al. 1996). A positive association between blood pressure and lead in blood has been observed in men with levels as low as 7 $\mu g\ dl^{-1}$ in blood with no evidence of a threshold (Schwartz 1988).

[1] Based on the publication: Vork K.L., Hammond S.K., Sparer J., and Cullen M.R. "Prevention of Lead Poisoning in Construction Workers: A New Public Health Approach", American Journal of Industrial Medicine 39:243-253 (2001)

There are few descriptions of comprehensive strategies for controlling lead poisoning in the workplace (Hipkins et al. 1998 ;Baser 1992; Lusk et al. 1995; Papanek et al. 1992). Although regulations exist and strategies have been proposed, lead poisoning continues to occur. This is particularly true among bridge construction workers involved in the burning and removal of lead paint on bridge surfaces. During an aggressive program to repair Connecticut's bridge infrastructure in the early 1990s, a new approach to preventing lead poisoning in construction workers was established called the Connecticut Road Industry Surveillance Project (CRISP). CRISP was a National Institute for Occupational Safety and Health (NIOSH) funded demonstration project designed to monitor and prevent lead poisoning during bridge repair projects through a coordinated network of state agencies and local labor unions. At the time CRISP was initiated in 1991, OSHA exempted construction work from its 1978 lead standard which had lowered the permissible exposure limit (PEL) to 50 $\mu g\ m^{-3}$ and added provisions for blood lead monitoring and requirements for medical removal at blood lead levels reaching 50 $\mu g\ dl^{-1}$. As a result, the PEL of 200 $\mu g\ m^{-3}$ for construction workers remained. CRISP anticipated the 1993 OSHA requirements and progressively reduced the medical removal level in each year of the project to levels below that required by OSHA. These lower blood lead level requirements along with the use of contract specifications rather than regulations to achieve health and safety goals are important distinctions between the CRISP program and the subsequent OSHA requirements.

The CRISP approach was first described and contrasted with the 1993 OSHA lead in construction standard by Maurer et al (1995c) in 1995 who initiated and implemented CRISP. This chapter further characterizes CRISP and shows that, compared to similar groups of workers protected by the OSHA standard alone, workers from the CRISP program had lower blood lead levels overall.

3.3 Methods

3.3.1 History and development of CRISP

Yale University proposed this demonstration project which was supported in 1990 by NIOSH. Investigators proposed to demonstrate that workers could be protected and high blood lead levels prevented through contract specifications mandating a comprehensive lead health protection program (LHPP) (Maurer et al. 1995c). The investigators worked with the Connecticut Departments of Health Services (DHS) and of Transportation (ConnDOT), the Connecticut Construction Industries Association (CCIA), and state construction trade unions to establish contract specifications and the LHPP for which ConnDOT assumed the cost.

From November 1990 through September 1992, CRISP investigators visited several field operations and worked with ConnDOT to finalize the contract specifications. During this time, a 50 μg/dl medical removal requirement and follow-up with on-site personnel was introduced on lead related bridge project sites (Maurer et al. 1993). By 1993, specific contract requirements for lead health protection addressing medical surveillance, biological monitoring, day to day industrial hygiene and environmental monitoring, specified respiratory protection for particular tasks and hygiene facilities were adopted by ConnDOT and implemented on lead related projects. The contract specifications and the LHPP supported by ConnDOT also ensured compliance with all relevant OSHA regulations.

In addition, CRISP differed from the 1993 OSHA 29 CFR 1926.62 lead in construction standard, which set a blood lead level of 50 $\mu g\ dl^{-1}$ for medical removal protection in that CRISP initially set the medical removal protection level at 40 $\mu g\ dl^{-1}$. In 1994, the medical removal protection level was lowered to 35 $\mu g\ dl^{-1}$. Then, during 1995 and into the first part of 1996, the medical removal protection level was further reduced to 30 $\mu g\ dl^{-1}$. When blood lead levels over 25 $\mu g\ dl^{-1}$ were detected, the industrial hygiene consultant was responsible for recommending additional protective and hygiene measures to the contractor and if subsequent blood lead levels remained high, medical removal to a lower exposure job was required.

3.3.2 Components of the CRISP lead health protection program

CRISP ensured compliance through contract specifications and pass-through cost provisions to achieve its health and safety program goals. Specifications required prospective contractors to get at least three bids from industrial hygiene (IH) firms to conduct on-site industrial hygiene and environmental monitoring, provide medical surveillance, biological monitoring, hygiene facilities and respiratory protection for their employees, and to agree to comply with specified ventilation, equipment and materials (Castler 1995). From those 3 bids ConnDOT selected the IH firm which was then employed and paid as a subcontractor on the job. In addition, CRISP used a centralized system located at the Connecticut Department of Health for managing blood lead and medical monitoring data (Maurer et al. 1995b). Features of each component were constructed from the synthesis of existing regulatory requirements and the experience of the investigators.

3.3.2.1 Respiratory protection

For all projects involving leaded paint, respiratory protection was required. Minimum respiratory protection for tasks that were anticipated to reach certain airborne concentration levels was explicitly written into the contract specification. CRISP specified several types of devices for respiratory protection, depending on the task being performed. For abrasive blast cleaners, air-supplied helmets with capes were typically employed. For other highly exposed workers such as the vacuum collection crew, painters, welders and flame cutters, a powered air-purifying respirator equipped with a high efficiency filter was used. (Castler, 1995). If air-sampling data (e.g. less than 500 $\mu g\ m^{-3}$) justified lower levels of respiratory protection, half face air purifying respirators were permitted.

3.3.2.2 *On-site industrial hygiene monitoring*

CRISP health and safety program specifications directed on-site industrial hygiene technicians to conduct personal air sampling every fourteen days on selected workers who performed specific tasks such as dust collection equipment operations and filter changes or at the discretion of the on-site industrial hygienist. Airborne lead dust monitoring was required monthly for the first three months for other tasks that pose an airborne lead exposure risk at the work site and on workers who perform tasks where exposures were unknown or unclear. Monthly reports summarized field records and personal air sampling conducted routinely on the contractor workforce by the on-site industrial hygiene technicians. At a minimum, these reports provided results of these samples as 8-hour time weighted averages as well as information about the task and worker sampled. In many cases the actual sampling time was also provided. Reports also described standard industrial hygiene sampling procedures, equipment, methods, field quality assurance protocol and accredited laboratories.

3.3.2.3 *Centralized medical monitoring and blood lead level management*

Project entry blood lead testing occurred during the initial medical exams. In general, subsequent testing occurred monthly for the first three months followed by testing every three months and upon exit from the job. If a blood lead level of 25 $\mu g\ dl^{-1}$ or greater was detected, blood lead testing reverted to monthly intervals. An airborne action level that triggered additional blood lead testing was set at 30 $\mu g\ m^{-3}$ over an 8-hour period without regard to the use of respiratory protection. Blood sampling was conducted at any of the CRISP approved clinics. Sampling was conducted using the Centers for Disease Control and Prevention (CDC) protocol for venipuncture blood draws and an accredited laboratory performed the analyses. These results were reported within 24 hours to a centralized location at the Connecticut DHS and if blood lead levels were greater than 25 $\mu g\ dl^{-1}$, the CRISP IH investigator followed up with the on-site contractors and industrial hygiene personnel. If blood lead levels exceeded the threshold (which decreased from 40 $\mu g\ dl^{-1}$ to 30 $\mu g\ dl^{-1}$ during CRISP), medical removal of the worker was mandated (Maurer et al. 1995a; Maurer et al. 1995c).

3.3.3 *CRISP bridge projects*

For the present study, thirty-three bridge projects involving workers who were enrolled into the CRISP program were selected to represent the most frequently hired industrial hygiene firms, and to span the range of start dates, project duration and locations within Connecticut. They have been classified into three groups according to major activity performed during the project. These groups are 1) paint removal by abrasive blasting methods, 2) ironwork involving torch cutting, burning or welding on painted surfaces, and 3) projects involving both iron work and abrasive blasting.

3.3.4 The CRISP enrolled workforce

Information on workers was collected during the initial blood lead sampling. This included demographics, craft affiliation, employer, job location and recent occupational tasks. This information along with ConnDOT records listing the names of companies awarded painting and ironwork contracts was used to categorize workers into employer groups. Ironwork, painting and general contractors used job titles such as foreman, laborer and equipment operator. Laborers assisting in an abrasive blast paint removal activity located inside a containment structure classified together with those assisting with road resurfacing would create a group with more diverse exposure experiences than classifying laborers who work for a painting contractor with painters. Therefore, contract workers and others were grouped according to the major duties performed by their employer. Employer groups consisted of: 1) painting contractors whose employees performed paint removal and reapplication (mainly painters, abrasive blasters, recycling equipment operators, laborers and foremen); 2) contractors who performed both iron work and abrasive blast paint removal ('mixed worker group'); 3) iron work and welding contractors (iron workers, welders, laborers and foremen); 4) employers of craft workers (the craft worker group) who performed general duties such as road resurfacing and containment building (e.g. general contract carpenters, heavy equipment mechanics, operators, and drivers and laborers); and 5) employers of engineers and industrial hygiene firms (the professional group) (mainly inspectors, project engineers, and environmental, health, and safety personnel). The fourth and fifth groups were comprised of workers not directly involved with paint burning, removal or cleanup. Employer groups were determined by matching employee job titles, reported employer and ConnDOT contract award listings. Twenty-three workers had insufficient employer information and were excluded from the analysis.

3.3.5 Non-Connecticut worker comparison groups

Data from workers who conducted work outside of Connecticut were obtained for two comparison groups, abrasive blasters and ironworkers. A group of 88 painter/blasters who conducted work during 1994 in Connecticut under CRISP were compared to 132 painter/blasters also working in 1994 but outside Connecticut and therefore not under the CRISP protocol. The latter workers were employed by one of 35 construction companies who contracted with an Ohio physician's clinic to have their workers medically screened during abrasive blasting bridgework in 1994. Each group was screened and periodically monitored for blood lead. Most workers had more than one blood lead test (Maurer et al. 1995c).

In addition, data collected from a group of 85 ironworkers monitored as part of a research project in New York (Levin et al. 1997) was compared to data from 72 CRISP ironworkers that conducted work in 1994. Tasks performed on these projects were similar (i.e. welding, rivet busting, torch cutting, needle gun chipping and grinding). Each group was screened and periodically blood lead monitored using similar protocols - approximately monthly, using a certified laboratory for analysis.

3.3.6 *Statistical methods*

Frequency, average and standard deviation measures were calculated for both bridge project and worker group characteristics. Workers were divided into five broad groups by employer type (see above). The metric of blood lead concentration chosen for evaluation was the maximum level observed for each worker in each year ('peak blood lead concentrations') as this was the most rigorous test of worker protection. Peak blood lead levels among these groups for each year of the demonstration project were stratified by yearly intervals from 1992 through 1995. The 1992 strata included a few months in 1991 and the 1995 strata included a few months into 1996. Groups were further stratified by first year and continuing (hereafter referred to as 'return') worker status and the difference in each subgroup average among worker peak blood lead levels was examined.

3.4 Results

3.4.1 *CRISP enrolled bridge projects*

The CRISP program monitored over 90 bridge projects. Thirty-three bridge projects representing the most frequently hired industrial hygiene firms, and the range of start dates, project duration and location within Connecticut are listed in Table 3.1. Most projects were monitored over multiple years. The largest project involving the greatest number of contract employees began in late 1992 and was monitored into 1996 and included both ironwork and abrasive blast paint removal. Many projects were monitored during 1994 or 1995 that involved 25 or fewer workers. In 1994, approximately equal numbers of ironwork and abrasive blasting projects were monitored, whereas in 1995-1996, many projects involved ironwork only. On bridge projects where information was reported, surface paint had high lead content; on most bridge projects at least one sample contained over 30% lead and the range of maximum sample values was 7% to 74%. Average levels ranged from 3% to 41% although some of these results came from very few measurements and about 30% of the bridge projects were missing this information in industrial hygiene reports. Three industrial hygiene firms monitored these projects, although one firm monitored two thirds of them.

3.4.2 *Characteristics of CRISP worker groups*

Table 3.2 displays the demographic characteristics of and the blood lead levels measured in workers prior to starting work on a CRISP monitored project. Painting contract and mixed workers (i.e. workers who performed both abrasive blasting and ironwork) were hired mostly in 1994 whereas all other groups were hired mostly in 1993. The proportion of in-state workers decreased in all but the ironworker group, which increased over time. This may have been due to the heavy demand for painting contract work in Connecticut during this period. The proportion of the workforce that was female remained very low in all groups. The percentage of minority workers increased over time in all but the iron and professional worker groups. The proportion of smokers increased over time among the ironworkers and in the group performing both ironwork and paint removal by abrasive blasting, but no trend emerged in the other three groups.

Ironworkers showed an increasing trend in average age that was not seen among other workers. The average initial blood lead levels of workers in all three groups performing paint burning, removal or cleanup was much more elevated in the early years than in later years of the CRISP demonstration project. The painting contract employees had the highest arithmetic average initial blood lead level of 31.2 $\mu g\ dl^{-1}$ in 1991/92, which decreased to 8.9 $\mu g\ dl^{-1}$ in 1995/96. Average initial levels among the professional and craft worker groups continued to be very low (less than 7 $\mu g\ dl^{-1}$) throughout the entire CRISP observation period. Twenty three workers with insufficient employer information were mostly Connecticut residents, all male, mostly white smokers in the age range 30 to 46 with low initial blood lead levels (5 - 9 $\mu g\ dl^{-1}$) (Table 3.2).

3.4.3 Year to year peak blood lead levels

The peak blood lead level for each individual worker in each year was identified. This measure was used to represent worst-case levels observed within each worker group during the year. The distribution of the annual peak blood lead level among worker groups, percentiles and the maximum levels for each worker group during years 1992, 1993, 1994 and 1995 and the percent in each group who returned to CRISP monitored bridge projects are displayed in Table 3.3.

The total number of workers increased in each group over time, and the proportion of workers who returned to CRISP-monitored projects from previous years increased among all but the craft worker group, which decreased from 54% to 41%. Ninety-fifth percentiles of peak blood lead levels ranged from 6 to 74 $\mu g\ dl^{-1}$. After 1992, in all groups, half of the blood lead levels never reach 25 $\mu g\ dl^{-1}$. Among the professional workers, 95% of workers had peak blood lead levels less than 12 $\mu g\ dl^{-1}$ in any year. However, in years 1993, 1994, and 1995 maximum levels of 19, 40 and 32 $\mu g\ dl^{-1}$ respectively were reached by three workers (all were inspectors). Ninety five percent of the craft worker group never reached 25 $\mu g\ dl^{-1}$, while the 95th percentile of the ironworker group decreased from 36 to 23 $\mu g\ dl^{-1}$ and the mixed worker group from 44 to 29 $\mu g\ dl^{-1}$ from 1992 to 1996. Painters experienced the greatest decline, with the maximum falling from 84 to 60 $\mu g\ dl^{-1}$ in 1992-1996 and the 95th percentile from 74 in 1992 to less than 42 $\mu g\ dl^{-1}$ in subsequent years. The median levels fell by approximately 50% for the 3 major lead exposed groups and the median peak blood lead for all workers was 15 or less by 1995 (Table 3.3).

The proportion of painters reaching or exceeding 50 $\mu g\ dl^{-1}$ (the OSHA medical removal level) decreased from 21% in 1992 to 1% in 1995 (Figure 3.1).

Note that in Table 3.3, the 50th percentile levels in the painter group sharply decreased from 1992 to 1993 but then slightly increased from 1993 to 1995. The proportion of workers who returned from a CRISP project conducted in the previous year (and who therefore had higher blood lead levels from past exposures) also increased substantially (over 3 fold from 1993 to 1995). However, when the newly hired and return workers were analyzed together, decreases in blood lead levels from year to year were obscured (data not shown). When analyzed separately, these subgroups each showed noticeable declines. Figure 3.2 shows changes in the arithmetic average of the peak levels from 1993 to 1995 in the first year subgroup of craft workers and in two subgroups of painters, ironworkers, and professionals. From 1993 to 1995, the mean blood lead level dropped among all first year worker groups. The only subgroups that increased were the two with the lowest blood lead levels, the professional returnees and the craft worker returnees (measured from 1994 to 1995). The average blood lead levels declined the greatest for ironworkers among all subgroups.

3.4.4 *Comparison of CRISP protected workers to Non-Connecticut workers*

To examine the effect of the CRISP intervention compared to only the presence of OSHA regulations, workers with a job title of painter/blaster from among painting contractors who worked either under CRISP or on a non-Connecticut abrasive blast paint removal bridge project were studied.

Figure 3.3 compares the cumulative percent of workers' peak blood lead levels among Connecticut painter/blasters to levels from the painters who worked in a state with only an OSHA program. Both groups were 100% male. The CRISP group was slightly older with a mean age of 37 ± 8 years compared to a mean age of 34 ± 8 years (t-test $p = 0.001$) in the non-Connecticut group. Levels were much lower for the CRISP group ($p < 0.001$), with a median of 17 $\mu g\ dl^{-1}$ and only 1% above 50 $\mu g\ dl^{-1}$ compared to a median of 34 $\mu g\ dl^{-1}$ and 21% above 50 $\mu g\ dl^{-1}$ for the non-Connecticut group. Higher blood lead levels in the non-Connecticut group may be due to the lack of implementation of OSHA worker protection provisions. The extent of OSHA compliance or industrial hygiene oversight among this group is not known.

Figure 3.4 compares the effect of the CRISP intervention to protection under the OSHA regulations, for ironworkers. Both groups were 98% male and 59% of the CRISP group was at least age 37 and 59% of the non-Connecticut group was at least 35 years of age. Levels were significantly lower for the CRISP group ($p < 0.001$), with a median of 9 $\mu g\ dl^{-1}$ and 100% below 30 $\mu g\ dl^{-1}$ compared to a median of approximately 12 $\mu g\ dl^{-1}$ and 94% below 30 $\mu g\ dl^{-1}$ for the non-Connecticut group. The New York ironworkers were probably better protected than most outside of Connecticut because of the presence of a research team that conducted regular air and blood lead monitoring throughout the year and documented implementation of OSHA worker protection provisions (Levin et al. 1997).

3.5 Discussion

CRISP was created during the early 1990s in anticipation of an intense program to rehabilitate Connecticut bridges. Its major goal was to protect and monitor workers known to experience high blood lead levels during bridge repair. Approximately 2000 workers, and over 120 contractors benefited by the program's success because it substantially reduced the occurrence of high blood lead levels, those that require medical removal protection (50 µg dl^{-1}) under the 1978 OSHA General Industry Standard and the 1993 Lead in Construction Standard.

Measures such as average and incremental change in blood lead level have been used by others to report exposures (Maurer et al. 1995c; Levin et al. 1997). From a public health perspective the major goal of CRISP and other lead prevention programs is to ensure that the concentration of lead in the blood is always as low as possible. A rigorous test of the success of this program would examine the maximum lead concentration experienced by each worker in a given year. Therefore the best approximation, the peak of measured blood leads, was the metric chosen for evaluation in this study.

Unlike the experience of blasters and ironworkers in the 1980s and early 1990s with levels in the 80 µg dl^{-1} to 100 µg dl^{-1} range (Fischbein et al. 1984; Frumkin et al. 1993; Landrigan et al. 1982; NIOSH 1992a; Osorio et al. 1995; Risk et al. 1992; Waller et al. 1992), over 99% of the CRISP cohort maintained blood lead levels below 50 µg dl^{-1}. Within the CRISP cohort, worker blood lead levels decreased over time. This is particularly evident when workers were subdivided by newly hired and returning worker status. The percent of CRISP painters and ironworkers with elevated blood lead levels was also significantly smaller than among compared groups in other states, outside of the CRISP system.

There is limited information about the CRISP and non-Connecticut cohorts beyond the demographic, job title and blood lead testing characteristics (Levin et al. 1997; Maurer et al. 1995c). Therefore, the conclusions drawn from these comparisons are stated with caution. Under the assumption that these groups are reasonably comparable, the slight differences in age and frequency of blood lead testing are unlikely to explain the changes in blood lead levels observed in this analysis. In fact, the CRISP workers were older and in the absence of recent exposure, would be expected to have had higher blood lead levels due to a higher expected body burden.

A key difference between the current OSHA standard and the CRISP model was the contract specifications mandating the development and implementation of a site-specific health protection program. When spelled out in the contract specifications, health and safety could not be ignored or easily underbid by the contractor; different implementation mechanisms, a system of pass-through payment for costs, and a greater ownership of the health and safety provisions could therefore be created. These features may be absent under a broad requirement of OSHA regulatory compliance.

In 1993 through 1995, when CRISP covered nearly all bridgework in Connecticut, there were several smaller projects (e.g. with 25 or fewer workers) that were likely to entail sporadic and frequent relocation. The CRISP centralized blood lead monitoring and follow-up may have also played a key role in reducing higher blood lead levels by providing continuity of health care and early intervention for this easily overlooked group of workers.

Another way in which CRISP may have reduced blood-lead levels is in controlling work practices for projects conducted under its supervision. A recent study sponsored by the National Cooperative Highway Research Program reveals there is a high degree of variability in contractor practices and technology among state and local highway agencies for removing lead paint from bridges (Appleman 1998a). However, the Connecticut specifications required particular work practices, equipment and materials during lead related bridge projects. These requirements may have mitigated or prevented exposures observed in similar projects conducted without these specifications. For example, all ConnDOT bridge projects involving the abrasive blasting of lead-based paint were conducted dry. In contrast, CRISP required Steel Structures Painting Council class 1 or 3 containment enclosures with additional requirements for sealing in debris and a minimum negative pressure with airflow through the enclosure required under the OSHA ventilation standards (Castler 1995). General ventilation during dry abrasive blasting operations has not been found to be an effective means of controlling airborne concentrations of lead to levels that have been observed by wet methods, vacuum blasting or chemical stripping which produce considerably less airborne dust (Mickelsen & Johnston 1995; Mickelsen & Haag 1997; Frenzel 1998). Needle guns were used for small jobs. Compared to abrasive blasting, this technology would have substantially reduced the airborne concentrations of lead generated during removal operations (Randall et al. 1998).

Other requirements may have provided greater protection for workers. For example, all abrasive blast material was required to be recyclable steel grit, contamination of abrasive mix was not permitted to exceed 0.1% by weight and total lead content was not to exceed 200 parts per million (Castler, 1995). Compared to other abrasives such as copper slag, steel grit produces much lower airborne concentrations of lead (Adley et al. 1999).

Numerous studies have examined the cost, efficiency and effectiveness of various technology for lead paint removal ((Mickelsen & Johnston 1995; Mickelsen & Haag 1997; Frenzel 1998; Smith 1996; Randall et al. 1998; Bates 1996). These and other issues such as the competing interests of environmental protection and challenges related to the bridge location and area where paint removal takes place may also affect worker exposures (Huffman 1999; Seavey et al. 1996; Zamurs et al. 1998). Further research is needed to evaluate the relative impact of these and other work related conditions that may impact worker exposures. In Connecticut during CRISP, factors such as air and surface dust lead content at work sites, containment characteristics, hygiene practices and facilities and administrative practices varied among bridge projects.

CRISP is an effective strategy that continues to be implemented in Connecticut (with some modifications) and could serve as a model for other programs.

Table 3.1 **Thirty-three Connecticut Road Industry Surveillance Project monitored Bridge projects during 1992 – 1996**[a]

Bridge information			% Lead content						
project ID	active years	lead related work	N	AM	SD	GM	Max	IH firm	# workers
094-170/171	92, 93, 94 95, 96	AB/IW	62	3	(5)	1	19	B	659
103-220	93	IW	9	24	(4)	24	29	B	20
50-179/181	94	AB/IW	----	20	----	---	---	B	29
103-217	94	AB	1	14	-----	14	14	B	8
130-151/160	94	IW	5	34	(6)	34	41	B	8
165-266	94	IW	6	26	(21)	19	58	B	5
173-223	94	AB	----	----	----	---	----	C	12
34-235/252	94	AB	---	----	----	---	----	C	13
159/148/164/ 165	94	IW	---	----	----	---	----	C	5
63-458	94	AB	3	23	(2)	23	25	B	34
83-219/106-104	94,95	IW	17	12	(15)	2	44	B	28
85-124	94, 95	AB	30	15	(8)	12	29	B	25
87-131	94, 95	AB	64	41	(14)	38	74	B	40
172-244	94, 95	IW	24	20	(10)	13	32	B	25
172-251	94, 95	AB	---	----	----	---	----	B	15
105-130/182	94, 95, 96	IW	1	32	----	32	32	B	35
059-134	94, 95, 96	AB/IW	12	28	(16)	23	57	B	15
171-213	94, 95, 96	AB	16	32	(15)	18	43	A	37
082-223/252	94, 95, 96	AB/IW	---	----	----	---	----	C	310
15-211/233	95	IW	3	18	(2)	17	19	C	7
42-236	95	IW	---	----	----	---	----	B	14
128-126	95	AB/IW	---	----	----	---	----	C	4
173-260	95	AB	7	24	(8)	23	29	B	25
102-239	95, 96	AB	6	29	(7)	29	37	B	13
151-246/247	95, 96	AB	67	21	(14)	15	69	C	85
15-204/222	95, 96	IW	3	31	(22)	23	50	B	11
148-162	95, 96	IW	6	11	(3)	10	15	B	2
158-173	95, 96	IW	2	4	(5)	2	7	C	5
138-197	95, 96	IW	22	7	(10)	1	26	B	5
172-253	95, 96	AB	---	----	----	---	----	A	15
124-151	95, 96	AB	---	34	----	---	----	C	28
063-376/480	95, 96	IW	---	----	----	---	----	B	82
15-232/242	96	IW	7	19	(18)	12	57	B	13

[a] -, missing information; SD, standard deviation; AB, abrasive blasting; IH, industrial hygiene; IW, iron work; GM, geometric mean; AM, arithmetic mean

Table 3.2 Characteristics and blood lead levels by year workers entered their first Connecticut Road Industry Surveillance Project monitored bridge project and grouped by employer type 1992-1995 N=1950[a]

		Percent				Age (years)	Initial blood lead ($\mu g\ dl^{-1}$)	
Year	N	CT resident	Male	White	Smokers	AM (SD)	AM (SD)	GM
Painting contract employees								
1992	47	64	100	89	64	35 (9)	31 (21)	24
1993	138	58	96	84	57	36 (9)	12 (11)	10
1994	304	48	97	86	64	33 (9)	12 (9.4)	9.1
1995	229	45	100	76	56	34 (9)	8.9 (7.3)	6.9
Mixed contract employees								
1992	35	100	97	97	46	32 (7)	19 (9.8)	17
1993	43	100	95	88	53	42 (10)	14 (7.6)	12
1994	79	49	89	93	52	35 (11)	9.8 (7.2)	8.2
1995	43	35	95	71	69	34 (11)	6.8 (5.1)	5.9
Ironwork contract employees								
1992	46	67	89	84	39	37 (11)	16 (11)	12
1993	170	72	98	91	44	38 (11)	9.1 (7.1)	7.6
1994	162	95	97	86	51	40 (11)	8.0 (5.3)	7.0
1995	101	96	98	89	50	40 (11)	6.9 (5.9)	5.7
Craft and labor workers								
1992	1	100	100	100	100	38	8	
1993	108	91	98	88	49	37 (10)	7.6 (4.9)	6.7
1994	22	95	95	100	55	39 (10)	5.3 (0.9)	5.2
1995	50	74	98	74	41	36 (11)	6.5 (4.4)	5.6
Professional workers								
1992	8	88	100	100	50	34 (6)	5.1 (0.4)	5.1
1993	131	89	92	91	31	38 (10)	5.6 (1.2)	5.5
1994	107	90	87	92	33	33 (10)	5.6 (3.5)	5.3
1995	103	85	91	89	44	34 (11)	4.5 (4.5)	4.3
Workers with missing employer information								
1992	1	100	100	100	100	40	5	
1993	2	100	100	50	100	46 (6)	9 (1)	9
1994	1	100	100	0	100	30	5	
1995	19	94	100	71	63	34 (11)	6 (4)	5

[a] years 1992 contain a few months in 1991 and 1995 include a few months in 1996. µg, microgram; dl, deciliter; CT, Connecticut; AM, arithmetic mean; SD, standard deviation; GM, geometric mean; N, number of bridge workers.

Table 3.3 - Annual peak blood lead levels (µg dl^{-1}) of Connecticut Road Industry Surveillance Project monitored workers grouped by employer type 1992-1995[a]

Year	N	% returned	Percentile			Maximum
			5th	50th	95th	
Painting contract employees						
1992	47	---	6	27	74	84
1993	159	13	5	13	40	79
1994	414	27	5	14	41	64
1995	447	49	4	15	38	60
Mixed contract employees						
1992	37	---	9	20	44	50
1993	65	34	6	14	34	38
1994	114	32	5	13	35	43
1995	137	69	3	11	29	39
Ironwork contract employees						
1992	46	---	5	14	36	45
1993	198	30	3	6	31	48
1994	223	27	5	7	21	47
1995	202	50	5	5	23	39
Craft and labor workers						
1992	1	---	8	8	8	8
1993	116	---	5	6	22	27
1994	52	54	5	6	16	32
1995	83	41	3	5	21	27
Professional workers						
1992	8	---	5	5	6	7
1993	148	5	5	5	11	19
1994	188	39	5	5	10	40
1995	201	43	3	5	10	32

[a] years 1992 contain a few months in 1991 and 1995 include a few months in 1996. µg, microgram; dl, deciliter.

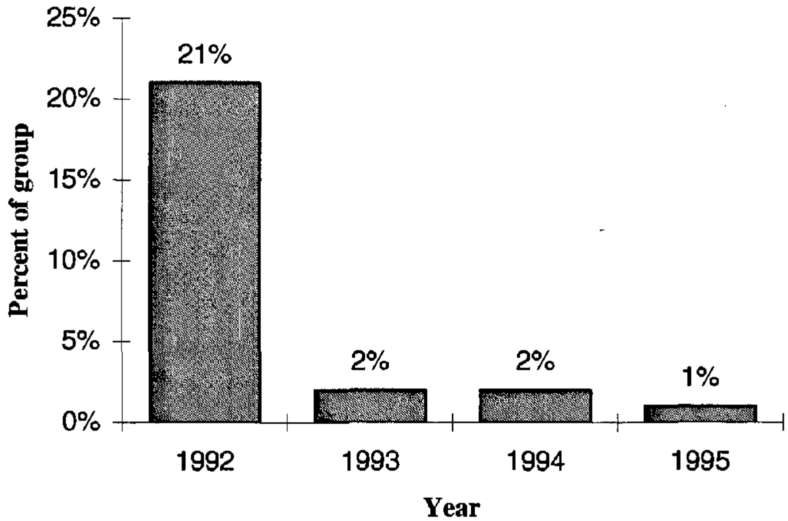

Figure 3.1 - Percent of CRISP monitored painting contract employees who reached or exceeded 50 μg dl^{-1} (micrograms per deciliter) during years 1992 - 1995 (the OSHA medical removal level). Note that, among this group of workers, peak blood lead levels decreased from 21% in 1992 to 1% in 1995.

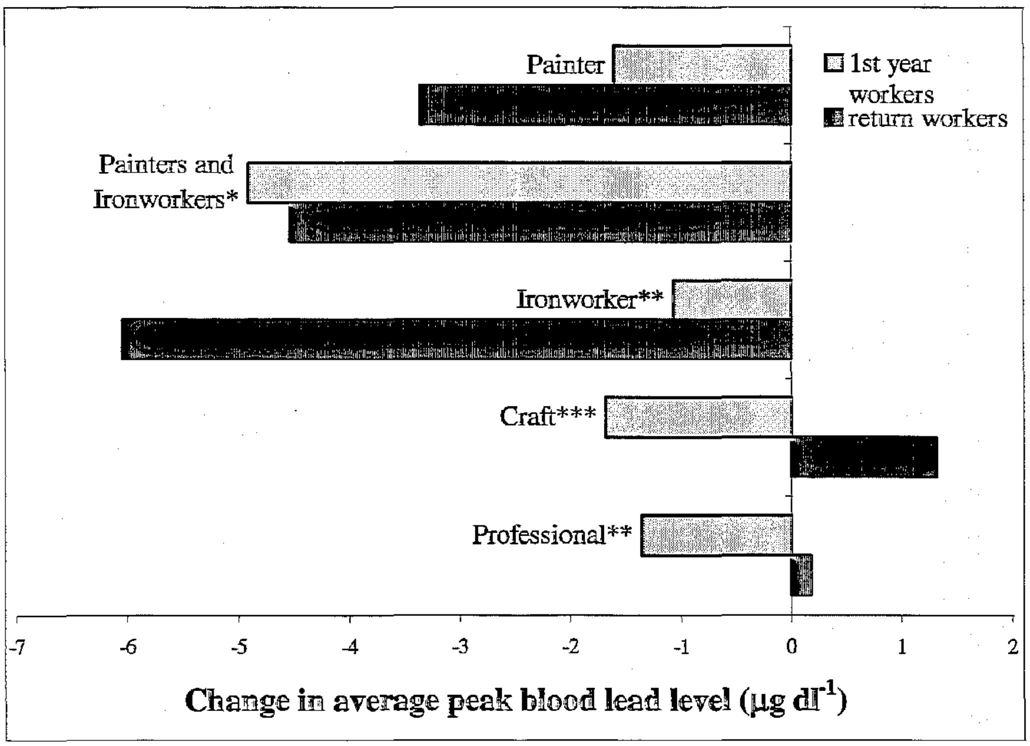

Figure 3.2 - Change in average peak blood lead (µg dl^{-1}) from 1993 to 1995 in CRISP monitored newly hired (i.e. first year) workers and those workers who were hired in years prior to 1993 and 1995 (i.e. return workers). Note that the average blood lead levels declined the greatest for ironworkers among all subgroups.* Statistically significant change; p-value < .05 for both 1st year and return worker groups. ** Statistically significant change; p-value < .05 for the return iron worker and 1st year professional worker group. µg/dl = micrograms per deciliter. *** Due to an insufficient number of returnee workers in 1994, changes for craft returnees were measured from 1994 to 1995.

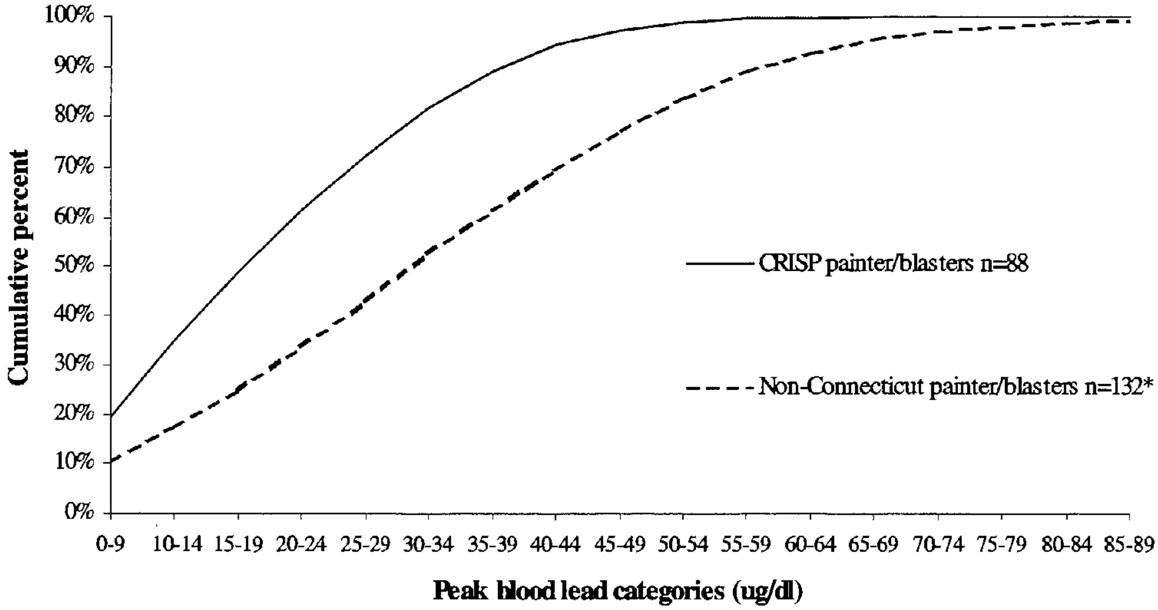

Figure 3.3. The effect of the CRISP intervention on the peak blood lead levels among Connecticut painter/blasters compared to levels from the painter/blasters who worked in a state with only an OSHA program. Note that levels were much lower for the CRISP group (p-value < 0.001 for the test of statistical significance in the difference between groups), with a median of 17 $\mu g\ dl^{-1}$ and only 1% above 50 $\mu g\ dl^{-1}$, compared to a median of 34 $\mu g\ dl^{-1}$ and 21% above 50 $\mu g\ dl^{-1}$ for the non-Connecticut group. $\mu g\ dl^{-1}$, micrograms per deciliter; n, number of workers; *, statistically significant; p-value < .05

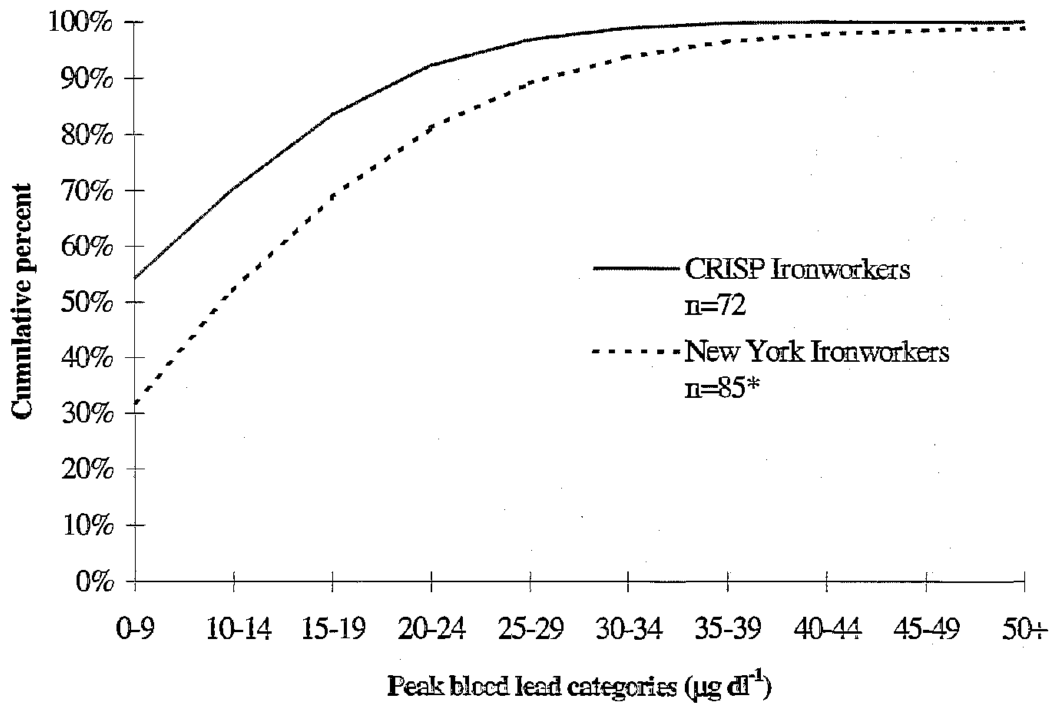

Figure 3.4 - The effect of the CRISP intervention compared to protection under the OSHA regulations, for ironworkers. Levels were significantly lower for the CRISP group (p-value < 0.001 from the test for statistical significance in the difference between groups), with a median of 9 µg dl^{-1} and 100% below 30 µg dl^{-1}compared to and median of approximate 12 µg $dl^{-1}$and 94% below 30 µg dl^{-1} for the non-Connecticut group. µg dl^{-1}, micrograms per deciliter; n, number of workers: *, statistically significant; p-value < .05

CHAPTER 4 DEVELOPMENT OF CONLIS: A SIMULATION MODEL FOR PREDICTING BLOOD LEAD LEVELS DURING BRIDGEWORK

4.1 Abstract

Lead exposures among bridge workers are monitored by task-based or 8-hour time weighted average personal breathing zone sampling and periodic testing of a worker's lead level in blood. Current methods of estimating lead dose from recent work exposure fall short in two broad areas. First, workplace industrial hygiene monitoring practices fail to account directly for the impact on exposure of work-related conditions such as air and surface dust lead content, containment characteristics, hygiene and administrative practices or from inhaling lead when a respirator is used to reduce exposure. Second, they fail to take into account the obscuring effect of total body burden. Using blood- lead *per se* to examine short-term intake can be misleading because lead in the blood eliminates from the body at a much slower rate than does daily changes in task-based air concentration during the course of a lead-related bridge project. This chapter develops a new model structure to address these shortcomings by directly accounting for the influence of exposure events and control techniques on the lead body burden of construction workers. The underlying model structure is based on physical principles of mass transport through the environment and the human body.

The model, named 'CONLIS' for CONstruction Lead Intake Simulation, is comprised of two modules. The front-end module is a structural equation that describes two pathways and the events in time that result in a lead dose rate. The back-end module contains a transfer function for converting dose rate to body burden. This transfer function is the solution to a set of simultaneous differential equations representing a previously validated pharmaco-kinetic model developed by Bert and colleagues (Bert et al. 1989). Each equation represents lead transport between one of several simulated body compartments including blood, soft tissue, trabecular bone and cortical bone. The equations also model routes of intake into and elimination from the body. Routes of intake include inhalation and swallowing, while urine, sweat, hair and nails are the modeled pathways for elimination.

CONLIS is demonstrated through MATLAB scripts developed as part of this project. These scripts generate time series predictions of lead in the body compartments. Lead flow through the human body from single pulse and constant intervals of repetitive dosing is included in this demonstration. The finite-width pulse-response simulation demonstrates the model's behavior during the initial stages of compartment loading and release over a 40-day period. Once calibrated for a specific workforce, CONLIS provides the structure for estimating lead dose under a broad range of exposure and control scenarios encountered by bridge workers.

4.2 Nomenclature

Equation	Symbol	Units	Definition
4.2	τ	-	dummy variable of integration
	α	$\mu g\ d^{-1}$	rate of lead mass inhaled
	β	$\mu g\ d^{-1}$	dietary lead
	ρ	-	fractional uptake of air lead
4.3	$\Phi(t)$	-	State Transition Matrix
4.4	$\delta(t)$	-	Dirac delta function
4.1	$\mathbf{A}$	hr^{-1}	body burden transfer and elimination matrix
4.15	A_h	m^2	hand area
	a_{ij}	d^{-1}	transfer coefficient for lead from compartment i to compartment j
4.1	$\mathbf{B}$	-	dose transfer matrix
	b	d^{-1}	coefficient of blood lead eliminated in urine
	c	d^{-1}	coefficient of blood lead eliminated in hair, nails, and sweat
4.14	C_A	$\mu g\ m^{-3}$	airborne lead concentration near a work crew
	C_{am}	$\mu g\ m^{-3}$	lead concentration from ambient air
4.12, 4.13	$C_{bll}(0)$, $C_{bll}(t_e)$	$\mu g\ dl^{-1}$	blood lead concentration at the beginning and end of an exposure interval respectively
	C_t	$\mu g\ m^{-3}$	lead concentration in the personal breathing zone from a task
	C_w	$\mu g\ m^{-3}$	background workplace lead concentration
	dx_i/dt	$\mu g\ d^{-1}$	rate of accumulation of lead in compartment i
	E	$\mu g\ d^{-1}$	lead input from unmeasured sources
4.14	f_{duty}	-	worker job adjustment factor
4.15	f_{gut}	-	absorption factor from gut to blood
	f_{hyg}	-	personal hygiene factor
4.14	f_{lung}	-	absorption factor from lungs to blood
4.14	f_{resp}	-	respirator penetration factor
4.15	f_{wash}	-	fraction surface dust on hands after washing
4.8	I	-	identity matrix
4.10	i	-	index of body compartment
4.9	k	-	index of sub-interval within an exposure interval
4.15	L_h	$\mu g\ m^{-2}$	lead loading on hands
	L_s	$\mu g\ m^{-2}$	work area surface lead load
4.16	M_{rc}	$\mu g\ hr^{-1}$	dose rate from smoking
4.15	M_{rd}	$\mu g\ hr^{-1}$	dietary dose rate
4.14	M_{rt}	$\mu g\ hr^{-1}$	inhalation dose rate, task-specific
4.11	M_w	kg	body weight
4.10	$\mathbf{P}(t)$	-	proportional body burden vector at time t
	Q	$m^3\ hr^{-1}$	area ventilation rate
	q	-	fractional uptake of lead in digestive tract
4.14	Q_b	$m^3\ hr^{-1}$	breathing rate of a worker
4.15	R_{cig}	hr^{-1}	cigarettes smoked per hour
4.16	R_d	hr^{-1}	rate of hand-to-mouth activity while eating
4.1	t	hr	time
4.13	t_e	hr	duration of exposure interval
	t_k	hr	duration of exposure step
4.7	U	$\mu g\ hr^{-1}$	constant dose rate vector

4.1	**U**(t)	μg hr^{-1}	time dependent dose rate vector
4.1	$u_1(t)$	μg hr^{-1}	dose rate to the blood compartment
4.17	u_b	μg hr^{-1}	dose rate during blasting hours
4.19	u_E	μg hr^{-1}	dose rate during entire exposure interval (blasting + non-blasting)
4.18	u_{nb}	μg hr^{-1}	dose rate during non-blasting hours
4.11	V_b	m^3	blood volume
4.9	**X**(k)	μg	recursive-step body burden vector
4.1	**X**(t)	μg	body burden vector at time t
4.1	$x_1(t),x_2(t),x_3(t),x_4(t)$	μg	lead mass in the blood, cortical bone, trabecular bone and tissue compartment respectively
4.4	$\mathbf{X}_{imp}(t)$	μg	impulse body burden vector
4.7	$\mathbf{X}_{step}(t)$	μg	step body burden vector

The unit (-), signifies a dimensionless fraction; μg , microgram; d, day; hr, hour; m, meters.

4.3 Introduction

The relationship among exposure events, control techniques and changes in contaminant dose are not well understood in construction environments (Froines 1997). This understanding is particularly absent in lead-related bridgework. Previous chapters of this project have discussed the separate characteristics of lead exposure sources, control techniques and the blood lead levels (a measure of long-term body burden) among workers who have engaged in bridgework. In particular, Chapters 2 and 3 have characterized influences of factors such as lead paint content, containment characteristics, and hygiene and administrative practices on personal breathing zone (PBZ) concentrations during the performance of a task and techniques for monitoring and controlling blood lead levels among construction workers. However, neither PBZ nor blood concentration provides a clear estimate of recent lead dose. As well, inhalation lead intake is not an appropriate metric when there is more than one route and uptake of the contaminant by different routes is substantial, which has been true for lead (Castellino et al. 1995). Therefore, the primary goal of this chapter is to establish a procedure for estimating a recent dose of lead for a given worker. To meet this need, a hypothesized model structure is presented in this chapter. This quantitative structure links construction workplace conditions and exposure events to lead body burden. The proposed model will attempt to narrow the current shortcomings among two common methods of evaluating and controlling lead intake among workers during bridge construction work.

Current methods of estimating lead dose from recent work exposure fall short in two broad areas. First, they fail to account for the impact on exposure of work-related conditions such as paint, air and surface dust lead content at work sites, containment characteristics, hygiene practices and facilities and administrative practices. Second, they fail to take into account the obscuring effect of lead accumulated in the body. This chapter addresses the limitations of these current methods of estimating lead dose by developing a new model structure simulating the influence of exposure events and control techniques on the lead body burden of a construction worker. The underlying model is based on physical principles of mass conservation within the environment and the human body.

The model consists of a front-end and a back-end component, which together characterize the transport of lead from workplace contaminated air to body burden among workers. The back-end module is a physiologically based pharmaco-kinetic (PBPK) model that simulates the movement of lead through the blood, tissue, and trabecular and cortical bone (Bert et al. 1989). This module is used to separate a worker's past body burden of lead from that absorbed during recent lead exposure to derive an absorbed dose from measured blood lead levels. Components that represent mass flow from the task to the worker's blood comprise the front-end structure. These components are intended to represent phenomena described in the industrial hygiene and blood-lead evaluations performed during the Connecticut Road Industry Surveillance Project (CRISP) demonstration.

This chapter focuses on establishing a deterministic structure for describing the relationship among exposure, control and blood lead levels resulting from bridgework that involves coating operations. Modeled tasks best describe abrasive blasting activities because most of the CRISP industrial hygiene reports evaluated this type of operation (5 projects involved ironwork versus 9 projects that involved coating operations). Two objectives are pursued. The first objective is to establish the variables, rationale and equations that comprise a model simulating lead intake during coating operations. The second objective is to describe two methods for calculating lead dose over an exposure period. One method derives dose from measured changes in blood lead levels and the other method derives dose from workplace exposure variables. Each pair of dose estimates will be compared as part of an analysis of industrial hygiene intervention effect in Chapter 5.

Section 4.4 introduces variables used to represent phenomena in the work environment that may result in lead intake, absorption, distribution, and elimination from the human body. These variables are linked by equations to form a structural model (hereafter referred to by the acronym CONLIS for 'CONstruction Lead Intake Simulation'). Section 4.4.1 discusses and justifies the general methodology for model construction. Section 4.4.2 introduces the primary components of the model being developed. Sections 4.4.3 and 4.4.4 present the equations used to derive dose rates from blood lead and from environmental variables, respectively. Section 4.5 demonstrates CONLIS using a hypothetical scale factor for input and Bert's system of differential equations. CONLIS's behavior is illustrated through graphical presentations of responses to step and pulsed inputs. Section 4.6 summarizes the information presented in this chapter. The appendix to this project presents two MATLAB (2000) scripts that identify, solve and simulate an existing physiologically based pharmaco-kinetic model developed by Bert et al (Bert et al. 1989). Chapter 5 explores the strength and importance of relationships among intermediate components of CONLIS. For that analysis, specific information found primarily in CRISP records about bridge workers and their working environment will be put to use.

4.4 Methods

This project seeks to examine the relative strength and importance of several exposure conditions and control techniques on worker blood lead levels. To prepare for this type of analysis, we propose a multilevel model. By definition, such models are characterized by a hierarchical structure and are typically stochastic, where the relationships between constituent variables at one level of the model hierarchy are conditional on randomly varying variables at a lower level. Multilevel models were introduced into the environmental literature in 1985 to explore relationships between environmental lead and blood lead levels among young children (Bornschein et al. 1985). The advantage of this type of modeling was demonstrated by comparing the stability of results among single level and multilevel structures using multiple regression methods. Bornschein et al. (1985) concluded that stability of the multilevel structure was superior.

4.4.1 General model criteria

The criteria for this model generally follow those presented by Riley (1996) for a numerical model of transient wind fluctuations and radon entry into buildings.

First, the model should be able to reproduce analytical solutions to a range of values representative of potential workplace and biological conditions. Many factors can distort the output of a lead mass transport model at this stage. Accuracy could be affected by the resolution of the time step and the approximations made by the numeric method used for discretizing the derivatives in the equations. Factors such as the methods chosen to approximate variable profiles of lead dose rate across body compartment volumes such as in the breathing rate and volume of inhaled air of a worker could also affect accuracy.

Secondly, the model's predictions should match measured quantities of lead in the body that represent scenarios under which the model will be applied. In the context of blood lead transport modeling, several levels of validation could be employed. For example, comparisons to field measurements of blood lead measurements taken after performing a series of blasting tasks on a bridge provide strict tests of the model. Many factors can affect the model's predictive ability in these simulations. Factors such as the accuracy of the characterization of system properties (e.g., personal breathing zone air concentration during a task, respirator penetration of airborne lead, inhalation and ingestion attributes) can affect predictions on the front end of the system. As well, the limited accuracy of the compartmental representation of the adult human body on the back-end of the system model can distort model predictions.

The criteria for success at either of these stages should depend on the intended application of the model. In general, though, the requirements for the first stage (analytical tests) are much stricter than for the second (laboratory or field measurements). Without some success matching analytical solutions, any success at the experimental validation stage is likely coincidental. If the model is to be used for prediction in a specific situation, the criteria for success at the experimental or field validation stage must be fairly stringent. However, if the model is to be used in an exploratory fashion, that is, to elucidate qualitative features of the problem, the simulation results need not precisely match measurements from specific field or laboratory data. Capturing the qualitative features of the laboratory or field data may suffice.

A good example of this type of modeling application can be seen in the OSHA lead in construction standard in the design of workplace exposure control requirements (OSHA, 1993). Measurements taken by NIOSH during field investigations inside and outside of blast hoods during abrasive blasting were used to establish an air concentration distribution in the personal breathing zone of workers and a range of respirator penetration values. An OSHA contractor used these values as inputs to a PBPK model. Modeled blood lead levels were compared to measurements of blood lead from the state of Maryland's adult blood lead registry to validate the results presented by OSHA. These results appear in Table 4 in the preamble to the lead in construction standard (OSHA 1993). The analysis focused on very broad questions, and therefore did not require the use of a model that had been tested and validated at a particular construction site under consideration.

The next three sections present the rationale and specific equations for the front-end module and a back-end module of CONLIS.

4.4.2 Components of CONLIS

CONLIS has two primary components: a back-end module that has undergone prior calibration and testing and a front-end module developed in this chapter. The back-end of CONLIS consists of a PBPK model developed by Bert et al (1989) with minor modification. Namely, the transport coefficients in Bert's original work were expressed in units of day^{-1}. The current model uses both day^{-1} (to compare with the original model) and equivalent coefficients calibrated in hr^{-1} to reflect the emphasis on the short-term changes in body burden of interest in construction work. Bert's model calibration and testing were performed using two sets of chamber studies and the cumulative body burden of lead observed during autopsies of people of different ages (Bert et al. 1989). Blood lead levels observed in the chamber studies were in the same range as those found among construction workers enrolled in CRISP and summarized in Chapter 3 of this project. The Bert model can be used to set initial conditions in each of four compartments representing different body tissues and distinguish recent uptake and dynamics of lead in an adult worker from that of lead dynamics from past uptake. Then, the observed change in blood lead from recent lead uptake can be compared to that expected under the assumption of no lead uptake. However, the Bert model by itself is insufficient to characterize exposure pathways and intake patterns. An input (front-end) module that adequately links the pathways, routes and patterns of lead intake among construction workers to the Bert model needs to be developed. Until this project, this type of module had not been developed.

Equations describing the steady state or time weighted average rate of lead entering the body are determined in two steps. First, a simplifying assumption is made that lead absorbed into the blood can originate from any of five different pathways during a particular exposure period. The model derives inhaled dose rates from estimates of air concentration inside the respirator, in the PBZ of a worker, or from lead contaminated cigarette smoke by multiplying each concentration by the breathing rate. Lead from contaminated hands or a dietary source multiplied by an ingestion rate determines an ingested dose rate. Second, CONLIS calculates the lead entry rate into the blood by multiplying the dose from the lungs and gut by their respective absorption factors and adding up each dose during a particular time interval.

There are two important features incorporated into the front-end module. First, this module allows for the exploration of both background and work-related lead sources that increase blood lead levels. Pathways to lead exposure such as dietary, ambient air and cigarettes that are significant sources of lead exposure in the general population may be important sources for workers as well (ICRP. 2002). During work, surface dust loading of lead in the construction workplace may play a significant role in addition to airborne lead. Second, this front-end module allows for the exploration of interventions that reduce blood lead levels. Restrictions in task assignment, equipping dust generating devices with local exhaust ventilation and changing other work-related factors (e.g., the type of respiratory protection device used by workers described in Chapter 3) are all examples of interventions that can influence the evolution of blood lead levels among workers.

4.4.3 *Deriving lead dose from blood lead levels (back-end module)*

A PBPK model developed by Bert et al. supplies the uptake, transfer and elimination coefficients and body compartment structure. This bio-kinetic model incorporates a set of parameters that have been calibrated from three sets of observations. After making several simplifying assumptions, the Bert model contains four lead accumulation compartments: blood ('1'), cortical bone ('2'), trabecular bone ('3') and tissue ('4'). This transfer of mass is presented as a set of four first-order ordinary differential equations representing a mass balance for lead in each of 4 transfer compartments:

Lead accumulation rate in:
blood = $dx_1/dt = \rho\alpha + q(\beta + a_{46}x_4) + E - x_1(a_{12} + a_{13} + a_{14} + b) + a_{21}x_2 + a_{31}x_3 + a_{41}x_4$
cortical bone = $dx_2/dt = a_{12}x_1 - a_{21}x_2$
trabecular bone = $dx_3/dt = a_{13}x_1 - a_{31}x_3$
tissue = $dx_4/dt = a_{14}x_1 - (a_{41} + a_{46} + c)x_4$

Bert's model also includes two uptake compartments: lung ('5') and digestive tract ('6'). Note that the transfer term 'a_{46}' is included with an 'x_4' mass term. This represents transfer of mass from the tissue (compartment 4) via liver fluids (e.g. bile) to the digestive tract (compartment 6) and back to the blood (compartment 1). Bert used the term 'E' to represent an adjustment factor to account for unmeasured lead sources. The nomenclature for the Bert et al model equations is as follows:

x_i = mass of lead in compartment i (μg)
dx_i/dt = rate of accumulation of lead in compartment i (μg d^{-1})
a_{ij} = transfer coefficient for lead from compartment i to compartment j (d^{-1})
b = coefficient of blood lead eliminated in urine (d^{-1})
c = coefficient of blood lead eliminated in hair, nails, and sweat (d^{-1})
α = rate of lead mass inhaled (μg d^{-1})
β = dietary lead (μg d^{-1})
E = lead input from unmeasured sources (μg d^{-1})
ρ = fractional uptake of air lead
q = fractional uptake of lead in digestive tract

Bert and colleagues (1989) build a model based in part on previous work of Marcus (1985); Batschelet et al. (1979); Bernard (1977) and Rabinowitz et al. (1976). Bert and co-authors tested their model against three sources of measurements depicting lead accumulation in the adult human body. In particular, Bert obtained data from autopsy studies that contained accounts of lead accumulation among people of differing age, allowing Bert and colleagues to correct some of the shortcoming of prior models developed by Rabinowitz (1975) and Bernard (1977). According to Liu et al. who compared the Bert model to six other models and to published postmortem data from the 1960s, the Bert model predicted blood lead levels particularly well for the group < 50 years of age. Table 4.1 presents the values found through Bert's calibration and employed in the back-end of CONLIS.

Bert et al employed numerical methods to evaluate these equations. However, an analytical solution is possible. This solution derived and its use in CONLIS is described in the next part of this section.

Bert's set of differential equations is linear and time-invariant. The equations can therefore be represented using matrix notation per equation 4.1.

$$\frac{d\mathbf{X}(t)}{dt} = \mathbf{AX(t)} + \mathbf{BU(t)} \qquad (4.1)$$

In equation 4.1, **X(t)** is the vector of body burden mass in units of (μg), comprised of elements (x_1,x_2,x_3 and x_4) representing the lead mass in blood, cortical bone, trabecular bone and tissue, respectively. The 4x4 constant matrix **A**, with units (hr^{-1}), represents coefficients for the rate of transport of lead between body compartments as well as elimination from the body via urine and alimentary tracts. The constant, unitless input transfer matrix **B** represents pathways of entry for lead. However, because of the way the model is constructed, it is specifically comprised of a 4x4 identity matrix. Finally, **U(t)** is the input vector of absorbed mass rate (dose rate) in units of ($\mu g\ hr^{-1}$). **U(t)** is comprised of elements (u_1, 0, 0, 0), representing absorption exclusively to the blood compartment. It should also be noted that Bert scaled blood volume to include soft tissue and bone volumes and estimates blood volume based on the weight of an individual. Specifically, Bert assumes that quantities of body weight and blood volume are related by equation 4.11. Where no weight data are available, Bert assumes a weight of 70 kg (ICRP 2002). Since weight is part of the available data in my research, Bert's estimate for blood volume will be followed. The general solution to the differential equations represented by 4.1 is equation 4.2:

$$\mathbf{X(t)} = \mathbf{e}^{(\mathbf{At})}\mathbf{X(0)} + \int_0^t \mathbf{e}^{\mathbf{A(t-\tau)}}\mathbf{BU}(\tau)d(\tau) \qquad (4.2)$$

The first additive term is the zero-input response, where **X**(0) is **X** evaluated at t = 0, and the second term is a convolution integral representing the zero-state (forced) response.

Also, $e^{(At)}$ is known as the 'state transition matrix'. The state transition matrix is evaluated by using MATLAB's built-in exponential-matrix function EXPM(A). The EXPM function uses the Pade approximation to perform matrix expansion (MATLAB 2000). An alternate method using Laplace transforms computes $e^{(At)}$ as the inverse-Laplace transform of the matrix $(s\mathbf{I}-A)^{-1}$, where 's' is the Laplace complex frequency operator. MATLAB also has functions enabling this method, however the EXPM function method is more straightforward. From this point forward, the state transition matrix will be represented as the symbol Φ, i.e.:

$$\Phi(t) = e^{(At)} \tag{4.3}$$

4.4.3.1 Impulse Response

The solution to Bert's PBPK model as expressed by equation 4.2 can be evaluated for any arbitrary forcing function $\mathbf{U(t)}$. The most elementary case is $\mathbf{U(t)} = \delta(\tau)$, where $\delta(\tau)$ is an ideal impulse vector represented by the 'Dirac delta function' per equation 4.4.

$$\mathbf{X}_{imp}(t) = \Phi(t)\mathbf{X}(0) + \int_0^t \Phi(t-\tau)\mathbf{B}\delta(\tau)d(\tau) \tag{4.4}$$

Equation 4.4 is of interest because one property of convolution with the delta function is the fact that, for any arbitrary continuous function F(t) :

$$F(t) = \int F(t-\tau)\delta(\tau)d(\tau) \tag{4.5}$$

With equation 4.5, the complete impulse response can be determined from inspection as

$$\mathbf{X}_{imp}(t) = \Phi(t)\mathbf{X}(0) + \Phi(t)\mathbf{B} \tag{4.6}$$

The second additive term of equation 4.6 is termed the 'transfer function', because for any arbitrary input $\mathbf{U(t)}$, since $\mathbf{X(0)}$ is a vector of constants, $d\mathbf{X(t)}/\mathbf{U(t)} = \Phi(t)\mathbf{B}$. The overall system response to any arbitrary forcing function $\mathbf{U(t)}$ can therefore be computed by convolving $\Phi(t)\mathbf{B}$ and $\mathbf{U(t)}$ and adding the zero-input response.

4.4.3.2 Step response

The step response is calculated as equation 4.2 where $\mathbf{U(t)} = \mathbf{U} = [u_1\ 0\ 0\ 0]$ is constant for $t>0$. The solution derived from equations 4.2 to 4.6 can be expressed as equation 4.7:

$$\mathbf{X}_{step}(t) = \Phi(t)\mathbf{X}(0) + \int_0^t \Phi(t-\tau)\mathbf{B}\mathbf{U}d(\tau) \tag{4.7}$$

Evaluating the integral of equation 4.7 yields equation 4.8:

$$\mathbf{X_{step}(t) = \Phi(t)X(0) + (\Phi(t) - I)A^{-1}BU} \quad (4.8)$$

Note that the new quantity '**I**' is a 4x4 identity matrix. Also note that in many references, the second additive term of 4.8 is expressed as $\mathbf{A^{-1}(\Phi(t)\text{-}I)BU}$. However, equation 4.8 is correct because in this special case these multiplied terms are commutative. The expressed version of equation 4.8 has been chosen because it is advantageous for speeding up repetitive calculations since $\mathbf{A^{-1}B}$ only has to be calculated once.

4.4.3.3 Repetitive step response

Repeated exposures to varying lead concentrations are treated as a time series of delayed steps. In CONLIS, an entire exposure interval t_e is subdivided into k sub-intervals of duration t_k; i.e., $t_e = \Sigma_k(t_k)$ with k>0 (e.g., if t_e is the number of days in a month for a month-long exposure interval, then t_k might be represented as one day). Each of these intervals is assigned a lead uptake rate **U(k)**, which is assumed constant over the sub-interval. For periods of non-exposure CONLIS ignores background lead intake (i.e., **U(k)**=0 during non-exposure). Also recall that **U(k)** = $[u_1(k)\ 0\ 0\ 0]$. For periods of exposure, the body burden at the end of the k^{th} interval is expressed as a recursive time series by a simple extension of equation 4.8. This expression is represented as equation 4.9.

$$\mathbf{X(k) = \Phi(k)X(k\text{-}1) + (\Phi(k) - I)A^{-1}BU(k)} \quad (4.9)$$

Two other facts are noteworthy when evaluating equation 4.9. First, when (k-1)=0, **X**(k-1) represents an initial body burden. Second, although in general intervals of t_k will be held constant, it is also possible for them to vary. In the latter case, it will be necessary to recompute the matrix $\mathbf{\Phi(t)}$ whenever t_k changes.

Equation 4.9 represents a powerful method of incorporating time-activity data into the model, as it directly relates dynamic body burden **X**(k) to the dynamic dose rate **U**(k). The equation will be used again when evaluating different scenarios simulating such activity and comparing with actual field data. A demonstration MATLAB script for the impulse, step and repetitive step response appears in the appendix to this project.

4.4.3.4 Estimate of body burden using measured blood lead concentration

The back-end module requires an estimate of initial body burden for its solution, as this forms the initial condition. This section derives dynamic expressions for body burden and blood lead using the back-end module of CONLIS. These expressions will later enable prediction of blood leads during a work related exposure interval given an exposure rate and certain assumptions. The first step is to use equation 4.8 to estimate proportion of total body burden in each compartment for a worker of a given age.

CONLIS determines initial conditions for solving 4.8 by assuming body compartment lead levels are in pseudo-steady state based on blood lead prior to work exposures. The stimulus for equation 4.8 is a step representing a certain average lifetime exposure level, the exact magnitude of which is not important, since at this stage the result is normalized. The time t is set to the age of the worker and **X**(0) is set to zero (assuming no exposure at birth). Equation 4.10 represents the vector of proportional allocation among compartments of total lead burden in an adult human, with **X**(t) and its elements $x_i(t)$ representing the result of solving equation 4.8 using these assumptions.

$$\mathbf{P}(t) = \mathbf{X}(t) / \Sigma_i x_i(t) \qquad ; i = 1..4 \qquad (4.10)$$

CONLIS uses default values for **P**(t) in the absence of information about the age of a worker. The default proportions are $p_1 = 0.025874$ for the blood compartment, $p_2 = 0.94423$ for the cortical bone compartment, $p_3 = 0.027053$ for trabecular bone compartment and $p_4 = 0.00284$ for the tissue compartment. These proportions represent how mass is allocated in each compartment of the Bert model after the lead has accumulated in the body for a 20-year old worker.

The second step estimates blood volume. Bert's formula per equation 4.11 is employed for this purpose.

$$V_b = (M_w)(0.75)(1.5) \qquad (4.11)$$

Regarding 4.11, M_w (kg) is the body weight of a worker. In the absence of information on body weight, CONLIS uses an average body weight of 82 kg from a study of construction workers conducted in 1991 (Linn et al. 1993). As well, a conversion factor of 0.75 dl kg^{-1} is incorporated that approximates the blood volume per kilogram of body weight (ICRP. 2002). An adjustment factor of 1.5 that was included in the Bert model is also incorporated into CONLIS to account for the effect of rapid exchange between a portion of the soft tissue and blood (Bert et al. 1989; Rabinowitz et al. 1976).

The quantity $C_{bll}(0)$ is the key measured input parameter, which corresponds with the initial measured blood lead level before the onset of an exposure interval. This quantity is converted to an initial burden (**X**(0) is **X** at t = 0, the start of the exposure interval) by equation 4.12.

$$\mathbf{X}(0) = [(C_{bll}(0))(V_b) / p_1(0)]\, \mathbf{P}(0) \qquad (4.12)$$

Let the length of an exposure interval (typically one month) be designated as t_e, which is divided into k equal sub-intervals (sub-intervals are typically 1-day; however the only absolute criterion is that the dose rate is assumed constant over the sub-interval). Using the iterative procedure outlined in section 4.4.3.3 and equation 4.12 as the initial condition, the blood lead at the end of this interval is expressed by equation 4.13. Also, note that the body burden at time t_e is given by $\mathbf{X}(t_e)$.

$$C_{bll}(t_e) = x_1(t_e) / V_b \qquad (4.13)$$

4.4.4 Deriving lead dose from workplace variables (front end module)

The back-end module described in the previous section links lead dose to body burden. The front-end module of CONLIS is comprised of equations characterizing intake pathways resulting from airborne lead, smoking, dietary intake and surface dust. Each term represents either directly or indirectly observed or derived variables. Dose is derived through both inhalation and ingestion routes. The objective is to describe the most representative factors that change the body burden of lead in a worker or group of workers. Dynamic equations are scaled to 1-hr events. The principle of mass balance underlies the transfer of lead along the inhalation pathway from a source to a worker's blood.

Figure 4.1 displays the sequence of events leading to a change in lead body burden. The figure begins with a source and ends with a change in body burden. Terms representing events in this figure are discussed in the sub sections 4.4.4.1 to 4.4.4.3.

4.4.4.1 Airborne pathway

For parameters representing each pathway, we assumed that air concentrations of lead near a work crew remain constant during the time step of 1 hr. Inhalation sources are represented as constant concentrations over this interval and include concentrations contributed from background workplace lead C_w, task related lead C_t and ambient lead C_{am}. The concentration C_A represents the sum of these sources (i.e., $C_A = C_w + C_t + C_{am}$).

The PBZ concentrations obtained from blasters, painters and foremen who performed jobs other than abrasive blasting directly were also distinct (from blasters and from each other). This issue is addressed by specifying a dimensionless fraction characteristic of each job, f_{duty} (e.g., for blasters, $f_{duty} = 1$; for other job titles $f_{duty} < 1$). This parameter appears with respirator penetration factor and task-based lead concentration in equation 4.14.

Findings in Chapter 3 suggested that components of CRISP Lead Health Protection Program (LHPP) affected workers blood lead levels. Key components included on-site industrial hygiene monitoring, respiratory protection and blood lead monitoring and management. The primary object of on-site industrial hygiene monitoring was to establish and maintain exposure-control measures such as respiratory protection and hygiene practices. The effect of respiratory protection devices is an important factor in control lead intake during lead-related bridgework. A few studies have examined the degree of mass penetration into blast hoods and helmets during abrasive blasting activity (Sussell et al. 1992; Feletto). Others have examined the effect of powered air purifying and negative pressure respirators in reducing pollutant intake (Myers et al. 1986).

Respirator penetration of a particular device links the concentration inside to the concentration outside the respirator by the fraction f_{resp} appearing in equation 4.14.

The amount of lead deposited into the lungs and subsequently absorbed into the blood depends on the deposition rates, which are in turn dependent on the shape and size distribution of particles and the worker's breathing rate. Clearance rates are in turn dependent on the region of the lung in which the particle deposits and the particle's solubility (Castellino et al. 1995). Previous studies of healthy outdoor workers found that breathing rates could vary substantially. Linn et al. (1993) found that the mean breathing rates among a cohort of workers engaged in heavy construction activities to be 1.55 $m^3\ hr^{-1}$ corresponding to the average weight of 82 kg among the study's subjects. Coupled with these figures, it is estimated that at nominal breathing rates, adult lungs absorb approximately 35% of inhaled lead mass from ambient air (ICRP. 2002). The remaining mass is either ingested or exhaled.

A worker who inhales lead containing may also swallow a fraction of the particles cleared by the upward propelling action of the cilia lining the lungs. However, a study conducted on adult human volunteers revealed that under normal conditions, about 8-12% of lead that is ingested is absorbed (Rabinowitz et al. 1976). Therefore, the cilia-cleared mass was not included as a pathway in CONLIS because the amount of mass absorbed from this pathway is relatively small (<5%).

To compute the rate of inhaled lead mass ($\mu g\ hr^{-1}$) absorbed to a worker's blood from the lungs during the performance of a task, the concentration of lead in the air inside the respirator must be related to the concentration of lead absorbed. Equation 4.14 incorporates this relationship, with f_{lung}, which represents a dimensionless lung to blood absorption fraction. The term Q_b ($m^3\ hr^{-1}$) represents a worker's breathing rate. The rate of task-specific inhaled lead mass absorbed, M_{rt}, is specified by equation 4.14.

$$M_{rt} = C_A f_{duty} f_{resp} f_{lung} Q_b \qquad (4.14)$$

4.4.4.2 Hand and dietary pathways

The lead dose rate from the gut due to dietary intake into a worker's blood is determined by a number of factors, including the dietary ingestion rate R_d (hr^{-1}), dietary mass M_d (μg), and the intestinal absorption fraction f_{gut}. Additionally, the degree of lead intake through the digestive tract depends on workplace hygiene and the worker's eating and hygiene habits (i.e. skin cleanliness). Briefly mentioned in Chapter 2, Connecticut projects revealed surface lead dust loading L_s of 450-650 $\mu g\ m^{-2}$ prior to cleaning the workplace. A fraction, f_{hyg}, of L_s is assumed to be deposited onto hands of area A_h, resulting in a personal loading of $L_h = (L_s)(f_{hyg})$. In terms of mass, the amount of intake from this source is $(L_h)(A_h)$. Finally, a 15 to 20-fold decrease in L_h was recorded from measurements taken before and after cleaning surfaces and washing hands. Therefore it is appropriate to introduce a hand washing fraction f_{wash} as another determinant. The resultant rate of uptake due to these ingested sources is estimated by equation 4.15.

$$M_{rd} = (0.5\ L_h\ A_h\ f_{wash} + M_d)\ R_d\ f_{gut} \qquad (4.15)$$

Some evidence suggests that cigarette smokers may incur an additional exposure risk. Studies conducted prior to 1975 estimated that the daily intake of 1 μg $cigarette^{-1}$ for smokers (ICRP. 2002). Workers who smoke may have substantially different exposures even though they may work in an environment with the same airborne lead concentration. A mass variable M_{cig} (μg) (the amount of lead contained in the tobacco of one cigarette) and rate variable R_{cig} (hr^{-1}) are used to characterize in part, the exposure to lead from smoking a cigarette. The other source of lead exposure from smoking a cigarette comes from the same hand pathway as in equation 4.15, a fraction of the surface dust L_h is also transferred onto the paper of a cigarette each time a cigarette is smoked. Since the lead transferred during an episode of eating would not be available for transfer onto the paper of a cigarette, an adjustment fraction of 0.5 in equations 4.15 and 4.16 is assumed to account for the shared transfer of lead load from the hand. The lead uptake rate due to smoking (μg hr^{-1}) is represented by equations 4.16.

$$M_{rc} = (0.5\ A_h\ L_h\ f_{wash} + M_{cig})\ R_{cig}\ f_{lung} \qquad (4.16)$$

4.4.4.3 Combined pathways

The entire rate of lead uptake for each hour of a blasting task is the sum of all three exposure pathways, equations 4.14 to 4.16, represented by equation 4.17.

$$u_b = M_{rt} + M_{rd} + M_{rc} \qquad (4.17)$$

When workers are performing duties that do not generate airborne lead, workplace area and ambient concentrations affect their PBZ concentrations. During non-blasting time, airborne lead sources include C_{am}. The default concentration assumed in CONLIS for non-blasting hours is 0.1 μg m^{-3}. A second default quantity is the breathing rate during mild activity (i.e., non-blasting), assumed to be 0.65 $m^3\ hr^{-1}$. Also, for this case, it is assumed that the worker is not wearing a respirator ($f_{resp} = 1$), and that a worker's exposure is not affected by duty assignment ($f_{duty} = 1$). With these assumptions, a different uptake rate u_{nb} is estimated for non-blasting hours (the subscript 'nb' refers to non-blasting hours) given by equation 4.18.

$$u_{nb} = (0.1)(0.65)\ f_{lung} \qquad (4.18)$$

Let the quantities $u_b(k)$ and $u_{nb}(k)$ indicate the rates of lead uptake during the kth hour of an exposure interval attributed to blasting and non-blasting tasks, respectively. An expression u_E for the lead dose for the entire interval is given by equation 4.19 (note that at any given time, only one of the summed terms is non-zero).

$$u_E = \sum_k u_b(k) + \sum_k u_{nb}(k) \quad (4.19)$$

4.4.5 Validity and parameter sensitivity of the CONLIS model

4.4.5.1 Validation method for CONLIS

We performed a two-stage validation test of CONLIS. Initially, the analytical solution to the Bert equations was compared to the Bert model reproduced in Simulink, a software package for modeling, simulating and analyzing dynamic systems (MATLAB 2000). Simulink uses numerical methods to simulate dynamic systems. A simple pulse stimulus was applied to both models and the outputs were compared. The Runge-Kutta numerical integration method was employed in the Simulink model to reproduce the method of simulation described and implemented by Bert and colleagues (1989). The purpose of this test was to validate that the dynamics of Bert's model were accurately reproduced.

We implemented a second stage of validation by comparing CONLIS predictions to real-world measurements. First, we compared CONLIS predictions to the same experimental data used by Bert. This test assures that Bert's original assumptions are incorporated into the present model (such as the relationship between body weight and blood volume). For this test, the CONLIS model is applied to data from three subjects of the Rabinowitz study 'A', 'B', and 'D' and compared to Figure 3 of the Bert study.

Second, we conducted a validation test, which incorporated the front-end module of CONLIS. This validation test includes the distribution of PBZ concentrations of lead among workers who are performing open abrasive blasting in ventilated enclosed workplaces on a highway bridge in Kentucky, the corresponding air concentrations of lead inside blast hood and the subsequent changes in blood lead levels among blasters. For each parameter in the front-end of CONLIS, when standard deviations where available, they were incorporated. Otherwise assumptions about the distribution of values were made in the absence of data.

Specifically, the means and measures of variance for exposure inputs to CONLIS are derived from values reported by Sussell et al. (1992) from the Kentucky bridge-project study. For some parameters, means and measures of variance are derived from values reported in field and chamber studies conducted on healthy adult men (Rabinowitz et al. 1976; Hursh et al. 1969; ICRP. 2002). For other parameters values are based on my interpretation of the conditions described in the general clinical and occupational literature (Linn et al. 1993; Castellino et al. 1995; Levin et al. 1990). The initial validation test using bridge worker data set all parameters the arithmetic mean except the initial blood lead, which was allowed to vary randomly over 1000 exposure simulations. CONLIS predictions were compared to measured blood lead levels from the Kentucky bridge project study.

4.4.5.2 *Preliminary test of parameter sensitivity by Monte Carlo simulation*

We conducted a preliminary test of parameter sensitivity by Monte Carlo simulation. The approach described in this section follows the approach taken by (Repace et al. 1998) for evaluating workplace passive smoking exposure and risk. In the simulation, each individual parameter in equations 4.14 - 4.16 is represented by a distribution of values rather than a single mean value. For example, the physiological parameters $C_{bll}(0)$, M_w, Q_b, f_{lung}, f_{gut} the behavioral parameters R_h and R_{cig} and the work assignment parameter f_{duty} will differ between individuals and from day to day for a given individual. The physical parameters of workplace exposure, such as C_A, and L_s and the techniques used for exposure reduction such as $f_{resp,}$ f_{wash} and f_{hyg} will differ for different workplaces and from day to day for a given workplace. The parameters M_{cig} and M_d will differ as a result of variations in product design. Finally, the shape of some parameter distributions is assumed normal and others are assumed to be lognormal.

For the purpose of this initial Monte Carlo simulation, we have assumed that all of the variation in each parameter occurs between exposures. That is, the set of values randomly selected at the beginning of a time series remains constant throughout the realization. Each blasting task was cycled as a binary process alternating with background ambient lead concentration alone (see Figure 4.2).

Table 4.2 lists 18 parameters and their assumed distributions included in the front-end module of CONLIS. We conducted a preliminary variability and uncertainty assessment of seven parameters included in CONLIS. Sensitivity analysis by Monte Carlo simulation assumes no correlation between parameters (Bevington & Robinson. 1992). Where correlation between two or more parameters was suspected (e.g., bodyweight and initial blood lead or respirator penetration and PBZ lead concentration), only one of the suspect variables was allowed to vary.

4.5 Results

In this section, the response of CONLIS to a simulated pulse dose of lead and the transient buildup in response to a constant and intermittent repetitive dose (step) is demonstrated.

4.5.1 *Response of the system to a pulse dose of lead*

Figure 4.3 displays the results of the system's impulse response according to the definition of section 4.4.3.1, equation 4.6. In this figure, the vertical axis represents a single absorbed dose of 1 μg of lead. Uptake and elimination within each body compartment occurs from the hypothetical condition where there is no prior body burden of lead (i.e. zero state). The blood compartment mass begins to decline immediately after the dosing ceases on day 1. The mass in the remaining body compartments however continues to accumulate throughout the 300-day exposure interval. The amount of mass in the blood, cortical bone, tabecular bone and tissue are plotted using lines with circles, crosses, asterisks and Xs, respectively.

4.5.2 Step response

Figure 4.4 displays the step response of the system according to the definition of section 4.4.3.2 equation 4.8. In this figure, the vertical axis represents a daily-absorbed dose of 1 μg of lead. Uptake and elimination within each body compartment occurs from the hypothetical condition where there is no prior body burden of lead (i.e. zero state) and the time course of accumulation is displayed from day one over 300 days allowing the lead mass in the blood compartment to reach steady state. The time step is one day. The amount of mass in the blood, cortical bone, trabecular bone and tissue are plotted using lines with circles, crosses, asterisks and Xs, respectively.

Figure 4.5 demonstrates the application of equation 4.9, the repetitive step response. In this figure, a unit-amplitude pulse dose is delivered over 9 days. During that time, 1 μg dose of lead in the blood compartment increases approximately linearly with very small amounts of mass transferred to the other body compartments or eliminated in the urine. The blood compartment mass begins to decline immediately after the dosing ceases on day 9. The mass in the remaining body compartments however continues to accumulate throughout the 40-day exposure interval.

4.5.3 Model validation tests

CONLIS is validated and demonstrated in three steps. First, the explicit solution to Bert's equations (i.e., equation 4.9) is compared with the implicit solution represented by the Simulink model. Second, the experimental data from Rabinowitz as used in the Bert article is reused to compare CONLIS with Bert's results. Third, data for each parameter in equations 4.14 to 4.18 is compiled from the literature to generate point estimates and distributions of one-hour mean lead dose, u_E, during a bridge rehabilitation project located in Kentucky (Sussell et al. 1992).

The simulation of Figure 4.6 demonstrates equivalency of the explicit solution to Bert's equations (i.e., equation 4.9) with the implicit solution represented by the Simulink model. The stimulus to both models is a unit pulse dose-rate (1 μg day^{-1}) applied for 10 days, followed by 40 days of no exposure. The zero-state case for $\mathbf{X}(0)$ is assumed.

Bert et al calibrated their model to the short-term changes in body burden found from the experiments conducted by Rabinowitz et al. (1976) and one study subject from the experimental study data collected by Griffin et al. (1975). The long-term changes in levels of lead in the cortical bone were calibrated to the autopsy studies conducted by

Barry (1975). The calibrated model was tested against three other study subjects from the Griffin study.

A similar test is performed on CONLIS. The Figures 4.7 – 4.9 compare the output of the present CONLIS model (using Bert's assumptions) with the observed blood-lead concentrations vs. time from three of the Rabinowitz study subjects; namely subjects 'A', 'B', and 'D'. Subject 'E' is not evaluated because of incomplete stimulus data supplied by Bert and Rabinowitz. The results shown in Figures 4.7 – 4.9 mirrors Bert's Figure 3 validation test.

In Table 4.3, the distribution of predicted blood lead is listed along with observed blood lead levels obtained from blasters during the Brent Spence bridge project performed in Kentucky in 1991. Predicted blood lead values resulted from setting all parameters to the arithmetic mean of each parameter distribution and allowing only the initial blood lead level to vary. Good agreement between predicted and observed blood lead values was found by graphical inspection when all parameters were set to the mean value and only initial blood lead was allowed to vary suggesting that mean values in the model approximates reality.

4.5.4 Monte Carlo simulation of exposures among abrasive blasters in a bridge containment structure

Figure 4.10 displays the frequency of predicted blood lead from a Monte Carlo simulation. Fourteen variables from the front end of CONLIS were allowed to vary randomly at the beginning of each month long exposure scenario. One thousand exposures were simulated. When all the parameters listed in Table 4.2 are allowed to vary, the blood lead distribution that results from this Monte Carlo simulation appears to be lognormally distributed.

Table 4.4 lists the proportion of total variance contributed by each of 7 parameters. As expected, variance in PBZ lead concentration contributes to more than half (80%) of the variance in the predicted blood lead level.

4.6 Discussion

This chapter has presented CONLIS, a new transient, work-factor blood-lead kinetic model for relating lead exposure in the workplace to blood lead levels among workers. The model core is comprised of two modules. The front-end module is a set of equations that describe two pathways and the events in time that result in a lead dose rate. The back-end module contains a transfer function for converting dose rate to body burden, representing a physiologically based pharmaco-kinetic model developed by Bert and colleagues. This module describes lead uptake and body kinetics. Equations represent dose over time.

We demonstrate lead flow through the human body from single pulse and constant intervals of repetitive dosing. CONLIS is operated through MATLAB scripts developed as part of this project to rapidly generate time series predictions of lead in body compartments and, for the purpose of exploration, to generate lead dose over time due to tasks and conditions present in construction workplaces on highway bridges.

My simulation scenario was restricted to variation in parameter values between realizations. Under that restriction, the dominant variable was PBZ lead concentration as expected. However, it is possible that most of the variability in PBZ lead concentration occurs from hour to hour within each time series in which case the mean of each parameter could be most representative of an individual worker exposure experience. Some evidence supporting this possibility was provided by the comparison between predicted and observed blood lead levels in Table 4.3.

CONLIS agrees well with the Bert model and as well as Bert's model with the Rabinowitz observations. The accumulation and slow release on the cortical bone was calibrated to age related levels of lead in the general population exposed to lead from gasoline combustion. The accumulation and release of lead among workers exposed to much higher levels of lead during abrasive blasting operation for example, may not be well represented by the kinetics of lead in the general population. However, simulations of the Brent Spence bridge rehabilitation project conducted in 1991 predicted observation of blood lead when environmental parameters were set to mean values. When only initial blood lead was allowed to vary, shorter-term kinetics were reasonably well represented by the Bert et al equations.

In a Monte Carlo simulation, seventeen parameters are included in the front-end module of CONLIS with parameter values supplied from one bridge project conducted in 1991 prior to the promulgation of the lead in construction standard in 1993. A preliminary parameter sensitivity analysis found that PBZ lead concentration and breathing rate parameters contribute the most to the variability in predicted blood lead from CONLIS. However, further research is indicated to fully explore parameter contributions.

In Chapter 2 of this project, it was shown that there were several influences between bridge projects that affected PBZ lead concentrations. For example, the mean PBZ concentration paint removal by abrasive blasting was significantly affected by the content of lead in the paint, the degree to which the work was enclosed and whether the work was carried out with local exhaust attachments on equipment. To evaluate the effects of factors related to a particular bridge project, C_A and dimensionless indicator terms for enclosure, equipment type and percent lead in the paint would have to be added to CONLIS.

4.7 Conclusion

CONLIS establishes a means to explore parameter influence on blood lead. Reductions in inhaled lead concentration due to control techniques anywhere along pathways that lead to lead dose could be explored. For example, local exhaust devices could be installed to limit source generation of lead particles during the performance of a task. Also, duty assignments could be required to limit exposure, respiratory protection could be provided to limit intake from airborne particles and calcium rich foods and beverages provided to limit ingested lead uptake (i.e. dose).

When bridge projects do not conform to regular cycles of production, CONLIS simulations are highly dependent of accurate characterization of time-activity and air concentration in the personal breathing zone of workers. The ability to accurately predict blood lead levels when several control techniques in an industrial hygiene intervention has occurred and abrasive blasting activity is irregular is further explored in Chapter 5.

Table 4.1: Summary values for transfer and elimination rates in the Bert model (day^{-1})

Variable	AM	SD	Description
a12	0.00578	0.002	transfer rate from blood to cortical bone
a21	0.0000325	0.00002	transfer rate from cortical bone to blood
a13	0.0024	0.002	transfer rate from blood to trabecular bone
a31	0.00229	0.002	transfer rate from trabecular bone to blood
a14	0.001835	0.0004	transfer rate from blood to trabecular bone
a41	0.00235	0.003	transfer rate from tissue to blood
a46	0.01143	not reported	transfer rate from tissue through digestive tract to blood
b	0.021	0.012	transfer rate from blood out through urine
c	0.00292	0.001	transfer rate from tissue by hair, sweat and nails

AM, arithmetic mean; SD, standard deviation.

Table 4.2: Parameters included in the CONLIS model

Symbol	Parameter definition and units	AM	SD	Distribution type	Reference
$C_{bll}(0)$	Initial blood lead concentration in (μg dl^{-1})	43.20	4.55	N	Sussell (1992)
f_{duty}	Adjustment fraction for not directly performing the task	1.0	0	constant	Sussell (1992)
C_A	Task-related airborne lead concentration (μg m^{-3})	10600*	2.22	LN	Sussell (1992)
f_{resp}	Penetration fraction of assigned respirator	0.003*	2.06	LN	Sussell (1992)
f_{lung}	Absorption fraction of lead from lungs to blood	0.35	0.05	N	Hursh (1969)
Q_b	Breathing rate (m^3 hr^{-1})	1.60	0.46	N	Linn (1993)
L_s	Workplace surface lead loading (μg m^{-2})	140*	3.07	LN	Sussell (1992)
f_{gut}	Absorption fraction of lead from gut to blood	0.08	0.035	N	Rabinowitz (1976)
M_w	Body weight (kg)	81*	1.21	LN	Linn (1993)
f_{hyg}	Adjustment for area hygiene	0.50	0.29	N	-
f_{wash}	Lead retention after washing hands	0.50	0.29	N	-
A_h	Area of hands (m^2)	0.09	0.009	N	-
M_d	Mass of lead in food (μg)	30.0	5.0	N	Castellino (1995)
R_d	Food consumption rate (hr^{-1})	0.33	0.03	N	Castellino (1995)
M_{cig}	Mass of lead in cigarette (μg)	1	0.08	N	ICRP (2002)
R_{cig}	Smoking rate (hr^{-1})	0.33	0.03	N	Levin (1990)
L_h	Lead load on the hand = Ls x fhyg (μg m^{-2})	257	544	N	derived

AM, arithmetic mean; SD, standard deviation; * mean is geometric mean and deviation is geometric standard deviation; N, normal distribution; LN, lognormal distribution; μg, micrograms; hr, hour; m, meters; dl, deciliter; kg, kilogram.

Table 4.3: CONLIS-predicted versus measured blood lead levels (μg dl^{-1}) from abrasive blasters during the Brent Spence bridge rehabilitation project

Percentile of distribution	CONLIS-predicted blood lead levels N = 1000	Observed blood lead levels (Sussell et al 1992) N=5
0	51	49
5	53	49
25	55	50
50	57	55
75	58	59
95	60	61
99.9	63	61

μ, microgram; dl, deciliter; N, number of observation or simulations.

Table 4.4: Proportion of variance in blood lead distribution from varying one input parameter relative to blood lead variance from varying 14 parameters

Symbol	Parameter definition and units	Proportion of total variance = σ/σt
$C_{bll}(0)$	initial blood lead concentration in (μg dl^{-1})	0.00
C_A	task-related airborne lead concentration (μg m^{-3})	0.69
f_{lung}	absorption fraction of lead from lungs to blood	0.01
Q_b	breathing rate (m^3 hr^{-1})	0.11
f_{gut}	absorption fraction of lead from gut to blood	0.00
L_h	lead load on the hand = Ls x fhyg	0.00
Total		1.0

σ, variance of the outcome distribution of blood lead contributed from varying a single parameter; σt, total variance of the outcome distribution of blood lead contributed from varying 14 parameters

Figure 4.1: Sequence of events leading to a change in lead body burden

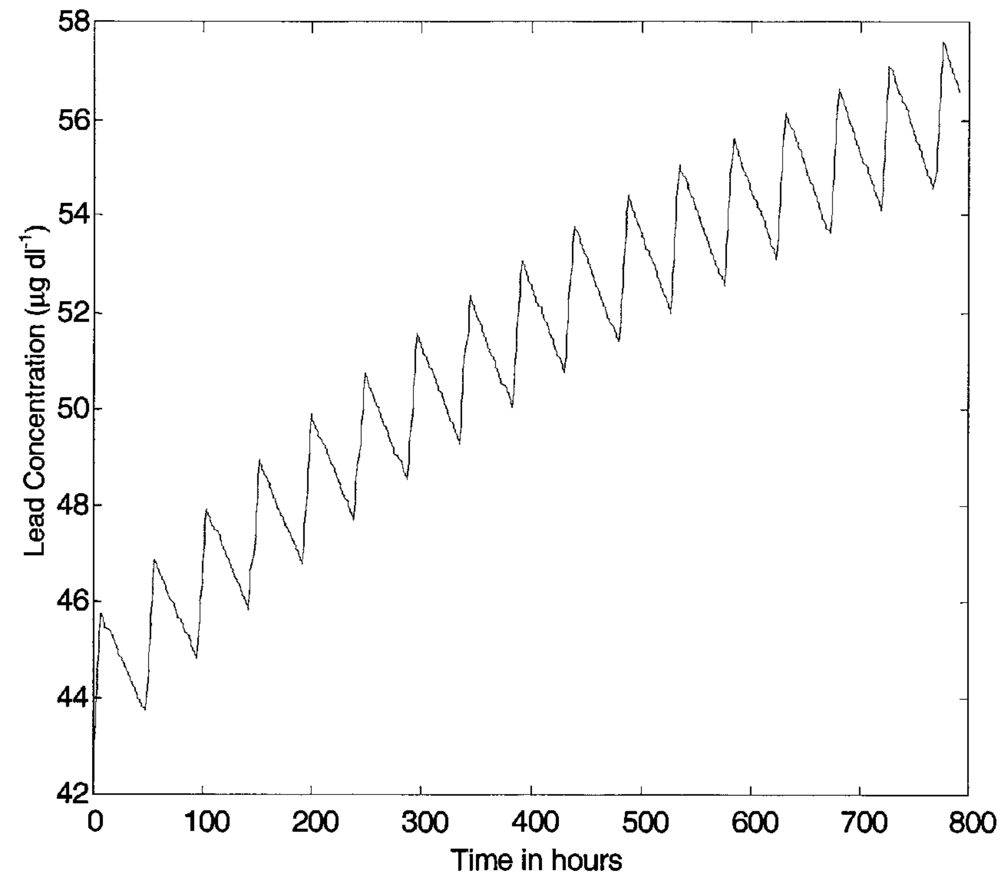

Figure 4.2: Repeated pulse response of CONIS model. Input values are randomly selected from distributions incorporated into CONLIS. Initial blood lead concentration was 43 μg dl^{-1} ending with a blood lead of 57 μg dl^{-1} after 33 days. Exposure is assumed to occur on regular cycles of 8 hours of abrasive blasting followed by 40 hours of non-blasting exposure to lead. μg, micrograms; dl, deciliters.

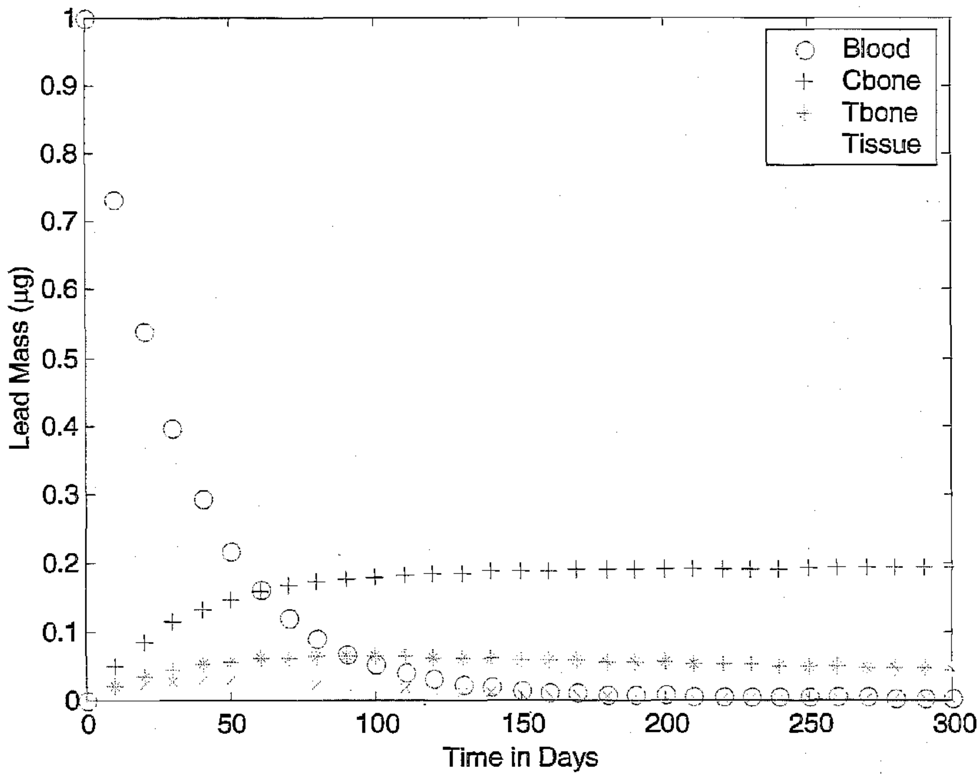

Figure 4.3: Impulse response of Bert 4-compartment model. μg, micrograms.

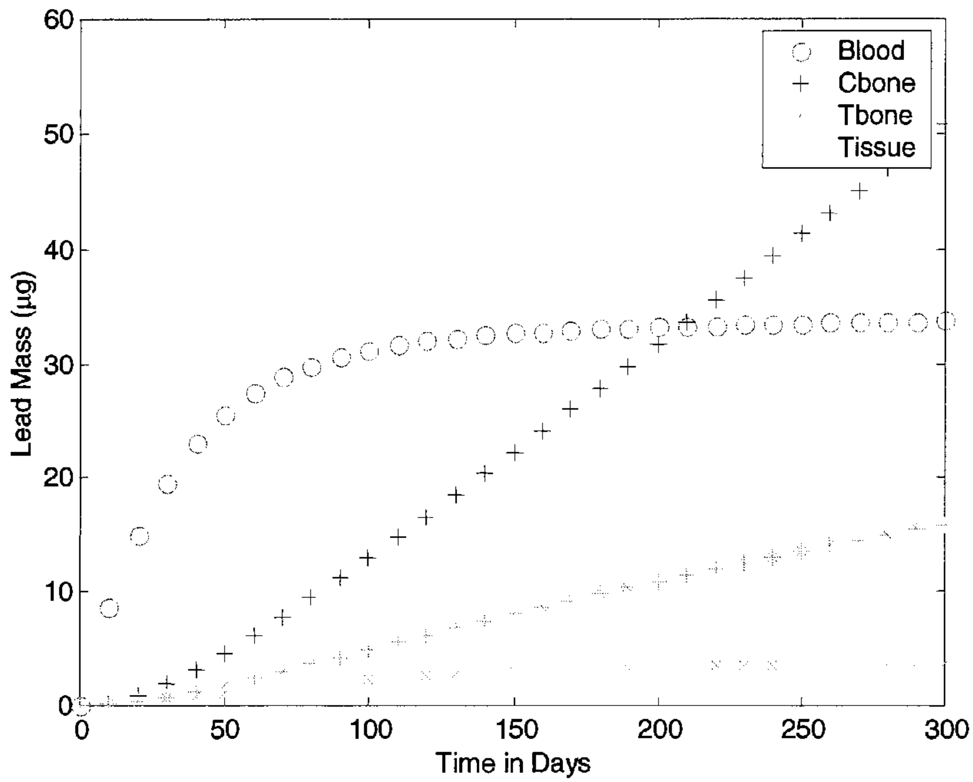

Figure 4.4: Unit step response of Bert 4-compartment model. μg, micrograms.

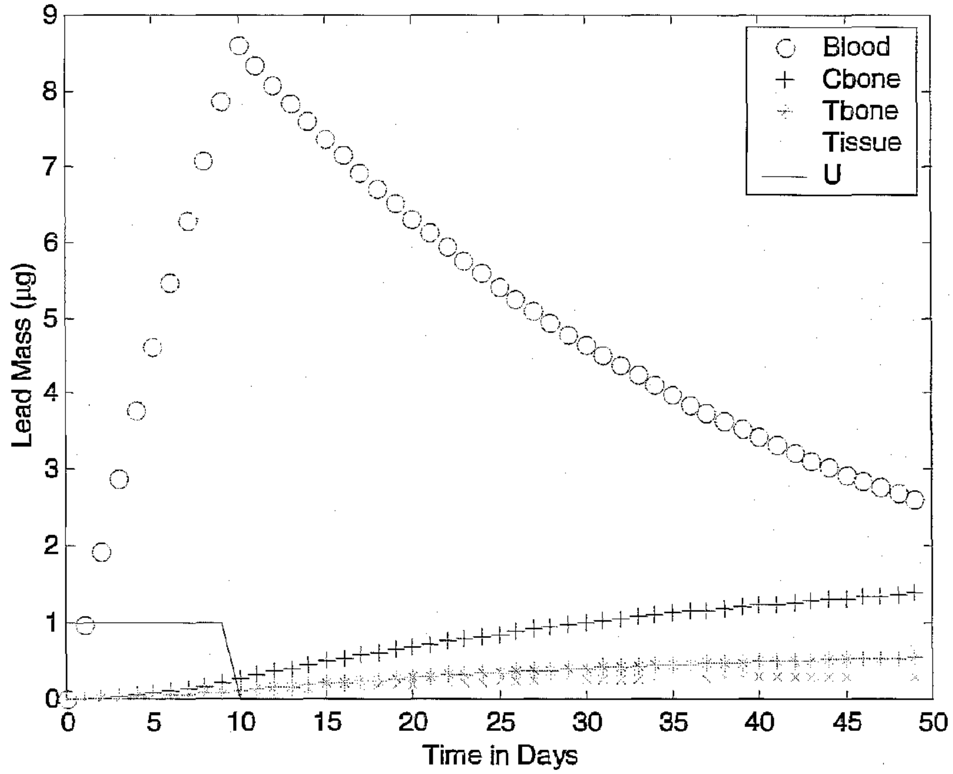

Figure 4.5: Finite-width pulse response of Bert 4-compartment model. μg, micrograms. U, 1 μg dose for first 9 days followed by zero input for 40 days.

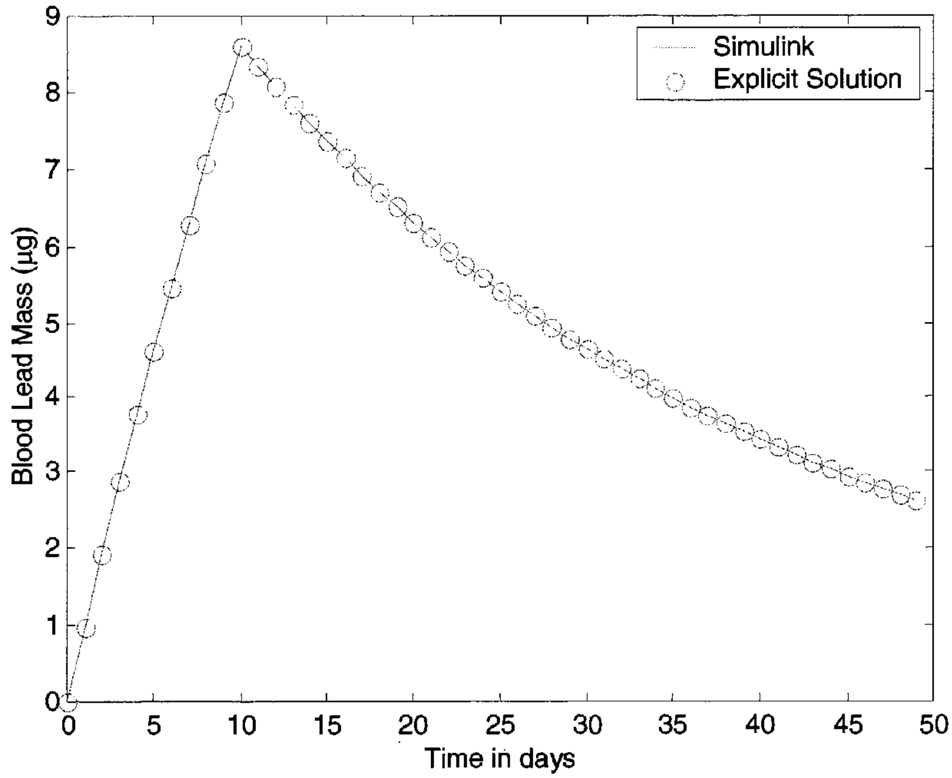

Figure 4.6: Comparison of finite pulse response of explicit solution with Simulink model. Pulse dose occurred for 9 days followed by zero input for 40 days. µg, micrograms.

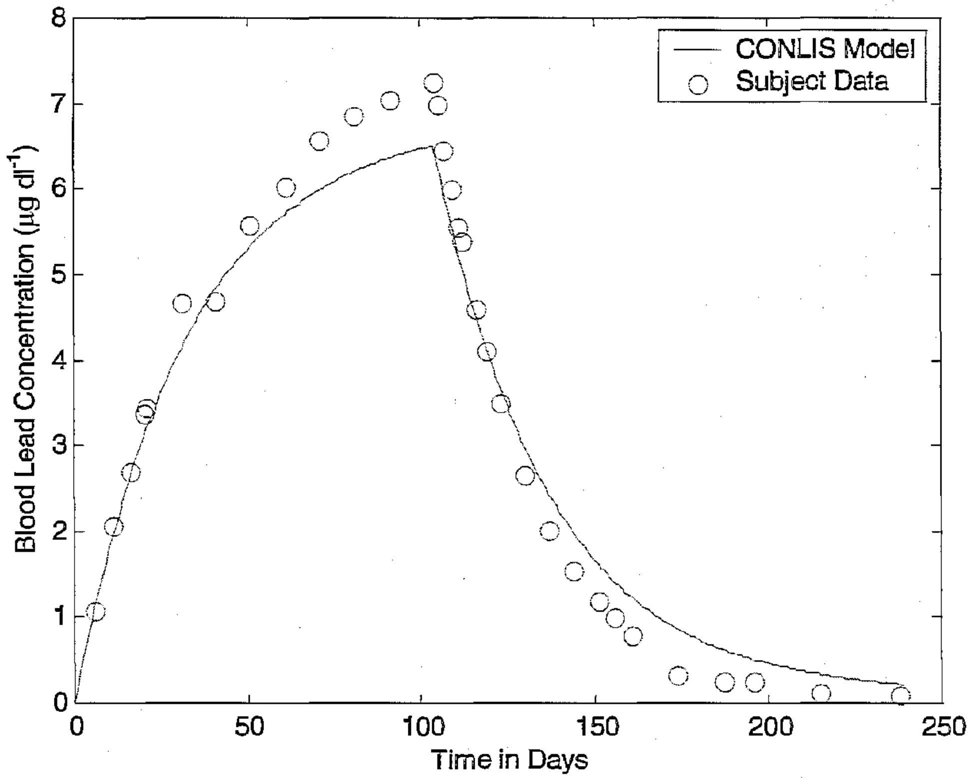

Figure 4.7: Validation test with Rabinowitz data for subject A. Daily intake of tracer lead was 204 μg d^{-1} for 104 days. μg, micrograms; dl, deciliters.

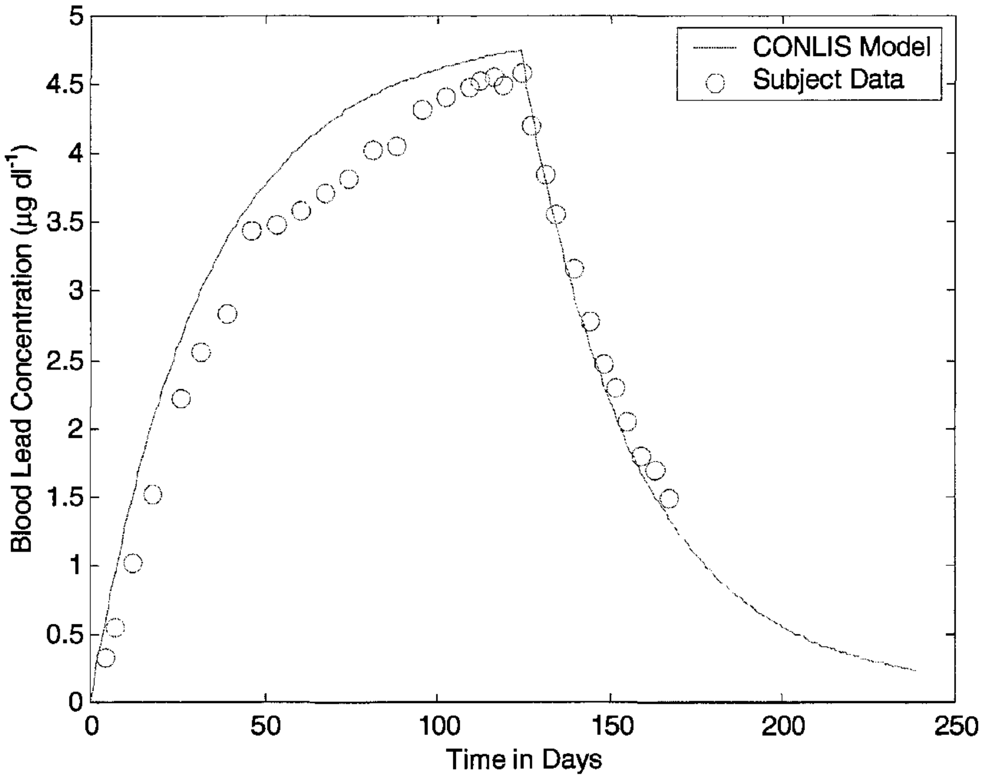

Figure 4.8: Validation test with Rabinowitz data for subject B. Daily intake of tracer lead was 185 µg d^{-1} for 124 days. µg, micrograms; dl, deciliters.

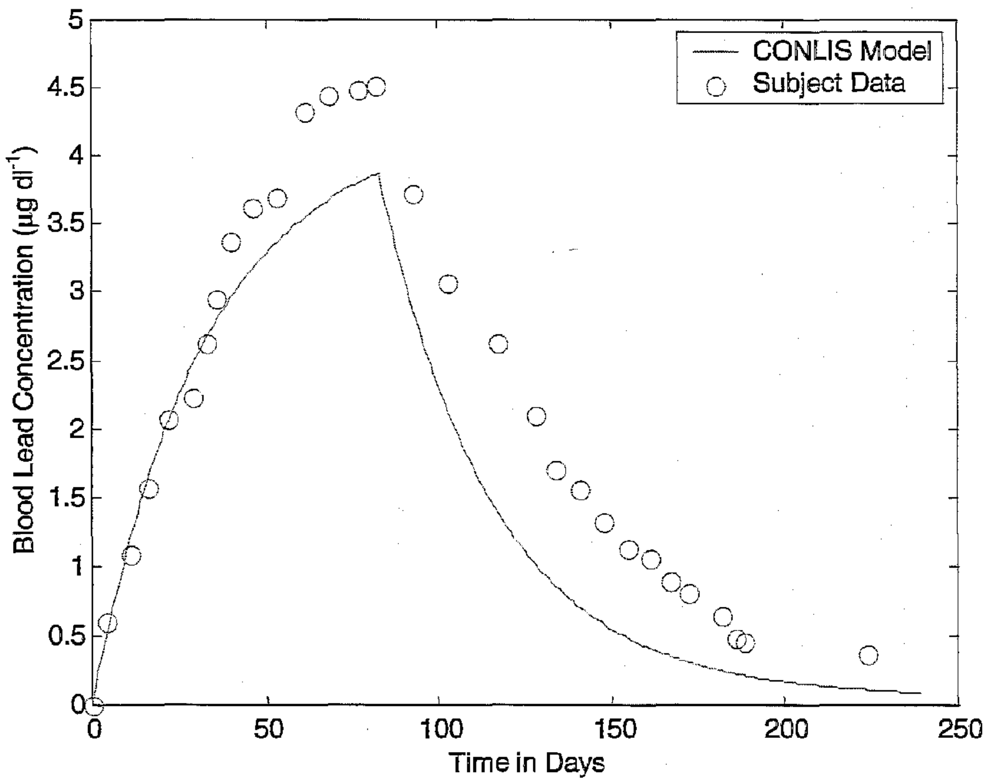

Figure 4.9: Validation test with Rabinowitz data for subject D. Daily intake of tracer lead was 105 µg d^{-1} for 83 days. µg, micrograms; dl, deciliters.

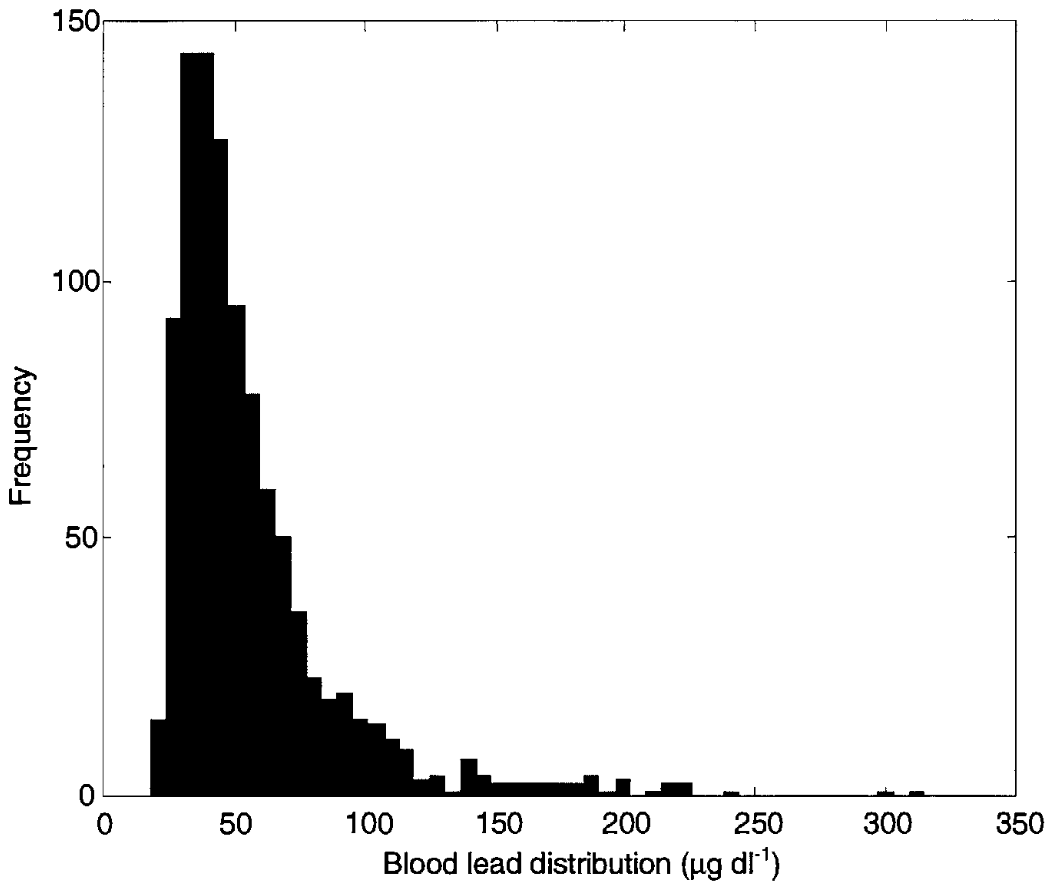

Figure 4.10: Frequency of predicted blood lead from Monte Carlo simulation varying 14 input parameters with mean and standard deviations listed in Table 4.2. μg, micrograms; dl, deciliters.

CHAPTER 5 USE OF CONLIS TO MEASURE THE PROTECTIVE EFFECT OF INDUSTRIAL HYGIENE INTERVENTION

5.1 Abstract

Since the passage of the OSHA Lead in Construction Standard in 1993, the effectiveness of lead health protection programs (LHPP) that address requirements under the standard remains largely unknown. Just prior to the promulgation of the OSHA lead in construction standard, Connecticut established an LHPP for bridge workers to demonstrate a new model program for exposure management practices during construction activities named CRISP, which stands for Connecticut Road Industry Surveillance Project. Starting out as a voluntary program, the LHPP was written into State contract specifications by 1993.

The first analysis in this chapter explores the effect of Connecticut's lead health protection program during 1994 and 1995 on exposures among 195 bridge workers. The simulation tool named CONLIS (CONstruction Lead Intake Simulation) was used to convert environmental and blood lead measurements to two separate estimates of dose. A simplified engineering analysis revealed that environmental and blood lead derived estimates of lead inhaled by a bridge crew differ by approximately 100-fold due to the effects of respiratory protection. Another analysis of program effect revealed that average lead dose declined over time for workers as a whole. For blasters, two-thirds of the cases of excess exposure that would have occurred in 1995 based on 1994 excess exposure rates were prevented.

Another part of Chapter 5 derives and tests a predictive model against field measurements collected in 1995 of lead absorbed by Connecticut bridge workers. Using CONLIS, we were able to derive an estimate of the adjustment in exposure due to respiratory protection in the CRISP project work environments. With the addition of this new estimate, dose average values obtained from environmental variables compare to most dose estimates from workers with the same job title and employer that were obtained from blood lead measurements. The last part of Chapter 5 illustrates how the new model can be deployed for program planning and exposure management in two exposure scenarios.

5.2 Nomenclature

Equation	Symbol	Units	Description
	$\mathbf{\Phi}(t)$	day^{-1}	state transition matrix
5.3	$\Delta x_1\ \Delta u^{-1}$	μg	change in blood compartment lead mass with respect to change in dose
	$\mathbf{A}^{-1}$	hr^{-1}	body compartment transfer and elimination matrix
	$AM[C_t]$	$\mu g\ m^{-3}$	arithmetic mean task-based PBZ concentration
	$AM[f_b]$	-	arithmetic mean blasting hours per day divided by 24
	B	-	uptake coefficient matrix
5.1	C_A	$\mu g\ m^{-3}$	airborne lead concentration near a work crew
	CI		confidence interval
5.1	C_t	$\mu g\ m^{-3}$	task-based personal breathing zone lead concentration
5.10	D_{al}	μg	dose-equivalent action level
5.6	D_b	μg	absorbed dose accumulated over month exposure interval
5.13	D_{bnew}	μg	model-predicted absorbed dose
	D_e	μg	anticipated dose accumulated over a month exposure interval
	DF	-	dose fraction
5.9	DF_{resp}	-	dose fraction due to respiratory protection
5.3	$f_{tb}(k)$	-	blasting hours per day divided by 24
	i	-	index reference to a specific worker
	I	-	identity matrix
5.7	I_{btotal}	μg	intake of lead for a work crew
	I_{inhale}	μg	intake of lead for an individual worker from inhaling lead
5.1	IF_a	-	group intake fraction derived from PBZ lead
5.8	IF_b	-	intake fraction derived from blood lead levels
5.1	IF_i	-	individual intake fraction
5.11	IRR	-	incidence risk ratio
	k	-	index for sub-interval within an exposure interval
	$M_{bll}(0)$	μg	mass in blood at beginning of exposure interval
5.5	$M_{bll}(t_e)$	μg	mass in blood at end of exposure interval
	P	-	workforce population
	PDF	-	prevented dose factor (inverse of a dose fraction)
	Pr		signifies the probability of a quantity
	Q	$\mu g\ hr^{-1}$	area ventilation rate
	Q_b	$\mu g\ hr^{-1}$	breathing rate
5.12	RPE	-	relative preventive effect
	t_b	hr	blast time
	t_e	hr	index for exposure interval
5.6	$U_{bll}(t_e)$	$\mu g\ d^{-1}$	calculated dose rate for exposure interval
5.2	$\mathbf{X}(k)$	μg	body burden vector at sub-interval k
	$\mathbf{X}(k-1)$	μg	body burden vector from previous sub-interval
	x_1	μg	lead burden in the blood compartment

The unit (-), signifies a dimensionless fraction; μg , microgram; d, day; hr, hour; m, meters.

5.3 Introduction

The OSHA Lead in Construction Standard promulgated in 1993 provided a specific set of health protection activities for construction contractors to follow. Three years later, a Special Emphasis Program (SEP) was launched that allowed OSHA to enter ongoing bridge projects and target risk management practices required at bridge construction workplaces (Dear 1996). Since the onset of the SEP no formal report of the program's impact on workplace safety and health has been generated. However, there is evidence that contractors continue to fall short of full compliance with OSHA's lead in construction standard. For example, random inspections have uncovered numerous OSHA violations (McAllister 2003). As well, recent data from State surveillance registries have documented elevated blood lead levels among workers from lead-using industries. These registries have identified that exposure levels above 25 $\mu g\ m^{-3}$ are often experienced among construction workers, a problem the OSHA standard was expected to eliminate if full compliance was achieved (Roscoe et al. 2002; CDHS 2002). Since the passage of the OSHA Lead in Construction Standard in 1993, the effectiveness of lead health protection programs (LHPP) that address requirements under the standard remains largely unknown.

A recent California study identified barriers to managing lead exposures during construction activities. That study identified that perceived work disruption, a threat to work quality, costs for blood lead testing, and the need for special tools and equipment were obstacles to improving health program practices (Materna et al. 2002). During focus group sessions, 'motivated contractors' cited a lack of resources as a major limitation.

Some of these barriers were removed in a NIOSH funded demonstration project. Just prior to the promulgation of the OSHA lead in construction standard, Connecticut established a LHPP for bridge workers to demonstrate a model program for exposure management practices during construction activities (Maurer et al. 1995a). This new model named CRISP, which stands for Connecticut Road Industry Surveillance Project, targeted both painting and ironwork contractors who engaged in lead-related bridgework during maintenance and demolition projects. An intensive air and biological monitoring program was pursued. Requirements prescribing a lead health protection program were written into contract specifications and pass-through costs were established.

A study conducted by Hammond et al. (1994) subsequently evaluated the presence and absence of preventive methods implemented as part of the LHPP in Connecticut. Workplace conditions were examined before and after implementation of the LHPP and the promulgation of OSHA's lead in construction standard. Investigators found that 2 out of 16 exposure reduction techniques specified under general worker health and safety regulations were implemented on jobs executed before the LHPP. After requiring the LHPP at Connecticut job sites, 12 out of 16 techniques were implemented 100% of the time, and the remaining 4 were usually implemented. Average blood lead levels were lower among workers from job sites with exposure control techniques in place than among workers without these controls. The Hammond study suggested that consistent implementation of exposure reduction techniques reduced blood lead levels. However, the effect from the change in OSHA regulation was not distinguished from the effect of the CRISP intervention.

The separate effects of the OSHA regulation and CRISP intervention were examined in Chapter 3 of this project. That study examined the efficacy of the CRISP LHPP in comparison with similar groups of workers protected through the OSHA Lead in Construction Standard. Using peak blood-lead as its principal metric of evaluation, the study concluded there was evidence that a CRISP-like program was superior in protecting workers to the other program. The study in Chapter 3 also showed that the distribution of blood lead levels among worker groups declined over time. However, using blood lead level as the outcome measure, it was not possible to distinguish how recent workplace lead exposure and control methods affected this decline.

Chapter 4 of this project introduced a model named CONLIS, which stands for CONstruction Lead Intake Simulation. The CONLIS model links bridgework operations that generate lead aerosol, components of an enforced LHPP, and lead intake among workers. CONLIS is a deterministic, dynamic model for predicting lead dose from specific sources of exposure. The model is able to derive two estimates of dose that pertain to a specific worker. As will be made clear the difference between two independently derived dose estimates for groups of workers estimate the fraction of dose that was avoided due to protective measures. As demonstrated in Chapter 4, CONLIS converts environmental measurement of lead in air and settled dust at the workplace, combines these measurements with information about respiratory protection, hygiene practices and task-based exposure timing from each worker and derives an estimate of blood lead over time. In addition, cumulative estimates of lead (referred to hereafter as anticipated lead dose (D_e) and absorbed dose (D_b), can also be obtained from CONLIS. D_e is derived from lead in air and settled dust at the workplace and exposure timing without regard to respiratory protection and hygiene practices. D_b is derived from two measures of lead in blood taken at two different points in time from each worker.

However, the amount of information required to fully characterize each worker's anticipated dose can take considerable time and money. Characterizing dose from air concentration and time-activity data becomes a tradeoff between uncertainty and cost (Rock 1995; Nicas et al. 2002). Even the well-funded CRISP LHPP described in Chapter 3 did not provide enough day-to-day personal monitoring data to perform matched-set comparisons between blood lead and air concentration dose estimates. Because of this scarcity, attempting to validate this model at the individual worker level with the goal of evaluating exposure intervention techniques is not likely to yield meaningful results. Instead, a group-level evaluation is indicated. Hence, Chapter 5 explores the effect of the CRISP intervention on worker groups.

CRISP LHPP was written into Connecticut Department of Transportation (ConnDOT) contract specifications by 1993 (Castler 1995). The compliance with LHPP requirements was progressively phased in during 1993 and adjustments were made to encourage continued reductions in blood lead levels and tighter lead controls in 1994 and 1995 respectively (Maurer et al. 1995a). Consequently, intervention is expected to be more effective during progressively later stages of the program. Chapter 5 first describes a set of exploratory analyses of the information collected during the CRISP LHPP. The primary objective is to look for evidence of changes in the amount of lead absorbed by the enrolled workforce as a consequence of LHPP intervention adjustments made between 1994 and 1995. The second part of Chapter 5 examines the accuracy of a predictive model using information collected during the latter years of the CRISP LHPP intervention and by applying a dose fraction derived from the exploratory analyses conducted in the first part of this chapter. The last part of Chapter 5 illustrates the utility of CONLIS for LHPP planning and management purposes.

5.4 Methods

The goal of this project is to develop a model that can be used as a non-invasive tool to plan and manage an effective LHPP. Chapter 5 presents a set of exploratory analyses designed to reach this goal. The first set of analyses explores the protective effect of the CRISP LHPP using three separate approaches. The first approach is a simplified engineering analysis. This analysis is followed by a more detailed analysis of the risk of exceeding a limit of lead exposure defined by the LHPP. Then, an analysis of covariance explores for significant differences in absorbed dose among workers with different employers and job titles.

5.4.1 Exploration of Intervention effectiveness

The effects of the CRISP intervention on the lead absorbed by enrolled workers are explored among workers involved in abrasive blasting activities. Open abrasive blasting (i.e. abrasive blasting conducted without local exhaust ventilation attachments (LEV)) was chosen because it is the most commonly used method to clean painted steal surfaces. This method was explained in Chapter 2 of this project and therefore only summarized here. Open abrasive blasting requires both operating and personal protective equipment (Smith & Beitelman 1994). During a typical workday, blasting occurs for about four hours, followed by one to two hours of vacuuming. Then, newly settled dust and debris is blown from blasted surfaces, followed by approximately two hours spent applying a primer coat. High-velocity mechanical disturbances during the surface-cleaning phase generate a great amount of debris. During the Connecticut demonstration project, for the purpose of protecting the surrounding community, emissions from this activity were controlled by requiring negatively pressurized containment structures with filtered exhaust air (Mickelsen 1995; Appleman 1997; Castler 1995).

Where possible, containment structures were designed so that the used abrasives and debris are directed through chutes or tubes into a barge or hopper. Additional vacuuming and sometimes mopping the containment floors and walls were sometime conducted after blasting prior to structure disassembly. Some blast equipment was operated and maintained outside of containment.

The LHPP required Contractors to assess worker exposures, decontaminate equipment and the work area, maintain blood lead testing and respiratory protection programs and provide facilities for decontaminating workers. Contract specifications, cost reimbursements and centralized monitoring provided incentives for compliance with LHPP requirements. Bridge projects and month-long exposure intervals were selected from CRISP records that were subjected to this baseline structure.

5.4.1.1 Data gathering procedures

A search was conducted of blood lead testing, industrial hygiene and engineering field records from bridge projects conducted during the CRISP demonstration. All records had been pre-processed to remove personal identifiers. The search focused initially on records that reported enough information about the daily activity of painting contractors so that an assessment of airborne lead exposure intensity could be derived. For the purpose of this study, exposure intensity is defined as the frequency and duration of abrasive blasting and the workplace airborne lead concentration generated there from abrasive blasting. A hand search was conducted of the available industrial hygiene monthly reports and the ConnDOT inspection records.

5.4.1.1.1 Bridge projects

Bridge projects were selected for further evaluation if reports included the following additional criteria:

1) Project records contained air samples that were collected during typical production processes using typical engineering and work practice controls;

2) Data were gathered by trained personnel and collected according to the protocol specified by the CRISP LHPP specification on workers performing tasks during active projects;

3) Project records included at least some information about the type of respirators worn by workers during the performance of certain pre-determined tasks. Without this information, there is no way to tell in the LHPP was actually implemented as planned;

4) Project reports containing records of training and oversight indicated that information was provided to workers about the proper use and maintenance of issued respirators. This information also indicates that the LHPP was implemented according to the program protocol.

5.4.1.1.2 *Painting Contractors*

An electronic search of the CRISP blood lead database was conducted to retrieve information about individual painting contract employees. Contractors were selected if they met the following inclusion criteria:

1) Contractors worked on primary or sub contracts that include abrasive blasting activity;

2) Work on a project was conducted during some portion of both 1994 and 1995;

3) At least two blood lead intervals that meet the selection criteria (see next subsection) were available for each of four job categories broadly defined as 'blaster', 'painter', 'laborer', and 'ancillary worker' which included equipment operators, foremen, inspectors and welders and mechanics.

5.4.1.1.3 *Blood lead intervals*

A primary outcome measure of interest in this investigation is the difference in lead absorbed among groups of workers during exposure to abrasive blasting activity under the influence of the CRISP LHPP. The method of calculating absorbed lead requires two blood lead measurements from each worker. Therefore, a worker's exposure interval was selected if more than one blood lead test was recorded during a month in which there was evidence that abrasive-blasting activity also occurred.

5.4.1.2 Variable definitions

In Chapter 4, we introduced 18 input variables and defined them in Table 4.2 in Chapter 4 of this project. For the present analyses, CRISP records provided input values for air concentration (C_A) near abrasive blasting work crews by using PBZ samples taken from workers who performed abrasive blasting. CRISP records also provided input values for ($C_{bII}(0)$), the concentration measured in the blood prior to the onset of an exposure interval. For all of the remaining variables, inputs were based on indirect information or by making an assumption about the input value.

Data routinely collected as part of the CRISP LHPP protocol were different from variables included in CONLIS. For example, the average and variance of absorbed lead among workers separated by smoking status and job title were examined instead of assigning different values to f_{duty} and R_{cig} in CONLIS.

The exposure scenario simulated in Chapter 4 assumed that blasting occurred for periods of 7 hours at regular cycles every other day for a fixed exposure interval of 33 days at one bridge project. In the present analyses, several additional variables were abstracted from CRISP reports. Firstly, during the CRISP demonstration, blood lead testing did not occur on the same day each month for an entire work crew. Therefore an exposure interval variable (t_e), defined as the time between two blood lead tests that were taken during an active period of bridge project work was abstracted because most exposure intervals included a set of unique dates. Secondly, each exposure sub-interval (k) has a specific $f_b(k)$, defined as the fraction of time in the sub-interval in which abrasive blasting occurred. The time series vector $f_b(k)$ is derived from information about daily blast time obtained from inspection and industrial hygiene records. Thirdly, it is possible that the level of lead in paint on bridges and the type of enclosure and equipment used by a contractor, the job tenure of a worker or other unmeasured factors might influence the level of lead absorbed by a worker. Thus, the bridge project site, contractor and age of each worker were identified from work records.

'Bridge project' is defined as the contract specified work on one or more bridge structures. This variable may account for the effects on dose estimates that may not have been captured by the air concentration and blast time. Contractor is defined as the employer responsible for the LHPP and work assignments of the workers eligible for study selection. This variable may capture the effects on dose estimates by the way the work is conducted or by the particular way that the lead health protection program is carried out. The title given to workers that indicates the labor or trade classification and duties defines 'job title'. Job titles were grouped as blaster, laborer, painter, and all others in which we subsequently refer to as ancillary workers. This variable should capture the type of task or cycle of tasks carried out by workers, and may identify subgroups of workers with significantly different levels of absorbed dose.

Blasting task personal breathing zone (PBZ) lead concentrations are at least 3 orders of magnitude higher than other work-related, ambient air and dietary sources of lead (ICRP. 2002; Castellino et al. 1995). Therefore, exposures to lead from ambient air and diet were considered negligible. No attempt was made to derive separate variables that represent cumulative dose from surface dust or non-blasting task exposures during work.

5.4.1.3 Simplified engineering analysis

To begin, a simplified engineering analysis provides an initial indication about the degree of worker protection achieved during abrasive blasting in a containment structure. This simplified analysis provides a rough estimate of lead intake by the workforce from abrasive blasting emissions.

The effect of worker protection is estimated by comparing two intake fractions, defined as the amount of a pollutant source that is taken in by an individual or population (Bennett et al. 2002). Several recent studies derived a population intake fraction by estimating the amount of widely distributed source emissions inhaled by the exposed general population (Marshall et al. 2003). The present study has extended the intake fraction to the construction workplace where information about abrasive blast emissions and task-based PBZ lead concentration and absorbed dose are assumed to provide an adequate first estimate of program effect for the entire workforce associated with that activity. An individual worker's incremental inhaled lead intake (I_{inhale}) is defined as the product of lead concentration measured in a worker's breathing zone (C_t), their breathing rate (Q_{bi}) and a quantity of exposure time (t). A worker's intake fraction (IF_i) is defined by equations 5.1a and b as the integrated incremental intake of lead released from abrasive blasting on a bridge by a worker in a containment structure during a given exposure time (t), per unit of emitted lead $(C_A)(Q)(t)$.

$$I_{inhale} = (C_{ti})(t)(Q_{bi}) \qquad (5.1a)$$

$$IF_i = \sum_{t=1}^{te} I_{inhale} / (C_A)(t)(Q) \qquad (5.1b)$$

One key simplifying assumption is that the air in the containment structures at each bridge project is well mixed during abrasive blasting. That is, under high velocity action from abrasive blasting, the concentration of lead in the breathing zone of a blaster is assumed to be similar to the concentration of lead in the ventilation exhaust air of the containment structure (i.e. $C_t \cong C_A$).

Workforce intake is derived from two different estimates of abrasive blast exposure. The first estimate of intake ignores any effects from protective techniques such as the use of respiratory protection, distance, hygiene, hazard barriers and engineering controls other than general ventilation among the entire project crew. Intake is derived from the average task-based personal breathing zone lead concentration measurements obtained from a statistically representative sample of workers involved in abrasive blasting activity. This group average PBZ lead concentration is denoted $AM[C_t]$.

The rate of source emissions is derived from task-based PBZ concentration estimates and area ventilation rates. In this context, task-based PBZ concentration is a reasonable surrogate of the lead emission rate in a enclosure based on the relationship $AM[C_t] = E/Q$ where E = emission rate (mass $time^{-1}$) of inhalable lead, Q = enclosure ventilation rate (volume $time^{-1}$). Inhalable lead in this context refers to particles available for inhalation (i.e , smaller particles). By assuming similar ventilation rates, the lead emission rates for abrasive blasting of lead from a bridge and viaduct project found by Conroy et al. (1995) can be found for measured concentrations during abrasive blasting in this study. Conroy et al found that emission to concentration relationships (equal to Q) were 6.4, 3.0, 8.5 and 7.3 in units of $\mu g\ s^{-1}$ per $\mu g\ m^{-3}$. Values for Q were approximately 20,000 $m^3\ hr^{-1}$, which are in the same order of magnitude as those measured in NIOSH studies and those recommended by the Steel Structures Painting Council (SSPC) (Mickelsen 1995); Appleman 1998b).

Intake estimates from PBZ lead concentration disregards the use of respiratory protection. The population Intake Fraction is therefore derived by equation 5.2.

$$IF_a = \sum_{i=1}^{P} IF_i \tag{5.2}$$

Since abrasive blasting on bridges often occurs sporadically, only a fraction of an individual worker's C_t and C_A values will be greater than zero.

So, by computing the cumulative exposure using an average lead concentration $AM[C_t]$, an average fraction of blast hours $AM[f_b]$ that occur during each worker's exposure interval, an average breathing rate (Q_b) and the number of workers in a crew, IF_a simplifies to the ratio of the average breathing rate to enclosure ventilation rate times the number of worker in a crew or $IF_a = (P)(Q_b)/(Q)$.

In extremely high exposure environments such as abrasive blasting projects, lead exposure during certain tasks cannot be controlled to any significant extent by general ventilation. Therefore, most tasks conducted in these environments require additional protective techniques. Exposure control during abrasive blasting and associated activity is mostly achieved through respiratory protection and maintaining personal and area hygiene. Also, in environments with poorly mixed air, increasing a worker's distance from the emission point, or constructing a material barrier between the worker and the lead source may substantially reduce a worker's exposure. Therefore, the second estimate of intake, obtained from an estimate of absorbed lead incorporates any effects from protective techniques such as the use of respiratory protection, distance, hygiene, hazard barriers and engineering controls other than general ventilation among the entire project crew.

Individual estimates of absorbed lead are derived from two blood lead tests. One blood lead measurement is taken at the beginning and the other at the end of a month-long exposure interval (i.e., $C_{bl1}(0)$ and $C_{bl1}(t_e)$ respectively). The absorbed dose is estimated using a back-calculation procedure. There are two general requirements for a valid estimate so derived. First, recent lead dose based on blood lead must remove that portion of the blood lead level due to the lead body burden accumulated over a lifetime of exposures. Second, when episodes of lead intake are not relatively constant, overlooking the timing of lead intake during an exposure interval may lead to excessive error. CONLIS employs a physiologically based pharmaco-kinetic (PBPK) dynamic model developed by Bert et al. (1989) combined with a record of blast time activity to address these requirements.

The dose estimation procedure is performed in several steps, summarized as follows. First, an initial body burden is estimated using Bert's model as explained in principle in section 4.4.3.4. The model is applied to estimate the initial body burden distribution among body compartments per equation 4.10. A standard age of 20 years was used (when other ages from 30 to 65 were examined, there was less than a 5% difference in the result). Two blood-lead concentrations ($\mu g\ dl^{-1}$), one at the beginning and the other at the end of a month-long exposure interval were converted to units of mass (μg), designated as quantities $M_{bll}(0)$ and $M_{bll}(t_e)$, respectively. This conversion was achieved by assuming a standard body weight of 70 kg for each worker and applying Bert's conversion formula (expressed as equation 4.11). The initial body burden is derived using equation 4.12. The proportion matrix and the observed beginning blood lead are required for this calculation. Second, the model is calibrated for the worker's sensitivity to body burden with respect to dose rate (i.e., $\Delta\mathbf{X}(t)/\Delta\mathbf{U}(t)$), the principle component of interest being the blood lead change $\Delta x_1/\Delta u_1$. The variable element requiring calibration of the model is the blast-time activity profile $f_b(k)$. Assuming an exposure interval of t_e days, the time series $f_b(k)$ ($k = 1..t_e$) is the number of hours on day 'k' day attributed to blasting divided by 24 (i.e., it is the fraction of blast-time to total time). Two calculations of body burden at t_e are performed using the iterative application of equation 4.9. $\mathbf{X}_0(t_e)$ is the ending body burden that would have resulted from no exposure, and $\mathbf{X}_1(t_e)$ is the ending body burden resulting from a unit dose-rate amplitude which includes the time-activity profile:

$$\mathbf{X}_0(k) = \mathbf{\Phi}(k)\mathbf{X}_0(k-1) \quad ; k = 1..t_e \qquad (5.3a)$$

$$\mathbf{X}_1(k) = \mathbf{\Phi}(k)\mathbf{X}_1(k-1) + (\mathbf{\Phi}(k) - \mathbf{I})\mathbf{A}^{-1}\mathbf{B}[f_b(k)\ 0\ 0\ 0] \quad ; k = 1..t_e \qquad (5.3b)$$

If equations 5.3a and 5.3b are iterated for t_e days, then the difference in the result represents the body burden sensitivity with respect to dose rate. In other words, the body burden sensitivity to dose rate is given by

$$\Delta\mathbf{X}(t)/\Delta\mathbf{U}(t) = \mathbf{X}_1(t_e) - \mathbf{X}_0(t_e) \qquad (5.4a)$$

The blood lead sensitivity with respect to dose rate is the first element of 5.4a, or

$$\Delta x_1/\Delta u_1 = \mathbf{X}_1(t_e)_1 - \mathbf{X}_0(t_e)_1 \qquad (5.4b)$$

The third step of this procedure back-calculates the dose rate that should have resulted in the observed ending blood lead. The result of equation 5.4b is used to derive this value. A recursive Newton-Raphson (Press et al. 1990) algorithm is employed which converges when the ending calculated blood lead matches the ending observed blood lead. For each of 'j' iterations and a beginning guess of $\mathbf{U} = [0\ 0\ 0\ 0]$, the dose rate is varied according to equation 5.5.

$$U(n+1)_1 = U(n)_1 + (M_{bll}(t_e) - x(t_e)_1)/(\Delta x_1/\Delta u_1) \quad ; n = 1..j \qquad (5.5)$$

Within this recursion, a second recursion over k days solves equation 4.9 as before to generate the beginning and ending body burdens. The recursion in j ceases when $(U(n+1) - U(n))/U(n)$ reaches a sufficiently small specified value (1 percent was chosen), indicating that this is the dose rate that would have resulted in the observed ending blood lead, or after 100 iterations. All of the cases studied successfully converged. After successfully converging, the calculated dose rate is assigned the value $U_{bll}(t_e)$. The fourth and final step of the procedure integrates this calculated dose rate over the t_e days of the exposure interval to derive the dose, according to equation 5.6.

$$D_b = \sum_{k=1}^{t_e} U_{bll}(t_e)\, f_b(k) \qquad (5.6)$$

Figure 5.1 contains an illustration of this back-calculation procedure. The MATLAB script that implements the procedure is included among the programs in the appendix to this project.

The first estimation of population intake was derived by equation 5.2. The second estimate of population intake is derived by equation 5.7 using the recently derived result of equation 5.6.

$$I_{btotal} = \sum_{i=1}^{P} D_b(i) / 0.35 \qquad (5.7)$$

The value 0.35 is the lung absorption fraction. The value (P) consists of the number of workers comprising an abrasive-blast containment crew. On large projects during the CRISP intervention, containment crews ranged from five to fifteen depending on the bridge project.

The blood lead derived intake fraction is represented by equation 5.8.

$$IF_b = I_{btotal} / (AM[C_i])(t_b)(Q) \qquad (5.8)$$

Both quantities of population IF assume that workers shared the same work environment for the same length of time. Another important assumption is that intake from ingestion of lead is negligible (i.e. $I_{gut} = 0$). These assumptions are additional simplifications, which may be valid for a limited number of projects with crews that work together consistently.

The program effect defined here as a 'dose fraction' is measured by comparing intake fractions calculated with and without regard to worker protection and assumes that intake by the ingestion route is zero. From equations 5.2 and 5.8 the intake with and without respiratory protection can be directly estimated as a dose fraction (DF_{resp}) by equation 5.9:

$$DF_{resp} = (IF_b / (IF_a) \qquad (5.9)$$

Dose fraction is a unitless ratio of intake derived from estimated PBZ lead inhaled without regard to the use of respiratory protection and the intake extrapolated from each worker's change in blood lead level.

5.4.1.4 Stratified risk analysis

The quantity D_b described in the previous section and derived by equation 5.6 is used in another analysis of the CRISP LHPP effectiveness. A second analysis uses 'program year' as an indicator of program effect in non-experimental outcome evaluation. Absorbed lead exceedences in 1994 and 1995 were compared using a single-group pretest-posttest design. This particular design is appropriate for the purpose of examining whether exposure control improved while workers were being served by Connecticut's intervention program (Posavac et al. 1997).

Program-year was chosen as the indicator of intervention exposure level based on the following rationale. The objective for choosing respiratory protection was to prevent exceeding an 8-hour time weighted average (TWA) PBZ lead concentration of 30 $\mu g\ m^{-3}$. In the LHPP an initial assumption was made about the combination of tasks and respirator class that would prevent such exceedences. In some cases, this meant that workers had to acclimate to new or upgraded respirator systems. Consequently, successful acclimation would reduce the proportion of exceedences and the workforce mean absorbed dose between 1994 to 1995. In other cases, the level of respiratory protection initially associated with a task was downgraded after an initial exposure assessment. Thus, a downgrade would raise the mean absorbed dose among some worker groups between 1994 and 1995.

An excess dose was defined as a worker's month-long dose that reached or exceeded the predicted lead absorbed (D_{al}) based on inhaling 30 ug of lead per cubic meter of air for 8 hours during each workday in the month. The quantity $D_{al} = 1395\ \mu g$ is derived by equation 5.10.

$$D_{al} = (30\ \mu g\ m^{-3})(168\ hr)(0.83\ m^3\ hr^{-1})(0.35) \qquad (5.10)$$

One hundred sixty eight hours was chosen to represent a 42-hr workweek for 4 weeks in a month. A breathing rate of 20 $m^3\ day^{-1}$ has been selected for this analysis. This rate may be low for active construction workers according to Linn et al. (1993) who found that a breathing rate of 31 $m^3\ day^{-1}$ was typical for moderate activity. If the larger figure were used in this analysis, dose estimates would increase by a factor of 1.6. The median value of 0.35 for a lung absorption factor was selected for this analysis based on the work of Hursh et al. (1969) and others (ICRP. 2002).

An exploratory analysis of the full data set was conducted to see if a stratified analysis was needed. For example, job titles that were assumed to encounter such tasks would be expected to experience a reduction in the proportion of dose exceedences due to issuing a respirator where none was issued before the exposure assessment. As well, an expected reduction in the proportion of exceedences may be more prominent in one job title versus others due to an upgrade in respirator class after an exposure assessment. Absorbed dose was examined by Shapiro-Wilk and Shapiro-Francia statistics to test the entire group for conformity to normal or log normal distributions (STATA 1997). When tests indicated poor conformity, the data was stratified into subgroups based on contractor and job title and the tests for conformity were repeated within each subgroup.

Subgroups of worker-intervals were initially examined for partial associations between the 30 $\mu g\ m^{-3}$ dose equivalent exceedence probability (Pr) and program year. A cohort incident risk ratio (IRR) modeling the proportion of workers with dose in excess of D_{al} among workers first enrolled in 1995 (D_{b1995}) compared to workers first enrolled in 1994 (D_{b1994}) was calculated by equation 5.11.

$$IRR = Pr\ (D_{b1995} \geq D_{al})\ /\ Pr\ (D_{b1994} \geq D_{al}) \qquad (5.11)$$

The impact of control at the program level, or relative preventive effect (RPE) measures the preventive effect relative to the year of the CRISP intervention by equation 5.12 (Kleinbaum et al. 1982).

$$RPE = 1 - IRR \qquad (5.12)$$

Confidence intervals (CI) for incident risk ratios and RPEs were calculated using (STATA 1997).

5.4.1.5 Regression analysis

The final analysis of the CRISP intervention that explored the relationship between intervention year and average absorbed lead. This relationship was examined after removing the influences of different job titles, contractors and level of exposure. Log transformed absorbed dose was initially examined for partial associations among anticipated dose and program year using a one-way log normal fixed effects analysis of variance (ANOVA) model (Kleinbaum et al. 1988). Anticipated dose under the assumption that all the intake of lead during bridgework is inhaled is derived by equation 5.13.

$$D_e = (I_{inhale})(0.35) \qquad (5.13)$$

The value 0.35 is the fraction of lead absorbed from the lungs to the blood of a worker. An F-to-remove approach presented by Selvin (1995) was used to contrast residual sums of squared variance and covariance among hypothesized and nested models. This approach allows the differences between two sums of squares to be formally assessed using Fisher's probability distribution (i.e., F-distribution). Adjustments were made to remove the effect of anticipated dose on absorbed dose when associations were significant. Adjusted models were re-analyzed for the effect of program-year on absorbed lead. Then, long-term blood lead levels derived from month-long absorbed dose estimates from the 1995 subgroup were compared to baseline and projected blood lead level estimates published in the OSHA lead standard (OSHA 1993).

5.4.2 Development of a model based on CRISP

This section described the formation of a predictive model that relates task-based exposure to absorbed lead using CONLIS and the CRISP intervention data. To begin, a predictive model structure is proposed from the results of study one and further explored. Data collected during the later phase of the intervention program (1995) from two large bridge projects were split into two sets using a random selection process. The first data set was used to adjust and calibrate the model. Derived in study one, a dose fraction (DF) is comprised of a dose incorporating respiratory protection divided by a dose absent the benefit of respiratory protection. For the purpose of the present study, individual DFs were calculated from the first half of the data set for each contractor and job title subgroup. A one way log normal ANOVA model was used to test for systematic differences among twelve contractor -job title groups and log transformed dose fraction. The F-to-remove approach was invoked to examine for partial associations among job titles, anticipated dose and dose fraction within each contractor group. This approach contrasts in residual sums of squared variance and covariance among full and nested models were examined. Adjustments were made to remove the effect of job title on dose fraction when associations within contractor groups were significant.

Then, the second data set was used to validate this initial predictive model. The mean dose fraction calculated from the first half of the data set was used for the dose fraction along with the second half of the data set. The proposed structure predicts absorbed lead as a log-linear function of a crew-based dose fraction, factors indicated by the variable 'contractor', mean task-based PBZ estimate of lead concentration during abrasive blasting and a profile of blasting activity. The proposed model was fit to the second half of the data set. Then, probability plots were generated to examine the data for differences in the mean observed and model-predicted dose.

5.4.3 Model demonstration

When an industrial hygienist is faced with making a decision, about whether a workplace or process presents a hazard to one or more members of a workforce, both professional judgement and statistical tests are recommended (Rock 1995). The last section of Chapter 5 illustrates the utility of the final model through posing a set of scenarios in which the statistical component of the decision process has been incorporated. Exposure intensity and program protection levels are perturbed and each set of predicted blood lead levels is compared. MATLAB 2000 and Microsoft Excel 97 were used to produce scenarios using the new prediction model.

5.5 Results

5.5.1 Selected bridge projects

Bridge projects used in the analysis were identified in ConnDOT project logs as lead-related and scheduled to start after January 1993. Industrial hygiene reports were available for 58 projects. Five or more monthly reports were available for twenty-eight projects. Eighteen of those projects were rejected because reports provided sparse air samples or did not provide daily accounts of blast cleaning or ironwork tasks. In industrial hygiene reports, five projects had records of blast time for each crew (delineated by bridge, shift or employer) in daily field notes. The ambient air section of four projects recorded daily blast hours separated by painting contractor. Inspection reports for one project recorded blast times for each containment structure and work shift on one of two bridge structures. Ten projects contained the requisite task-based personal breathing zone lead concentration, blast time and hygiene and LHPP respiratory protection information.

Ultimately, two large bridge projects met the selection criteria. The initial four eligible projects dropped to two after three contractors were excluded for not have enough paired blood lead results for each job category. Three bridge structures were included in these projects. One bridge was a thru-arch and the other a truss design ranging in total length from 1067 m to 3200 m. Both bridges were located away from major metropolitan areas, were constructed between 1938 and 1943, and had average lead content in the old surface paint ranging from less than 1% to 18% by weight.

5.5.2 Selected painting contractors

Seven painting contractors conducted abrasive blasting activity. However, four contractors were excluded because they did not have at least two blood lead intervals for each of four broadly defined job categories. Three contractors met the selection criteria.

5.5.3 Selected blood lead intervals

Five hundred sixty nine blood lead intervals met the initial inclusion criteria. Half of the intervals were from workers who were employed by contractor 5 on bridge project 1, the Goldstar bridge. The other half was split between employees of Contractor 2 and 7 who worked on project 2, the Arrigoni bridge.

A total of 235 workers were enrolled in the CRISP LHPP and reported being employed by a contractor and bridge project selected for study. Of those workers, 195 had blood lead tests during at least 2 of the 61 project months where blast time was available. Blood lead intervals from 195 workers were selected for analysis.

The most frequent period of testing occurred during the first six months of enrollment in the CRISP program. Multiple blood lead testing on individual workers can lead to workers changing their behavior (Posavac & Carey 1997). Also, later cycles of testing occurred more often in 1995. Therefore, blood lead interval selection was restricted to the first, second and third months in which two blood lead tests were available for each worker to control for the possible confounding effect of long-term blood lead testing on the relationship between program year and absorbed lead.

5.5.4 Descriptive data summaries

Characteristics of the project, contractor and blood lead intervals are listed in Table 5.1a for 1994 and in Table 5.1b for 1995.

5.5.4.1 Bridge project

Personal breathing zone lead concentration measurements for each bridge project were extracted from the monthly industrial hygiene reports using the selection criteria described in detail in Chapter 2. To summarize those criteria, air samples were included if they were taken in the PBZ of a worker during an abrasive-blasting task. Descriptive information accompanying the sample indicated that usual working conditions pertained during the monitoring period. PBZ lead concentration samples were collected and analyzed using recognized methods such as those published by NIOSH. Minor differences were observed when mean values were calculated separately for projects involving more than one contractor. Therefore an arithmetic mean PBZ air concentration AM[C_t] was calculated at the project level for each bridge project. Both projects selected for study conducted some enclosed work although only limited information was provided about containment structures.

Work schedule, containment and bridge-structure delineation were examined to establish the daily duration of blasting activity for each project's active workforce. Several variables impact this assessment. First, the number of painting crews involved in a blasting activity varied between projects and within a specific project over time. Also in some cases, there was more than one painting contractor involved (usually a main and a subcontractor) or more than one crew assembled because there was more than one bridge or blast containment structure associated with the project. In other cases, work shifts were long (i.e. 12 hours) and work, delineated into day and night shifts, was performed around the clock. In still other cases, the inspection and industrial hygiene reports were only available for one of two bridge structures where air and dust monitoring results indicated that blasting activity was occurring. In this case, the pace of work on each bridge structure was assumed to be similar unless the industrial hygiene reports indicated otherwise.

Daily blast time on a bridge project was calculated separately for each painting contractor. Exposure dates were determined by the interval between two blood lead tests and matched to the blast time on a particular bridge project and Contractor's crew. Estimates were made to separate blast time by containment structure, shift and crew. Only those intervals tagged as open abrasive blasting were counted as hours for which exposure occurred.

Blast time was a serendipitous finding in CRISP records, as it was not required by the written protocol and is not as yet a common practice among hygienists to record task activity on an hourly basis during active projects (as evidenced by many records without this information among CRISP reports). As a consequence, data from adjacent months had to be interpolated or extrapolated to months where blast time was missing but where records indicated that blasting had taken place during the month. No attempt was made to track blast times for individual workers.

5.5.4.2 Contractor workforce

About 60% of the intervals originated from painters and blasters. This job title mix is similar to previous studies of bridge workers (Cannon et al. 1996; Maurer et al. 1995a; Sussell 1997; Sussell et al. 1992). The average age and the proportion of male workers and smokers were similar to that of the larger CRISP population as well (Chapter 3 Table 3.2).

5.5.4.3 Blood lead interval

Approximately 96% of the paired blood lead levels came from male workers, half of who smoked. Average blood lead levels taken at the beginning of an exposure period ranged from 13 $\mu g\ dl^{-1}$ to 15 $\mu g\ dl^{-1}$. Coincidentally, this is in the same range as the annual peak blood-lead levels for the entire CRISP population of painter contract-employees (Chapter 3, Table 3.3). The average age and proportion of male workers, smokers and job title mix are similar to that of the larger CRISP population as well (Chapter 3 Table 3.2).

5.5.5 Simplified engineering analysis

Two bridge projects are evaluated during the last year of the CRISP demonstration (i.e., 1995). Intake and dose fractions for each bridge project are provided in Table 5.2a and Table 5.2b. Workforce intake is derived from two different estimates of abrasive blast exposure. The first estimate of intake ignores any effects from protective techniques provided to a project crew from respiratory protection.

Intake standardized to a crew size of 12 from bridge project 1 is 12 x 10^{-2} g day^{-1} and 32 x 10^{-2} on bridge 2. The rate of source emissions is derived from task-based PBZ concentration estimates, blast time and area ventilation rates. On bridge 1, abrasive blast time-weighted emission rate is 230 g day^{-1} and 640 g day^{-1} on bridge 2. The population intake fraction without regard to protective measures other than general ventilation is 5.0 x 10^{-4} on both bridge projects.

Intake derived from blood lead measures during bridge project 1 is 7.4 x 10^{-4} g day^{-1} and 7.3 x 10^{-4} g day^{-1} during bridge 2. The abrasive blast emission rate on bridge 1 remains 230 g day^{-1} and 640 g day^{-1} on bridge 2. Taking respiratory protection into account, the population intake fraction is 3.2×10^{-6} and 1.1×10^{-6} on bridge projects 1 and 2 respectively. The dose fraction for each bridge project, (i.e., the effect of respiratory protection on each bridge), is 6.4×10^{-3} and 2.3×10^{-3} on bridge project 1 and 2 respectively. These standardized estimates provide a transparent measure of protective effect. Intake estimated from task-based lead concentration produced during both bridge projects is 100-fold greater than intake estimated from blood lead. These findings suggest that the effect of respiratory protection is substantial and warrants further analysis.

5.5.6 Preventive effect relative to action-level exceedences

In another analysis, exposure estimates were grouped by employer and job title and explored for changes in the proportion of workers exposed to excess lead during 1994 and 1995. To conduct this analysis, the entire data set was first examined to see if estimates of absorbed dose conform to either a normal or lognormal distribution. Absorbed dose was examined by Shapiro-Wilk and Shapiro-Francia statistics (STATA 1997). Test results for each year appear in Table 5.3a and Table 5.3b. Acceptable conformity to a lognormal distribution was achieved once the data were stratified into subgroups based on year, contractor and job title.

Next, a cohort incident risk ratio was calculated. The proportion of workers with a dose in excess of D_{al} among workers first enrolled in 1995 is compared to the proportion first enrolled in 1994. Incident risk ratios and 95% confidence intervals were calculated for each subgroup. Then, the impact for each subgroup of project year on absorbed dose and their 95% confidence intervals were calculated. Estimates appear in Table 5.4.

When subdivided by contractor, a risk ratio of 0.19 (95% CI: 0.05 – 0.67) indicates that workers employed by contractor 2 regardless of job title, were only 19% as likely in 1995 than in 1994 to exceed the dose-equivalent action level. However, there was no convincing evidence that program year effected workers employed by contractors 5 and 7 who had risk ratios of 1.79 (95% CI: 0.64 – 5.03) and 0.53 (95% CI: 0.15 – 1.90) respectively.

When subdivided by job title, blasters were only 26% as likely in 1995 than in 1994 to exceed the dose-equivalent action level. However, there was no convincing evidence to suggest that program year affected laborers or painters who had risk ratios of 0.86 (95% CI: 0.25 – 3.01) and 2.89 (95% CI: 0.80 – 10.48) respectively. Ancillary workers experienced no exceedences.

An RPE of 0.81 (95% CI: 0.33 – 0.95) for contractor 2 indicates that 81% of the action-level exceedences that would have occurred in the absence of program-year improvements were prevented. Similarly, an RPE of 0.74 (95% CI: 0.06 – 0.93) for blasters indicates that 74% of the action-level exceedences that would have occurred in the absence of program-year improvements were prevented. These findings suggest that there were benefits to all workers exposed to the LHPP in 1995 who were employed by contractor 2 and to all blasters regardless of employer. The likelihood of exceeding the dose-equivalent action level among painters was almost 3 times greater in 1995 than 1994 but the difference was not statistically significant. Inadequate power may have been part of the cause of the failure to detect a difference. Power is lost when a continuous variable is dichotomized. Consequently, the next section explores the influence of program year on absorbed dose in an analysis of variance.

5.5.7 Regression analysis

A potential effect of program year was first examined by one way analysis of variance. There was a significant reduction in the mean absorbed dose (F-test 5.12, p-value 0.02) but with equality of variance (Bartlett's test for equal variances: chi2(1) = 2.31 Prob>chi2 = 0.13). There was a significant reduction in the mean blood lead level (F-test 6.24, p-value 0.01) but with equality of variance (Bartlett's test for equal variances: chi2(1) = 1.44 Prob>chi2 = 0.23).

The simplified engineering analysis in section 5.5.5 revealed that the estimated intake based on PBZ air concentration and blast time (referred to here as 'anticipated dose') was two orders of magnitude greater than intake derived from lead absorbed by workers (referred to here as 'absorbed dose'). Therefore, one objective is to identify the independent influence on absorbed dose from differences in anticipated dose between program years. Where appropriate, mean levels of absorbed dose are adjusted so that the influence from differing levels of anticipated dose is removed from any comparisons of absorbed dose between program years. The second objective is to compare blood lead concentration to absorbed dose as an outcome measure of program year effect. The assumption is that absorbed dose is a more accurate outcome measure because it eliminates the influence of body burden on the initial blood lead concentration. This section first identifies worker subgroups with significant differences in mean absorbed dose between program years. Then, these subgroups are examined for influences from anticipated dose that could distort an assessment of program year effect on absorbed dose and where feasible, remove that influence. This will allow for other aspects of the program year effect than a change in PBZ lead level to be detected. Finally, these steps are repeated after substituting blood lead as the outcome variable and the results are compared.

To examine correlation among variables, Shapiro-Wilk and Shapiro-Francia tests were performed on the distribution of absorbed dose and blood lead. These tests found that absorbed dose and blood lead conformed reasonably well to a log normal distribution when subdivided by contractor-job title groups.

As well, correlation between the program year and the log transformed blood lead concentration, absorbed dose, and anticipated dose was explored. Blood lead was highly and consistently correlated with absorbed dose as expected. Anticipated and absorbed doses were correlated within subgroups (contractor 2's ancillary workers, contractor 5's painters and contractor 7's blasters). Program year tended to be either positively or negatively correlated with anticipated dose (see Table 5.5a and Table 5.5b). The co-influence of anticipated dose on the relationship between program year and either blood lead or absorbed dose as an outcome variable were further explored among twelve contractor – job title subgroups.

The effects from the CRISP intervention on lead absorbed by workers were further investigated by comparing the mean absorbed dose of workers classified by program year using a one-way lognormal ANOVA model. Findings in Table 5.6 show there are significant differences in mean log absorbed dose between year 1994 and 1995 among blasters (F-tests 4.45, 5.98 and 6.49 and p-values of 0.05, 0.02 and 0.02 respectively). Tests for laborers of contractor 5 (F-test 13.78 p-value 0.001) and ancillary workers of contractor 2 (F-tests 10.57 and p-value 0.003) also indicate significant differences. Therefore, subgroups further evaluated for program year effect are 20, 21, 51, 56, and 71.

The relationships among absorbed dose, program year and anticipated dose were explored by the method of model comparisons. One model specifies that absorbed dose relates to year of the LHPP by a unique linear equation as a result of differences in anticipated dose and subgroup (model I, interaction). A second model restricts these linear relationships between LHPP years to have the same slope but different intercepts (model II, no interaction). A third model specifies that there is no influence of year on absorbed dose. The tests of relative model feasibility appear in Table 5.7.

For laborers employed by contractor 5 (subgroup 56), the model with no interaction between year and anticipated dose produced the best fit (significant at the 0.05 level). A good fit to models depicting interaction between anticipated dose and program year found that for four contractor-job title groups (subgroups 20, 51, 71 and 76). When anticipated dose is included in the model, there is no evidence to suggest that program year is related to absorbed dose among blasters and laborers who worked for contractor 7. In spite of this interaction between anticipated dose and year, the model depicting no interaction also produced a good fit for ancillary worker employed by contractor 2 and contractor 5's blasters (20 and 51). Therefore, mean absorbed dose was adjusted to remove the influence of anticipated dose for subgroups 20, 51 and 56. Although the unadjusted and adjusted mean absorbed doses are almost identical, values for each program year and each subgroup appear in Tables 5.8a and 5.8b respectively.

Among blasters and laborers who worked for contractor 5 and among contractor 2's ancillary workers, when the influence of anticipated dose was removed absorbed dose show a significant difference between 1994 and 1995. Both contractor 2's ancillary workers and contractor 5's blasters experienced significant decline in mean absorbed dose. Contractor 5's Laborers however experienced significant increase in mean absorbed dose from 1994 to 1995.

A slightly different pattern emerges when blood lead replaces absorbed dose (Table 5.9). Systematic differences in mean log blood lead between 1994 and 1995 are likely among blasters employed by contractors 5 and 7 (F-tests 4.22 and 4.72 respectively and p-values of 0.04) but not for blasters employed by contractor 2. Along with laborers of contractors 5, probable differences between 1994 and 1995 are probable among laborers employed by contractor 7 (F-test 14.33 and 4.82 and p-value 0.005 and 0.04 respectively).

A significant effect from program year on absorbed dose could be detected in 39% of the study population. When blood lead concentration replaced absorbed dose, the same groups produced a good fit to the no interaction model (subgroups 20, 51 and 56). However, no other groups produced a good to any model. This discovery and the fact that a single measure of blood lead can be temporally ambiguous suggests that blood lead may be insensitive to influence from anticipated dose if it were used as an outcome measure instead of absorbed dose.

An initial assessment indicated that absorbed dose declined between 1994 and 1995 among the study population. A more detailed analysis revealed that estimates of mean absorbed dose were significantly influenced by program year for three contractor-job title subgroups when adjusted for the influence of anticipated dose. These subgroups comprise 39% of the study population. Interaction between anticipated dose and program year influences absorbed dose among contractor 7's blasters and laborers and contractor 2's ancillary workers. Statistical interaction was also discovered between contractor-job title categories and program year. Therefore, in the next section a prediction model is derived from observations collected during 1995 of the CRISP demonstration.

5.5.8 Model development

A second part of this chapter seeks to describe the relationship between absorbed dose worker protection and exposure to lead during abrasive blasting activities. Two hundred seventy four observations collected during the final year of the CRISP demonstration were used to model average absorbed dose arising from workers subjected to similar conditions.

The simplified engineering analysis in section 5.5.5 estimated the fraction of PBZ lead estimated intake that was absorbed by a crew of workers from two bridge projects. Dose fractions from both bridge projects were found to be substantial. Therefore, a new variable that modifies estimates of absorbed lead from measurements of PBZ lead concentration is derived and examined in a model that predicts absorbed dose under similar work conditions. The first half of the data was used to dose fraction. Anticipated dose estimates from the second half of the data set were multiplied by the average dose fraction derived from the first half of the data to obtain the predicted value of absorbed dose 'D_{bnew}' by equation 5.14

$$D_{bnew} = (0.024)(AM[C_t])(t_b)(20)(0.35) \qquad (5.14)$$

The value 20 represents the breathing rate per day, 0.35 in the fraction of lead absorbed into the blood from the lungs and 0.024 is the average dose fraction determined from the first half of the study data set.

5.5.9 Model tests

The relationship between model-predicted dose D_{bnew} and absorbed dose derived from observations (D_b) for the entire set of observations and for groups of observations subdivided by contractor and job title. Figures 5.1 –5.11 display comparisons of the distribution of predictions relative to absorbed dose. The model accurately predicted absorbed dose for contractor 2's crew. Under prediction occurs where observations of absorbed dose was lower among contractor 5's crew and over prediction occurs where absorbed dose tended to be higher among contractor 7's crew.

Finally, absorbed dose derived from blood lead collected in 1995 over one month was extended over a year to represent chronic blood lead levels. These extrapolated blood lead levels were compared to OSHA's baseline and projected long-term blood lead levels from tables 6 and 7 published in the lead in construction standard. The subcategories of job titles were matched with the OSHA list of tasks most closely associated with each job title. Tables 5.10a and 5.10b display the percent of the worker population having blood lead levels at or below a given blood lead category. Long-term blood lead for each task/job title category derived from CRISP enrollees is within OSHA's baseline and projected blood lead distributions. This comparison provides additional evidence that CRISP intervention techniques resulted in better management of lead exposure than at baseline.

5.5.10 Hypothetical scenarios

CONLIS can be applied to decision scenarios for the purpose of planning and managing LHPPs. Three terms can be altered, namely task-based lead concentration, the frequency and duration of the task and dose fraction. Two scenarios illustrate how blood lead goals affect decisions when terms were perturbed.

5.5.10.1 Scenario 1: affect on the control of blood lead levels when no respiratory protection is needed

A newly hired 20-year old man is assigned to an abrasive blast activity that has been characterized as generating breathing zone air concentration levels with an arithmetic mean of 40 $\mu g\ m^{-3}$ and a geometric standard deviation (GSD) of 3.7. Upon employment, the worker's body weight and blood lead level was found to be 70 kg and 5 $\mu g\ dl^{-1}$, respectively. The State Department of Transportation contract specifications require the contractor to keep with 95% probability, the individual worker's blood lead levels below 20 $\mu g\ dl^{-1}$ among all employees. The Industrial Hygienist (IH) and Contractor work together to examine creative ways to optimize the anticipated production schedule with the required contract requirements for worker blood lead levels.

Case (a) in Table 5.11 shows that the newly hired worker can perform the high exposure task for a maximum of 105 hours during his first month of employment. Assuming that the worker performs this task for the maximum number of hours (i.e., before the worker's blood lead level is assumed to reach 20 $\mu g\ dl^{-1}$), case (d) shows that this worker's maximum number of task hours drops to 48 in subsequent months. Some options available to the IH and Contractor include reducing the number of highest air concentration levels during the performance of this task and thereby reducing the GSD or the AM or both. For example, when the GSD=2.7, cases (a) and (c) increases to 3.7, the maximum hours for the initial and subsequent months decreases from 105 and 59 to 88 and 48 respectively.

5.5.10.2 Scenario 2: affect on the control of blood lead levels when respiratory protection is needed

The same worker described in scenario 1 is assigned to an activity where a single task is found to produce much higher air concentrations than the other tasks involved in the activity and substantially higher than the exposure task in scenario 1. This task has been characterized as having an air concentration distribution with an AM=10,000 $\mu g\ m^{-3}$ and GSD=2.7. The worker is issued a respirator with an effective protection factor of 200 (GSD=1.5). Cases (f) and (h) in Table 5.12 show that the newly hired worker can perform the high exposure task for a maximum of 127 hours initially and 71 hours thereafter. This scenario illustrates that workers who accumulate lead to some occupational limit would need to reduce their number of blasting hours by 30% in the absence of other protective measures. Case (e) and (g) increase the GSD to 2.0.

Note in Tables 5.11 and 5.12 that there are some scenarios where the coefficient of variation (CV) is much higher than 10% and the departure of the 95th percentile from the arithmetic mean blood lead level is substantial. In these instances, a comparison of the arithmetic and geometric 95th percentile of the distribution indicates that the arithmetic parameters will produce an overestimate of the number of allowable exposure episodes.

5.6 Discussion

Mounting evidence reveals that even very low levels of lead in the human body result in adverse health outcomes. These lower levels are currently allowed often enough that exposure control in the workplace warrants considerable attention. To date, the metric used to determine control has either been the 8-hour time-weighted-average PBZ concentration, the blood-lead level, or the change in blood lead obtained after some extended interval of time. Because of the nature of construction work, staying below a limit of lead in the PBZ of a construction worker is often not achieved. Numerous examples appear in Chapter 2 of this project. When respiratory protection is needed to prevent inhaling levels of lead measured in the PBZ, the amount of absorbed lead dose is the measure of interest. This chapter introduces a method for deriving a measure of absorbed dose from blood lead, a long-term measure of absorbed dose that is confounded by past body burden of lead. In addition, this chapter explored the CRISP intervention effect by comparing data collected in 1994 to data collected in 1995 on two large bridge projects. The CRISP exposure-control program goals to maintain inhaled lead concentrations below an 8-hour TWA of 30 $\mu g\ m^{-3}$ were examined as well as the effect of program year where incentives to improve control techniques such as the use of better respiratory protection were progressively introduced. The second part of this chapter developed, tested and illustrated a predictive model from the CRISP data. Model predictions were compared to field data and planning and management scenarios illustrated the model's utility.

The ratio of two standardized intake fractions measured the overall reduction in absorbed lead achieved by the CRISP intervention. This initial estimate found a substantial protective effect. This method of measuring risk or preventive effect is common in the public health field. By estimating the ratio of intake fractions, the effect of personal protective techniques was made transparent.

Since data for several of the environmental variables introduced in the model were not available in the CRISP data set, the variables 'contractor' and 'job title' were introduced. These new variables served as surrogates to variables thought to have important influences on dose such as work environment, and duty assignments. A primary program goal of reducing the probability of inhaling an 8-hour TWA lead concentration was observed in some but not all worker groups. Interaction between job title, program year and anticipated dose was found in an analysis of program year effect on average absorbed dose. A significant and consistent reduction in absorbed dose occurred between years 1994 and 1995 for blasters regardless of who employed them. However, Table 5.9 showed that substantial increases from 1994 to 1995 in mean absorbed dose occurred among contractor 7's painters and contractor 5's laborers. One possible explanation for the consistent reduction among blasters is the change in respirator equipment from blasting helmets and hoods without a half mask air supply delivery system to one with such a system. Industrial hygiene records described incidences for example, where corrective action was taken when equipment was returned without internal facemasks indicating that masks were removed and the air supply was delivered to the entire hood or helmet. On the other hand, the increase in absorbed dose among painters and laborers may reflect the relaxing of protective measures – a provision spelled out in the LHPP. Again, industrial hygiene records described incidences where initial protection was downgraded after exposure assessments were completed.

A key-missing component of the predictive model called 'dose fraction' that represented the influence of removal mechanisms such as task-related respiratory protection was derived. The arithmetic mean dose fraction of 0.024 found in this study is consistent with limited prior research on workplace respirator penetration fraction. Previous studies that have characterized workplace penetration fractions of inhaled to task-based personal breathing zone pollutant concentration for various types of respiratory protection equipment were comparable to dose fractions in this study (OSHA 1993; Sussell et al. 1992). Viewed another way, the inverse of dose fraction produces the preventive dose factor (PDF) which is an absolute measure of protection. Therefore, the geometric mean PDF of 77 that was found in this study is consistent within an order of magnitude of respirator protection factors reported elsewhere. For example, Feletto (-) sampled air in the breathing zone and inside the blast hoods and helmets of workers during blasting activity were compared. Reported as a workplace protection factor, a ratio of outside-to-inside silica concentrations of 200 were typical.

Workplace protection factors of 1000 were estimated in lead aerosol environments that reached 20,000 μg m^{-3} in the breathing zones of workers and factors of 100 when PBZ lead concentrations ranged between 100 – 2000 μg m^{-3}. Workers were equipped with powered air purifying negative pressure air purifying respirators respectively (Vornberg 1985; Campbell et al. 1985).

Both of the studies presented in this chapter were limited. For example, blast time during the project was used to calculate the blast-related exposure time for each worker. The involvement of individual workers during active blasting could not be completely determined from the CRISP records since crew membership rotated among multiple containment structures and work shifts. Blast time was a serendipitous finding in CRISP records, as it was not required by the written protocol and is not as yet a common practice among hygienists to record task activity on an hourly basis during active projects (as evidenced by many records without this information among CRISP reports). As a consequence, data from adjacent months had to be interpolated or extrapolated to months where blast time was missing but where records indicated that blasting had taken place during the month. This approach employs standard values for parameters used to derive anticipated and absorbed dose such as PBZ concentration during abrasive blasting, hourly breathing rate, lung absorption and body weight. Measurements of workers actively engaged in bridgework were not available and if such information becomes available in the future, the findings presented here could be refined.

CRISP was a well-funded demonstration and the level of personal air sampling was unusually high and efforts to capture unique exposure scenario were formidable compared to routine projects. In some states, accumulating a library of well-characterized exposure scenarios during construction activity is discouraged. For example, the California Occupational Safety and Health Administration (CalOSHA) does not recognize air samples taken more than a year from the date of an active project (CalOSHA 1993). There are efforts to inventory task-based air samples from routine projects but such a database has not been made publicly available (OSHA 1996). Therefore, it is not expected that uncertainty in this parameter will improve in the near future.

Absorbed dose represents all sources of lead exposure but may not represent the true long-term dose. For example, no attempt was made to evaluate the impact on workers performing tasks with different particle size distributions. Although the model presented here a reasonable first approximation, other studies have indicated that particle size distributions differ substantially when generated from tasks involving lead combustion (Froines et al. 1995). Further study is needed to establish the particular size distribution from bridge related tasks. It was also assumed that any external ingestion sources are negligible relative to task related inhalation sources. It is entirely possible that ingestion from lead dust settled on workers' hands as well as on their food and beverages may be substantial. We are not aware of studies that have evaluated this particular source of lead intake.

The model developed in this project has undergone preliminary validation for a subgroup of bridge workers. It may not apply to other workers who are not directly engaged in abrasive blasting tasks. A full assessment of variability in standard parameters or other projects is needed to further assess inter individual and project variability. Therefore, model predictions should be used as a supplement to air and biological monitoring when assessing regulatory compliance. However, the broad policy implications of exposure control of lead in construction workplaces may be well served by this model. As illustrated in the previous section, this model can be used to explore the effectiveness of a particular intervention protocol.

5.7 Conclusion

This study demonstrates the exposure-control effect of the CRISP intervention. Long-term blood lead levels were compared to the OSHA baseline and projected blood lead levels revealing an improvement from baseline. This improvement implies that lower exposures can be achieved in construction workplaces. Estimates of anticipated and absorbed dose have been derived from data produced by the CRISP intervention and an estimate of average dose fraction has been calculated for three work environments. Furthermore, these findings indicate that an estimation tool can produce expected results. Consistency between model estimates and measurements of blood lead implies that the model-based approach is a useful supplement to industrial hygiene and medical monitoring in planning and managing exposures to lead during lead paint removal operations on bridges. Additional studies of other major tasks and other work sites are necessary to confirm these conclusions. Nevertheless, a prediction model that incorporates a few key parameters was tested showing no evidence of a difference from observations. A few illustrative scenarios demonstrate that a predictive model can serve as a useful supplement to industrial hygiene monitoring.

Table 5.1a: Characteristics of bridge project, contractor crews and workers enrolled in the CRISP LHPP in 1994

Date range of time-activity (month/year)		Bridge code	Contractor code	AM* PBZ lead during abrasive blasting (μg m³)	# Workers	% Smokers	Age AM (SD) (years)	% Blasters	% Laborers	% Painters	% Other job titles	Initial blood lead AM (SD) (μg dl⁻¹)
5/1993	1/1996	1	5	1860	132	44	35 (8.3)	33	10	43	13	12.5 (7.5)
11/1994	7/1995	2	2	6387	30	43	33 (7.9)	20	30	20	30	14.1 (7.9)
7/1994	6/1995	2	7	6387	64	47	30 (8.5)	25	28	22	25	15.4 (8.7)
12/1994	4/1995	3	4	8937	2	100	43 (19.8)	0	0	50	50	10.0 (1.4)
8/1994	10/1994	4	2	5756	15	27	39 (11.8)	27	0	27	47	11.3 (7.2)
1/1995	10/1995	8,9	8	5841, 9025	9	67	33 (9.8)	0	11	67	22	21.3 (6.3)

AM, arithmetic mean; SD, standard deviation; PBZ, personal breathing zone; μg, micrograms; m, meters; dl, deciliters; *same arithmetic mean PBZ lead concentration applied to both 1994 and 1995

Table 5.1b: Characteristics of bridge project, contractor crews and workers enrolled in the CRISP LHPP in 1995

Date range of time-activity (month/year)		Bridge code	Contractor code	AM* PBZ lead during abrasive blasting (μg m³)	# Workers	% Smokers	Age AM (SD) (years)	% Blasters	% Laborers	% Painters	% Other job titles	Initial blood lead AM (SD) (μg dl⁻¹)
5/1993	1/1996	1	5	1860	166	52	33 (10.3)	47	17	29	7	13.1 (7.5)
11/1994	7/1995	2	2	6387	67	47	32 (8.9)	15	25	22	33	11.6 (6.4)
7/1994	6/1995	2	7	6387	45	53	33 (8.2)	27	31	24	16	13.2 (6.7)
12/1994	4/1995	3	4	8937	4	25	51(10.5)	0	0	25	75	8.8 (2.6)
8/1994	10/1994	4	6	5756	4	50	33 (7.9)	25	0	50	25	16.0 (10.9)
3/1995	6/1995	5	1	6218	6	17	30 (3.1)	0	0	100	0	15.0 (6.2)
1/1995	10/1995	8	8	5841, 9025	25	68	34 (9.6)	4	36	40	20	18.5 (7.2)

AM, arithmetic mean; SD, standard deviation; PBZ, personal breathing zone; μg, micrograms; m, meters; dl, deciliters; *same arithmetic mean PBZ lead concentration applied to both 1994 and 1995

Table 5.2a: Intake and dose fraction for bridge project 1

Quantity description	Units	Anticipated	Absorbed
dose estimate	μg	101610	650
C_A	μg m^{-3}	1860	12
proportion from source	%	0.26	0.26
adjusted C_A	μg m^{-3}	484	3
Q	m^3 day^{-1}	480000	480000
Q_b	m^3 day^{-1}	20	20
N	#	12	12
I	g day^{-1}	0.12	0.00074
E	g day^{-1}	232	232
IF	-	5.0E-04	3.2E-06
DF			6.4E-03

μg, microgram; m, meter; g, gram.

Table 5.2b: Intake and dose fraction for bridge project 2

Quantity description	Units	Anticipated	Absorbed	Action Level
dose estimate	μg	280880	636.2	1395
C_A	μg m^{-3}	6800	15.4	33.8
proportion from source	%	0.20	0.20	0.20
adjusted C_A	μg m^{-3}	1338	3	7
Q	m^3 day^{-1}	480000	480000	480000
Q_b	m^3 day^{-1}	20	20	20
N	#	12	12	12
I	g day^{-1}	0.32	0.00073	0.00159
E	g day^{-1}	642	642	642
IF	-	5.0E-04	1.1E-06	2.5E-06
DF			2.3E-03	

μg, microgram; m, meter; g, gram.

Table 5.3a: Shapiro-Wilk test for conformity of absorbed lead dose (μg) to a normal distribution among workers enrolled in CRISP in1994 and grouped by contractor and job title*.

			statistic			p-value
Contractor	Job title	N	W	V	z	Prob. > z
2	ancillary worker	9	0.96	0.62	-0.75	0.77
2	blaster	6	0.97	0.33	-1.36	0.91
2	laborer	9	0.87	1.84	1.09	0.14
2	painter	6	0.82	2.23	1.35	0.09
5	ancillary worker	17	0.95	1.08	0.15	0.44
5	blaster	44	0.93	2.81	2.19	0.01
5	laborer	13	0.96	0.76	-0.53	0.70
5	painter	57	0.98	1.00	0.00	0.50
7	ancillary worker	14	0.88	2.14	1.50	0.07
7	blaster	14	0.95	0.84	-0.34	0.63
7	laborer	18	0.92	1.84	1.22	0.11
7	painter	13	0.92	1.45	0.73	0.23

*estimates of absorbed dose are log transformed; μg, microgram, N, number of dose estimates; W, V, z, test statistics; Prob > z, estimate of statistical significance.

Table 5.3b: Shapiro-Wilk test for conformity of absorbed lead dose (μg) to a normal distribution among workers enrolled in CRISP in1995 and grouped by contractor and job title*.

			statistic			p-value
Contractor	Job title	N	W	V	z	Prob. > z
2	ancillary worker	22	0.98	0.52	-1.33	0.91
2	blaster	10	0.96	0.59	-0.87	0.81
2	laborer	17	0.88	2.54	1.86	0.03
2	painter	15	0.87	2.50	1.81	0.04
5	ancillary worker	11	0.85	2.45	1.74	0.04
5	blaster	78	0.99	0.83	-0.42	0.66
5	laborer	29	0.96	1.15	0.29	0.39
5	painter	48	0.95	2.13	1.61	0.05
7	ancillary worker	7	0.91	1.20	0.29	0.39
7	blaster	12	0.97	0.44	-1.58	0.94
7	laborer	14	0.95	0.61	-0.98	0.84
7	painter	11	0.91	1.48	0.73	0.23

*estimates of absorbed dose are log transformed; μg, microgram, N, number of dose estimates; W, V, z, test statistics; Prob > z, estimate of statistical significance.

Table 5.4: The risk of exceeding the dose-equivalent workplace action level for lead in 1995 relative to 1994 among CRISP enrolled bridge abrasive blasting crews

Group description	N	Risk ratio	LCL	UCL
Contractor 2 all workers	89	0.19	0.05	0.67
Contractor 5 all workers	294	1.79	0.64	5.03
Contractor 7 all workers	109	0.53	0.15	1.9
Blasters	162	0.25	0.07	0.94
Laborers	98	0.86	0.25	3.01
Painters	148	2.89	0.8	10.48
Contractor 2 blasters	15	0.33	0.04	2.91
Contractor 2 non-blasters	74	0.16	0.03	0.73
Contractor 5 blasters	119	0.29	0.03	3.14
Contractor 5 non-blasters	175	3.37	0.96	11.84
Contractor 7 blasters	28	0.33	0.04	2.61
Contractor 7 non blasters	81	0.73	0.14	3.74

N, number of workers; LCL, lower confidence limit; UCL, upper confidence limit

Table 5.5a: Correlation between measures of blood lead, dose and project year for CRISP enrolled workers of Contractor 2*

Job title	Measure	Blood lead	Absorbed dose	Anticipated dose	Year
Ancillary workers N=31	Blood lead	1			
	Absorbed dose	0.95	1		
	Anticipated dose	0.32	0.36	1	
	Year	-0.51	-0.52	-0.34	1
Blasters N=16	Blood lead	1			
	Absorbed dose	0.98	1		
	Anticipated dose	0.04	0.15	1	
	Year	-0.45	-0.49	-0.32	1
Laborers N=26	Blood lead	1			
	Absorbed dose	0.91	1		
	Anticipated dose	0.21	0.16	1	
	Year	-0.34	-0.34	-0.45	1
Painters N=21	Blood lead	1			
	Absorbed dose	0.94	1		
	Anticipated dose	0.35	0.33	1	
	Year	-0.37	-0.22	-0.65	1

* Measures of blood lead and dose are log transformed; N, number of workers

Table 5.5b: Correlation between measures of blood lead, dose and project year for CRISP enrolled workers of Contractor 5*

Job title	Measure	Blood lead	Absorbed dose	Anticipated dose	Year
Ancillary workers N=28	Blood lead	1			
	Absorbed dose	0.90	1		
	Anticipated dose	0.23	0.28	1	
	Year	0.19	0.11	0.04	1
Blasters N=122	Blood lead	1			
	Absorbed dose	0.89	1		
	Anticipated dose	0.04	-0.04	1	
	Year	-0.18	-0.22	-0.20	1
Laborers N=46	Blood lead	1			
	Absorbed dose	0.88	1		
	Anticipated dose	0.18	0.11	1	
	Year	0.51	0.51	-0.03	1
Painters N=105	Blood lead	1			
	Absorbed dose	0.88	1		
	Anticipated dose	0.14	0.17	1	
	Year	0.03	0.03	-0.20	1

* Measures of blood lead and dose are log transformed; N, number of workers

Table 5.5c: Correlation between measures of blood lead, dose and project year for CRISP enrolled workers of Contractor 7*

Job title	Measure	Blood lead	Absorbed dose	Anticipated dose	Year
Ancillary workers N=21	Blood lead	1			
	Absorbed dose	0.78	1		
	Anticipated dose	0.18	-0.07	1	
	Year	-0.06	-0.26	0.56	1
Blasters N=26	Blood lead	1			
	Absorbed dose	0.86	1		
	Anticipated dose	-0.53	-0.51	1	
	Year	-0.60	-0.46	0.60	1
Laborers N=32	Blood lead	1			
	Absorbed dose	0.64	1		
	Anticipated dose	-0.25	-0.08	1	
	Year	-0.37	-0.08	0.47	1
Painters N=24	Blood lead	1			
	Absorbed dose	0.86	1		
	Anticipated dose	-0.05	-0.02	1	
	Year	0.31	0.37	0.2	1

* Measures of blood lead and dose are log transformed; N, number of workers

Table 5.6: Change in the distribution of lead absorbed from 1994 to 1995 among CRISP enrolled workers

Contractor	Job title	N	AM (µg)	SD (µg)	F-statistic[a]	Pr>F	chi^2*	Pr>chi^2
2	Ancillary	31	6.33	0.7	10.57	0.003	0.61	0.43
2	Blaster	16	6.6	0.7	4.45	0.05	3.06	0.08
2	Laborer	26	6.3	0.84	3.05	0.09	0.33	0.56
2	Painter	21	6.32	0.83	0.95	0.34	0.04	0.84
5	Ancillary	28	6.27	0.58	0.34	0.56	0.84	0.36
5	Blaster	122	6.22	0.65	5.98	0.02	2.88	0.09
5	Laborer	42	6.26	0.65	13.78	0.0006	0.39	0.53
5	Painter	105	6.31	0.72	0.08	0.77	1.59	0.21
7	Ancillary	21	6.66	0.48	1.38	0.25	1.81	0.18
7	Blaster	26	6.81	0.55	6.49	0.018	0.14	0.71
7	Laborer	32	6.23	0.66	0.21	0.65	3.35	0.07
7	Painter	24	6.03	0.73	3.59	0.07	0.31	0.58

[a]One-way ANOVA model
*degrees of freedom = 1; N, number of workers; AM, arithmetic mean of log transformed values of lead absorbed among workers in 1995, SD, standard deviation of log transformed values

Table 5.7a: Analysis of covariance between lead absorbed by CRISP enrolled workers, program year and estimates of anticipated dose

Contractor	Job title	Model	Residual SSE	Degree of freedom	F distribution	p-value	Direction of change from 1994 to 1995
2	Ancillary workers	I	8.82	27			
		II	10.23	28	4.32	0.05	down
		III	12.84	29	7.14	0.01	
2	Blasters	I	5.22	12			
		II	5.50	13	0.63	0.44	down
		III	7.09	14	3.75	0.07	
2	Laborers	I	14.54	22			
		II	15.48	23	1.42	0.25	down
		III	17.01	24	2.27	0.15	
2	Painters	I	12.29	17			
		II	12.30	18	0.01	0.93	down
		III	12.30	19	0.00	0.99	
5	Ancillary workers	I	7.70	24			
		II	8.24	25	1.66	0.21	up
		III	8.33	26	0.28	0.60	
5	Blasters	I	44.89	118			
		II	48.99	119	10.78	0.00	down
		III	51.74	120	6.67	0.01	
5	Laborers	I	12.01	38			
		II	12.70	39	2.17	0.15	up
		III	17.23	40	13.92	0.00	
5	Painters	I	50.68	101			
		II	51.89	102	2.40	0.12	up
		III	52.10	103	0.42	0.52	
7	Ancillary workers	I	4.31	17			
		II	4.34	18	0.11	0.74	down
		III	4.67	19	1.36	0.26	
7	Blasters	I	4.30	22			
		II	5.19	23	4.57	0.04	down
		III	5.45	24	1.15	0.30	
7	Laborers	I	11.25	28			
		II	13.33	29	5.19	0.03	down
		III	13.36	30	0.07	0.79	
7	Painters	I	8.50	20			
		II	10.41	21	4.50	0.05	up
		III	12.27	22	3.75	0.07	

Model I, absorbed dose interacts with anticipated dose; Model II, no interaction between program year and anticipated dose; Model III, no effect of year on absorbed dose. SSE, sums of squared error; Values for dose are log transformed

Table 5.7b: Analysis of covariance between measures of lead in the blood of CRISP enrolled workers, program year and estimates of anticipated dose

Contractor	Job title	Model	Residual SSE	Degree of freedom	F distribution	p-value	Direction of change from 1994 to 1995
2	Ancillary workers	I	7.02	27			
		II	8.40	28	5.31	0.03	down
		III	10.58	29	7.27	0.01	
2	Blasters	I	2.94	12			
		II	3.26	13	1.31	0.28	down
		III	4.10	14	3.35	0.09	
2	Laborers	I	7.71	22			
		II	8.92	23	3.45	0.08	down
		III	9.67	24	1.93	0.18	
2	Painters	I	5.41	17			
		II	5.41	18	0.00	1.00	down
		III	5.63	19	0.73	0.40	
5	Ancillary workers	I	6.40	24			
		II	6.40	25	0.00	0.95	up
		III	6.64	26	0.94	0.34	
5	Blasters	I	32.15	118			
		II	35.07	119	10.72	0.00	down
		III	36.24	120	3.97	0.05	
5	Laborers	I	7.85	38			
		II	8.69	39	4.07	0.05	up
		III	12.04	40	15.03	0.00	
5	Painters	I	31.06	101			
		II	31.84	102	2.54	0.11	up
		III	31.97	103	0.42	0.52	
7	Ancillary workers	I	4.42	19			
		II	4.50	20	0.34	0.56	up
		III	4.64	21	0.62	0.44	
7	Blasters	I	4.77	24			
		II	4.89	25	0.60	0.44	down
		III	5.28	26	1.99	0.17	
7	Laborers	I	6.46	28			
		II	6.48	29	0.09	0.77	down
		III	7.10	30	2.77	0.11	
7	Painters	I	4.44	21			
		II	4.79	22	1.66	0.21	up
		III	5.38	23	2.71	0.11	

Model I, blood lead interacts with anticipated dose; Model II, no interaction between program year and anticipated dose; Model III, no effect of year on blood lead. SSE, sums of squared error; Values for dose are log transformed

Table 5.8a: Unadjusted summary estimates of absorbed lead among CRISP enrolled workers in 1994 and 1995

		1994					1995				
Contractor	Job title	N	AM	SD.	Min	Max	N	AM	SD.	Min	Max
2	Ancillary	9	6.9	0.50	6	7.6	22	6.1	0.65	5.0	7.4
2	Blaster	6	7.0	0.33	6.5	7.4	10	6.3	0.74	4.9	7.3
2	Laborer	9	6.7	0.70	5.5	7.4	17	6.1	0.85	3.6	7.4
2	Painter	6	6.6	0.88	4.9	7.6	15	6.2	0.81	3.9	7.1
5	Ancillary	17	6.2	0.64	5.3	7.4	11	6.3	0.49	5.1	7.0
5	Blaster	44	6.4	0.73	4.5	7.6	78	6.1	0.58	4.8	7.4
5	Laborer	13	5.8	0.51	4.7	6.6	29	6.5	0.59	5.2	7.4
5	Painter	57	6.3	0.66	5.1	8.0	48	6.3	0.79	3.9	7.6
7	Ancillary	14	6.7	0.54	6.1	8.1	7	6.5	0.32	6.1	7.1
7	Blaster	14	7.0	0.47	6.3	7.8	12	6.5	0.52	5.7	7.4
7	Laborer	18	6.3	0.78	4.3	7.4	14	6.2	0.47	5.3	6.9
7	Painter	13	5.8	0.74	4.3	6.7	11	6.3	0.63	5.4	7.4

Values of absorbed dose are log transformed. AM, arithmetic mean; SD, standard deviation; N, number of workers

Table 5.8b: Adjusted summary estimates of absorbed lead among CRISP enrolled workers in 1994 and 1995

		1994					1995				
Contractor	Job title	N	AM	SD.	Min	Max	N	AM	SD.	Min	Max
2	Ancillary	9	6.9	0.32	6.2	7.3	22	6.1	0.65	5.0	7.4
2	Blaster	6	7.0	0.33	6.5	7.4	10	6.3	0.74	4.9	7.3
2	Laborer	9	6.7	0.70	5.5	7.4	17	6.1	0.85	3.6	7.4
2	Painter	6	6.6	0.88	4.9	7.6	15	6.2	0.81	3.9	7.1
5	Ancillary	17	6.2	0.64	5.3	7.4	11	6.3	0.49	5.1	7.0
5	Blaster	44	6.4	0.66	4.7	7.8	78	6.1	0.58	4.8	7.4
5	Laborer	13	5.8	0.51	4.7	6.6	29	6.5	0.59	5.2	7.4
5	Painter	57	6.3	0.66	5.1	8.0	48	6.3	0.79	3.9	7.6
7	Ancillary	14	6.7	0.54	6.1	8.1	7	6.5	0.32	6.1	7.1
7	Blaster	14	7.0	0.47	6.3	7.8	12	6.5	0.37	6.1	7.2
7	Laborer	18	6.3	0.78	4.3	7.4	14	6.2	0.39	5.6	6.8
7	Painter	13	5.8	0.74	4.3	6.7	11	6.3	0.52	5.6	7.1

Values of absorbed dose are log transformed. AM, arithmetic mean; SD, standard deviation; N, number of workers

Table 5.9a: OSHA table 6 baseline blood lead levels before lowering the PEL from 200 $\mu g\ m^{-3}$ to 50 $\mu g\ m^{-3}$

Subgroup	PDF	Percent workers in blood lead range ($\mu g\ dl^{-1}$)						AM
		<=15	15-25	25-30	30-40	40-50	>50	($\mu g\ dl^{-1}$)
abrasive blasting	100 - 600	35	54	65	76	84	100	32.1
associated misc act	10	35	53	61	78	84	100	28
combined blasting/painting	--	41	64	93	100			18.4
enclosure movement	10	52	65	82	100			17.9
industrial vaccuuming	1	100						6.1
spray paint with nonLBP	1	33	45	58	93	100		24.2

PDF, prevented dose factor (inverse of the dose fraction; AM, arithmetic mean; (μg, microgram; dl, deciliter

Table 5.9b: Percent of the worker subgroups with long-term blood lead level at or below category range derived from measured blood lead in 1995 during CRISP demonstration)

Subgroup	GM[PDF]	Percent workers in blood lead range ($\mu g\ dl^{-1}$)						Mean BL
		<=15	15-25	25-30	30-40	40-50	>50	($\mu g\ dl^{-1}$)
abrasive blasting	126		50		100			28.7
abrasive blasting	48	70	95		100			12.6
abrasive blasting	221	60	100					16.1
associated misc act	102	50	83		100			17.2
associated misc act	44	29	100					16.5
associated misc act	193	100						14.4
combined blasting/painting	56	20	100					16.2
combined blasting/painting	45	52	85	89	100			15.3
combined blasting/painting	170	75	100					12.5
enclosure movement	88	50	100					14.1
enclosure movement	44	46	69	77	100			17.7
enclosure movement	185	100						8.3

PDF, prevented dose factor (inverse of the dose fraction; AM, arithmetic mean; (μg, microgram; dl, deciliter

Table 5.9c: OSHA Table 7 projected blood leads after lowering the PEL from 200 $\mu g\ m^{-3}$ to 50 $\mu g\ m^{-3}$

Subgroup	PDF	Percent workers in blood lead range ($\mu g\ dl^{-1}$)						AM
		<=15	>15-25	>25-30	>30-40	>40-50	>50	($\mu g\ dl^{-1}$)
abrasive blasting	4000	100						6.6
associated misc act	50	86	100					9.6
combined blasting/painting	--	100						7.1
enclosure movement	50	100						7.6
industrial vaccuuming	50	100						5.0
spray paint with nonLBP	2	100						8.6

PDF, prevented dose factor (inverse of the dose fraction; AM, arithmetic mean; (μg, microgram; dl, deciliter

Table 5.10: Affect on the control of blood lead when no respiratory protection is needed (scenario 1)

Scenario 1	Inhaled air concentration task 1		Change in worker blood lead level		Target blood lead levels	Production constraint	Coefficient of variation
Case	AM ($\mu g\ m^{-3}$)	GSD	BLL(0) ($\mu g\ dl^{-1}$)	BLL(t) AM ($\mu g\ dl^{-1}$)	95th% (geometric) ($\mu g\ dl^{-1}$)	n (hrs)	SD/AM
a	30	2.7	5	16.2	20.0	105	0.11
b	30	3.7	5	13.9	19.9	88	0.19
c	30	2.7	20	17.2	19.9	59	0.08
d	30	3.7	20	15.7	20.0	48	0.12

AM, arithmetic mean; SD, standard deviation; BLL(0), blood lead levels prior to the onset of exposure; BLL(t), blood lead level at the end of an exposure; ug, microgram; dl, deciliter; m, meters; n, number of blasting hours in a month; GSD, geometric standard deviation; hrs, hours.

Table 5.11: Affect on the control of blood lead when respiratory protection is needed (scenario 2)

Scenario 2	Breathing zone air concentration task 2		Respiratory protection			Change in worker blood lead level		Target blood lead levels	Production constraint	Coefficient of variation
Case	AM (μg/m3)	GSD	AM	GSD	5th % (Protection Factor)	BLL(0) (μg/dl)	BLL(t) AM (μg/dl)	95th% (geometric) (μg/dl)	n (hrs)	SD/AM
e	10000	2.7	795	2	200	5	14.5	20	221	0.17
f	10000	2.7	423	1.5	200	5	15.5	20	127	0.13 .
g	10000	2.7	795	2	200	20	16.1	20	122	0.11
h	10000	2.7	423	1.5	200	20	16.8	20	71	0.09

AM, arithmetic mean; SD, standard deviation; BLL(0), blood lead levels prior to the onset of exposure; BLL(t), blood lead level at the end of an exposure; ug, microgram; dl, deciliter; m, meters; n, number of blasting hours in a month; GM geometric mean; GSD, geometric standard deviation; hrs, hours.

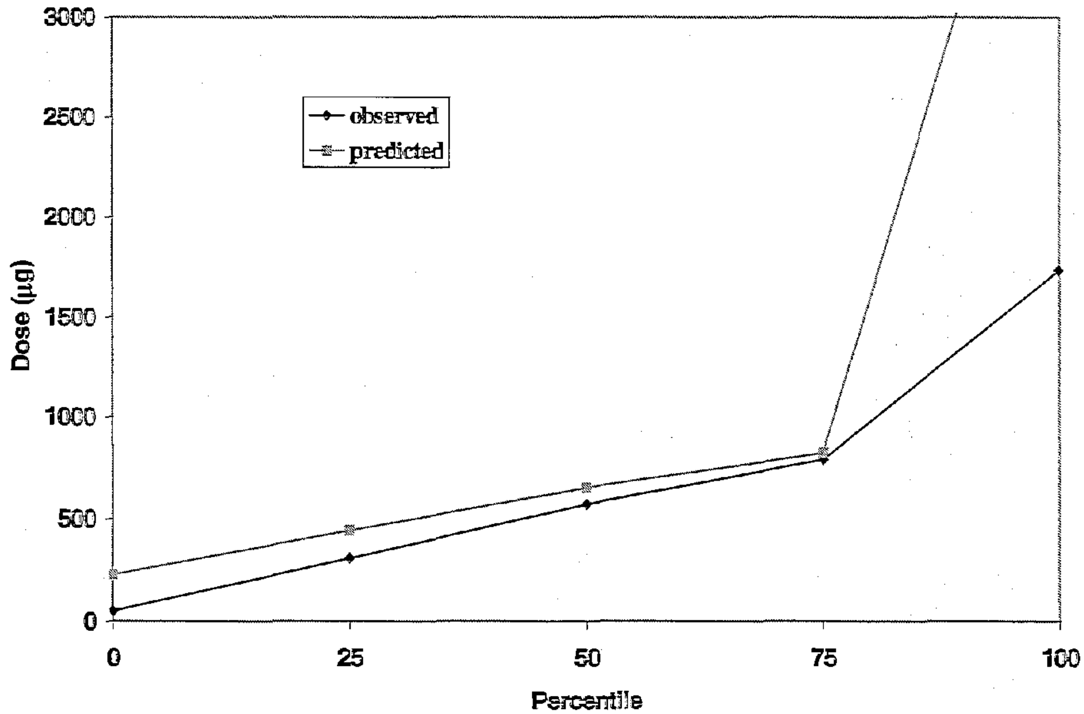

Figure 5.1: Comparison of model predicted and observed levels of lead absorbed among all selected bridge workers. N=121; μg, microgram

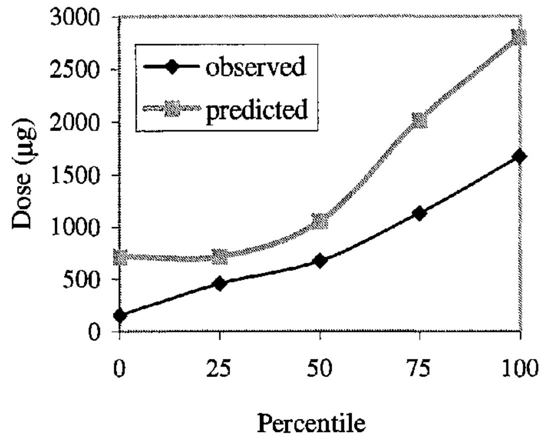

Figure 5.2: Comparison of model predicted and observed levels of lead absorbed among contractor 2 ancillary workers. N=6; μg, microgram

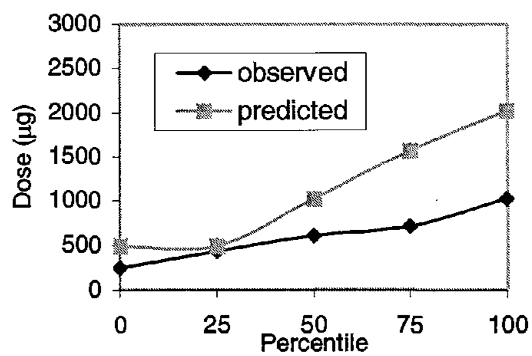

Figure 5.3: Comparison of model predicted and observed levels of lead absorbed among contractor 2 laborers N=6; μg, microgram

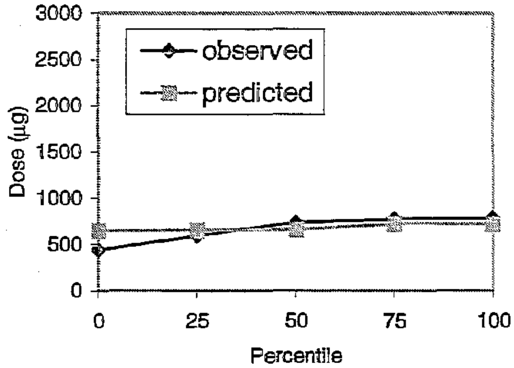

Figure 5.4: Comparison of model predicted and observed levels of lead absorbed among Contractor 2 painters N=5; µg, microgram

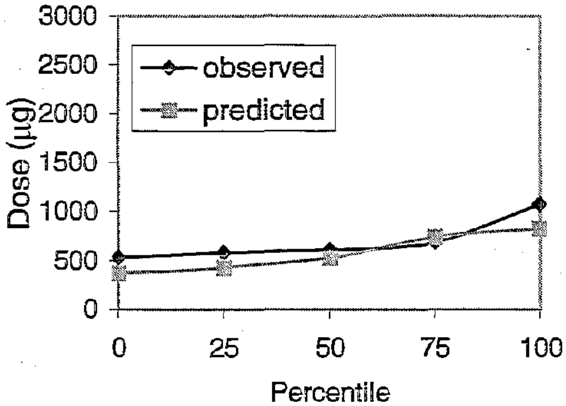

Figure 5.5: Comparison of model predicted and observed levels of lead absorbed among Contractor 5 ancillary workers N=7; µg, microgram

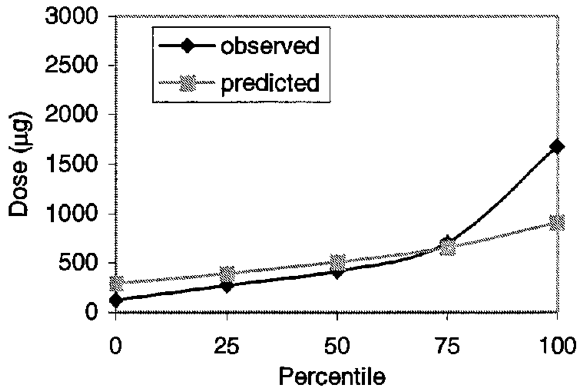

Figure 5.6: Comparison of model predicted and observed levels of lead absorbed among Contractor 5 blasters. N=40; µg, microgram

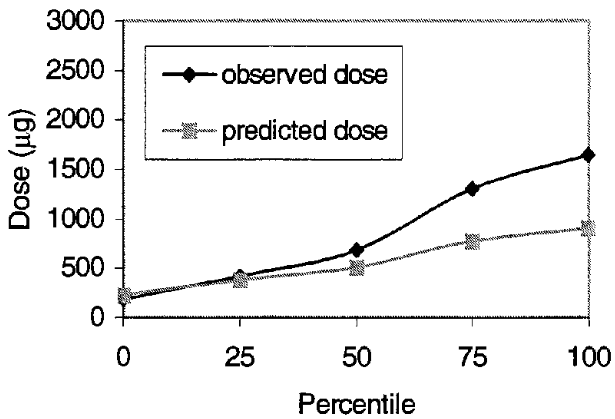

Figure 5.7: Comparison of model predicted and observed levels of lead absorbed among Contractor 5 laborers. N=13; µg, microgram

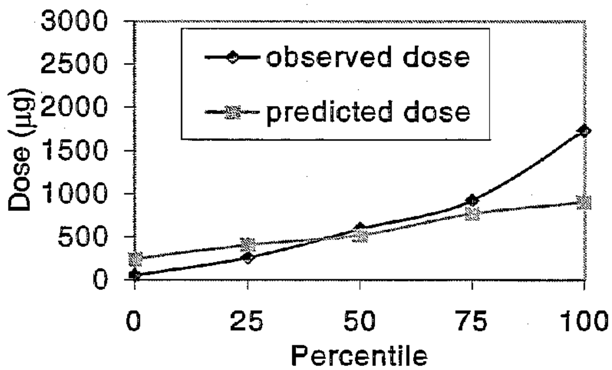

Figure 5.8: Comparison of model predicted and observed levels of lead absorbed among Contractor 5 painters N=27; µg, microgram

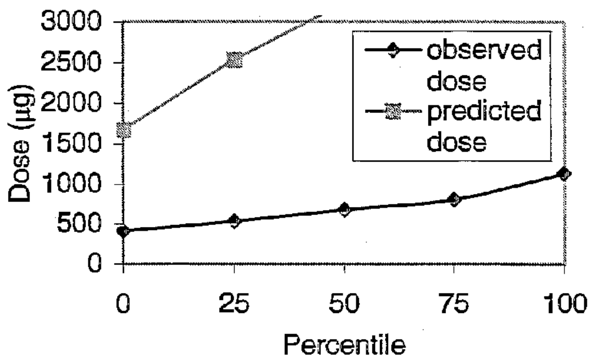

Figure 5.9: Comparison of model predicted and observed levels of lead absorbed among Contractor 7 blasters. N=5; µg, microgram

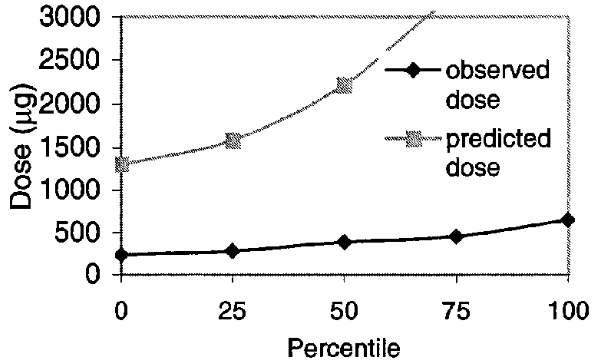

Figure 5.10: Comparison of model predicted and observed levels of lead absorbed among Contractor 7 laborers N=5; µg, microgram

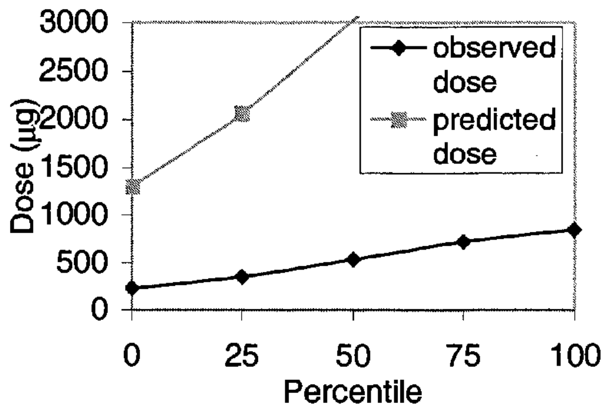

Figure 5.11: Comparison of model predicted and observed levels of lead absorbed among Contractor 7 painters N=4; µg, microgram

CHAPTER 6 CONCLUSIONS

6.1 Summary

The research presented in this project has culminated in the development of a new exploratory model designed to prevent occupational exposures to lead. To build this model, my investigation began by characterizing lead exposures during bridgework operations. A systematic review of 12 bridge projects that collected personal breathing zone lead concentration during bridge rehabilitation and repair tasks provided a profile of exposure. Parsing samples by sampling time, working environment, task execution practice and tool usage revealed new influences on airborne lead concentration. The analysis demonstrated that lead removal work produces multiple sources of airborne lead and that work performed in tightly enclosed structures produces the highest airborne lead concentrations and the need for a high degree of worker protection.

Then, we examined the effectiveness of a lead health protection program that was conducted in Connecticut call the Connecticut Road Industry Surveillance Project (CRISP). We conducted multiple comparisons of average and peak blood lead levels among the entire CRISP enrolled workforce noting that there was an overall reduction in blood lead among workers over time. As well, blood lead between two groups of blasters, one from the CRISP program and the other from blasters outside the CRISP program were much lower among CRISP enrollees suggesting that these workers were substantially more protected than workers protected under the OSHA regulation alone.

Encouraged by these findings, we investigated further the mechanisms of protection. To date, very few evaluations of worker protection programs could be found in the published literature and among these, none provided a model for linking environmental measurements of exposure, protection and absorbed dose among workers. As a consequence, the relationships between worker protection and absorbed lead remain largely unknown. In an effort to examine these relationships, an exploratory model was developed as part of this project.

This exploratory tool is a lead-flow simulation model named CONLIS (CONstruction Lead Intake Simulation) that simulates lead intake from the workplace and converts it to a level of lead in the blood of a worker. One of the unique features of CONLIS is that it can estimate dose from two types of measurements. CONLIS combines work methods, task exposure rates and air concentration to establish a measure of anticipated dose. Absorbed dose is derived from two measures of blood lead in individual workers and a physiologically based pharmaco-kinetic model published by Bert et al (1989).

The analytical solution of the Bert model equations incorporated into CONLIS was compared to Bert's numeric model and then to experimental observations published by Rabinowitz et al. (1976). Then, predictions from CONLIS using data from a NIOSH field study of bridge worker exposures during a bridge rehabilitation project were compared to blood lead levels among exposed workers. Good agreement was observed between predictions and measurement of lead in workers' blood.

Subsequently, we deployed CONLIS in further exploratory analyses of the effectiveness of the CRISP Lead Health Protection Program (LHPP) intervention. Dose estimates were examined for factors that affect exposure among abrasive blast crews. The impact of program year, inhaled air concentration, the frequency of production, breathing rate, initial body burden of lead, body weight and preventive effects introduced by the CRISP LHPP were examined systematically. An initial estimation of intake fractions revealed that two major bridge projects during the CRISP intervention each had a 100-fold difference between a measure of dose without regard to respiratory protection and absorbed dose among crews of 12 bridge workers. This difference provided an initial estimate of reduced lead intake attributable to worker protection techniques. A comparison of the proportion of occurrences among workers of excess dose from 1994 and 1995 provided additional evidence that exposure control was affected by project year and improved over time. The fraction of workers who would have experienced excess lead but did not also provided an estimate of differential benefit among workers grouped by job title. Blasters benefited substantially from protective measures over the two-year period regardless of their employer whereas estimates from other groups were not as strong or consistent.

An estimate of the average reduction from worker protection measures of lead taken in by workers (i.e. dose fraction) was derived from one half of the CRISP field data collected in 1995. This new value was multiplied to estimates of anticipated dose contained in the second half of the 1995 data set to predict absorbed dose. Regression analysis revealed that predictions of lead dose levels for the study group as a whole compared reasonably well to absorbed dose derived from blood lead measurements. When a random sample of the study population derived the dose fraction, project-averaged model predictions compared well to observations.

We also used CONLIS to explore in hypothetical scenarios how excess blood lead can be avoided and how alternative methods of protection can be evaluated. For a defined sequence of abrasive blasting activity, the model generates a distribution of blood lead levels. Simulations were performed for two alternate conditions. Scenarios demonstrate that variability in blood lead levels is due to the stochastic nature of both breathing zone lead concentrations and protective measures. Results reveal that future rates of abrasive blasting would be reduced to 30% of the original production rate when workers are allowed to reach the limit of exposure.

6.2 Future research

The impact of the LHPP on the bridgework workforce and preventive effect of specific techniques remain unresolved. CONLIS simulations provide a way to begin systematic investigation of impacts from specific lead paint removal activity and worker protection techniques on worker intake rates.

For bridge projects involving many crews, multiple containment structures, a variety of equipment and a variable work routine the monitoring and control of exposures can require substantial effort. To address this problem, this project derived a dose fraction estimated from task-based and biological measurements of lead accumulated over time. This fraction was further refined by an assessment of influences represented by contractor, program year, exposure intensity and job title variables. The program-wide dose fraction that provided an adequate metric for exploring relationships between abrasive blast activity, worker protection and blood lead levels may not be a sensitive enough metric for estimating exposures at much lower airborne lead concentrations or when exposure events are less frequent. Under these conditions a more detailed characterization of concentration and events may be required.

To thoroughly characterize the effects of exposure events, CONLIS could be used to produce a work-factor input from area or personal breathing zone concentration, dose fractions (i.e. reduced dose from worker protection practices and equipment) and a blood lead response for a typical worker. For a broader range of working conditions, such an investigation would determine the relative increase or decrease in lead intake, absorption and blood lead as a function of production and worker protection influences.

For example, one could calculate the impact on the likelihood of worker poisoning from environmental regulations that require tighter enclosures. As well, one could explore the impact of technological advances in enclosures that enable workers to clean surfaces every day instead of taking one to four days to dismantle, move and set up enclosures (e.g., rolling enclosures along the I-beams underneath a bridge). One could also calculate the effects of increasing the per hour cleaning rate from bigger and more powerful blast guns and more effective removal of visually impairing airborne debris while generating the more lingering and respirable particles.

CONLIS could be used to generate a table of predicted blood lead levels from a broad range of lead intake values and initial blood lead levels, an approach used for other toxic exposures. For example, Navy deep-sea repetitive diving tables (NOAA 2003) are used to avoid nitrogen toxicity. These tables allow the diver to monitor the rate of nitrogen inhalation for various dive conditions. This method avoids an invasive and potentially expensive regimen of frequent biological nitrogen monitoring.

CONLIS could be used to plan and implement exposure control systems in other hazardous occupational settings as well as in the broader context of episodic exposures to toxic agents. Such a tool could be useful too for industrial hygienists and engineers who are responsible for characterizing and mitigating immediate hazards and for continuously monitoring workplace conditions.

By combining a future CRISP-like program with modern control theory a systematic method could be constructed using a feedback and adjustment regimen. This would be similar to CRISP in principle but a much different system in practice. A combined program would apply CONLIS as a system state observer. This program enhancement could substantially condense the time and effort needed to demonstrate the optimum control of blood lead levels for an entire bridge workforce (Ogata 1990).

6.3 Closing remarks

The research presented in this project has provided an initial understanding of the impacts of a worker protection program on lead intake among construction workers. Although the influences on lead intake were intentionally simplified, the results and insights apply to a range of hazardous work conditions. The development and validation of the CONLIS model represents an important result of this research. It was demonstrated that CONLIS accurately predicts absorbed doses for two difference bridge projects and long-term blood lead levels within the bounds of baseline and full compliance levels projected by OSHA for this workforce.

Unlike models that assume a constant air concentration value, this dynamic model is especially suited for variable exposure conditions. To my knowledge, the research presented here represents the first time this technique has been applied to an exposure control intervention in an occupational setting.

CONLIS represents an approach that could have a broad range of potential applications for managing other occupational exposure-control systems. Because of the potential benefits of avoiding hazardous working conditions, ineffective control techniques and costly delays, investigations into other applications may be worthwhile.

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MATERIALS AVAILABLE FOR OTHER INVESTIGATORS

Data – STATA databases containing bridge project and air concentration data and worker information available from Kathleen Vork kvork@aol.com upon request.

Software - MATLAB programs containing CONLIS front and back end modules and programs for creating anticipated and absorbed dose estimates available from Kathleen Vork kvork@aol.com upon request.

TYPES OF CONTAINMENT SYSTEMS

Taken from Appleman 1997

Bridge-to-grade
Bridge-to-grade containment is commonly erected on bridges that are relatively close to grade. It is composed of tarpaulins draped vertically from the bridge structure or from tight horizontal cables spanning piers. The floor is covered with tarpaulins to contain the waste debris and accommodate collection and cleanup.

Suspended tarpaulins
Suspended tarpaulins are used for projects that generate relatively low volumes of debris. Basically, tarpaulins are draped from taut horizontal cables spanning piers. Work is performed from suspended scaffolds and debris is removed manually with periodic vacuuming or automatically through funnel shaped tarpaulin hoppers.

Ridged suspended platforms
Ridged suspended platforms are lightweight assemblies covered by plywood or grated work deck. They are suspended beneath a bridge structure and often used on large, elevated structures. A mechanical or pneumatic waste collection system can be added to reduce the amount of manual vacuuming and cleanup work. A gravity system of flexible hoses may also be used to discharge the waste debris to containers on a barge on grade beneath the structure.

Outrigger and cable
Outrigger and cable consists of a tarpaulin enclosure affixed to a flexible cable support system and is supported by outriggers bolted along the length and width of the structure.

They may also be installed as an independent system or used with a suspended platform assembly. These types of containment structure are used commonly on through-truss and deck-truss bridges.

Enclosed staging
Enclosed staging containment systems are also used on through-truss and deck-truss bridges. It includes a tarpaulin enclosure supported by tubular staging on the bridge structure or grade. It may also be installed as an independent system or used with a suspended platform assembly. A large main containment with divider walls is often used to maintain minimum recommended airflow velocities and reduce air concentrations of contaminants.

Mini enclosure
Mini enclosure or micro-containment is a small cross-sectional area in the direction of airflow. The entire system can be 1.2 m (4 ft) wide by 2.4 m (8 ft) high by 3.6 m (12 ft) long. This containment is ideal for intermittent blasting (spot blasting) on isolated areas. Waste debris is removed manually by vacuuming or automatically with flexible discharge hoses to collection hoppers on grade.

Side and partial containment structures
For projects that involve only partial removal of surface coatings, impermeable ground covers placed under the bridge or side containment structures are used to catch solid particles and keep the dust from dispersing outside the work area. Side containment structures can be suspended from handrails or outriggers as described above for full containment.

SSPC Containment classification system

SSPC Class 5 systems are used for ironwork activities. This is usually a ground tarp.
SSPC Class 4 systems are standard loose fitting tarpaulin walls and floor.
SSPC Class 1 – 3 systems are mechanically ventilated and tightly sealed and are meant to protect more sensitive areas in the near vicinity of the construction work.

DEFINITIONS

Lead exposure is defined as the mass of lead that is available for inhalation or ingestion. Exposure is expressed as a concentration, mass or surface area loading per unit of time and involves action that results in taking lead into the body such as breathing, eating or smoking by a person.

Short-term intake is defined as the mass inhaled or ingested over approximately one to five months that is available for absorption into the blood.

Uptake is the mass of lead actually absorbed into the bloodstream.

Body burden is defined as the current mass of lead in all body tissues that has been previously absorbed into the blood from the lungs or gut.

The origin of lead-containing material is defined here as a "lead source". Examples of lead sources include work tasks, food, beverages and dust.

Control techniques are defined as actions or tools used to reduce exposure during a particular activity such as administrative practices and protective or monitoring devices, the use of a particular respirator equipped with a HEPA filter or restricting a worker to tasks not considered being significant sources of lead.

A control strategy is defined as an overall goal and set of objectives in which one or more control techniques can be deployed to achieve.

Restricted duty is defined as work in which air concentrations were not expected to exceed an 8-hr TWA of 30 $\mu g\ m^3$. Restricted duty was invoked among workers enrolled in the CRISP demonstration project when blood lead levels reached 50 $\mu g\ dl^{-1}$ in 1992, 40 $\mu g\ dl^{-1}$ in 1993 and 30 $\mu g\ dl^{-1}$ in 1995.