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POLLUTION PREVENTION AND WORKER TOXIC EXPOSURES:

A METHOD

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List of Abbreviations

AC	Air Conditioner
ACGIH	American Conference of Governmental Industrial Hygienists
ANOVA	Analysis of Variance
ATSDR	Agency for Toxic Substances and Disease Registry
CAS	Chemical Abstract Service
DataRAM™	data-logging real-time aerosol monitor
GAO	General Accounting Office
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
ESS	Exposure Severity Score
IARC	International Agency for Research on Cancer
MIE	Monitoring Instruments for the Environment, Inc.
NFIB	National Federation of Independent Businesses
NIOSH	National Institute for Occupational Safety & Health
NJDEP	New Jersey Department of Environmental Protection
NJ P2 Act	New Jersey Pollution Prevention Act
OPP	Office of Pollution Prevention
OTA	Office of Technical Assistance
P2	Pollution Prevention
PM	Particulate Matter
PPA	Pollution Prevention Act
REL	Recommended Exposure Limit

List of Abbreviations

(Continued)

RfC	Reference Concentration
SARA	Superfund Amendments and Reauthorization Act
SPE	Source Proximate Effect
SPZ	Source Proximate Zone
STEL	Short Term Exposure Limit
TCA	Trichloroethane
TCE	Trichloroethylene
TLV	Threshold Limit Value
TRI	Toxics Release Inventory
TUR	Toxics Use Reduction
TURA	Toxics Use Reduction Act
TWA	Time-weighted average
USEPA	United States Environmental Protection Agency
VCA	vegetable-based cleaning agents
VOC	Volatile Organic Compound

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Abstract

Environmental health policy in the United States is shifting from the paradigm of control to that of prevention. Under the control paradigm, harmful substances are dealt with only after their production or acquisition. In contrast, the prevention paradigm seeks to change the processes by which goods or services are produced in order to achieve the same product, while reducing the generation and use of environmentally harmful substances. Intuitively, it would seem that programs that are designed to reduce the use of toxic substances and the generation of waste are likely to reduce occupational exposure to toxic chemicals as well. However, pollution prevention (P2) is not always beneficial to workers. Worker exposure to trichloroethylene, a probable human carcinogen, has resulted from the elimination of trichloroethane, due to its ozone depleting properties. Unfortunately, there is a scarcity of scientific knowledge as to the conditions under which pollution prevention increases or reduces the severity of occupational exposures. The research presented here is an attempt to contribute to scientific knowledge in this area.

This study examined the impact on occupational exposures of a P2 program at an air conditioner and dehumidifier manufacturing facility (the study facility). The overall goal is:

To demonstrate the value of considering occupational exposures in the design, implementation, and evaluation of pollution prevention programs.

In pursuit of the goal, there are two major objectives:

1. *To develop and validate a model that is capable of making use of the data available from the study facility to estimate past airborne concentrations of chemical contaminants.*
2. *To apply that model to investigate the impact of pollution prevention on occupational exposures at the study facility.*

In the first phase of the project, the airborne contaminant concentration model was validated by comparing model results to indoor measurements of particulate matter in the facility. The model is presented, followed by a brief description of the use of Monte Carlo simulation to deal with variability and uncertainty in model inputs. The method for measuring particulate matter is presented along with the number and location of measurements. This is followed by a description and tabulation of the model inputs. Modeled values for large compartments (> 39,000 m^3) differ from measured values by 25-60%. The results are worse for small compartments (< 5 m^3) indicating that the model is unreliable for these.

In the second phase of the project the model was used to evaluate the impact of pollution prevention on occupational exposures. The plant in this study eliminated a trichloroethylene (TCE) degreaser and undertook other process changes in order to be able to produce air conditioners and dehumidifiers without degreasing parts with TCE. The question that this study attempted to answer is 'What was the impact of the elimination of TCE on occupational exposures during the period 1994-1997?' In order to answer this question, interviews were conducted in which workers were asked where in the plant they worked and how much time during a shift they spent in each location. Concentrations of TCE, petroleum naphtha and mineral spirits were modeled. Due to uncertainty and variability of the input values, Monte Carlo simulation was used. In order to represent the effect of multiple exposures, exposure severity scores were for each job title, in each department, year and season studied. For a given job title, the exposure severity score is equal to the sum across exposures of TWA concentration divided by the exposure limit.

Results indicated that the worker population in the plant experienced an overall reduction in exposure severity. A small subset of workers experienced statistically significant increases in exposure severity. They had very low TCE exposures before the degreaser was eliminated and experienced increased naphtha exposure afterward. The increase in naphtha exposure was due to the use of a more volatile metal press lubricant so that parts would arrive at the assembly line relatively free of lubricant even though they were not degreased.

These findings suggest that other plants may be able to reduce occupational exposures while implementing P2 programs to reduce environmental releases. In addition, they indicate that modifications designed to accommodate production processes to pollution prevention can increase the exposure of some workers. Plant personnel whoa are responsible for designing and implementing pollution prevention would be well-advised to look for both potential occupational exposure reductions and potential new workplace hazards when projects are still in the planning stage. Policy makers should design and implement pollution prevention policies with explicit incentives for incorporating occupational health at the planning stage. The New Jersey Pollution Prevention Act touts the benefits of pollution prevention for occupational as well as environmental health. If the New Jersey Legislature wishes to transform its expressed concern about occupational health into action, it could amend the Pollution Prevention Act explicitly to require that pollution prevention plans include an evaluation of occupational hazards and that facility-wide permits issued under the Pollution Prevention Act be reviewed by qualified occupational health professionals.

In order to continue to build a base of scientific knowledge as to the impact of pollution prevention on occupational health, the model validated here should be used to estimate the impact on occupational exposures of pollution prevention programs in other industrial facilities. In addition, there is a need for policy research. The provisions of each state pollution prevention statute should be summarized in one place and for each of them, opportunities to incorporate occupational exposure considerations should be identified.

Significant Findings

A model that makes use of data available from the study facility to estimate past airborne concentrations of chemical contaminants was validated by using it to predict particulate concentrations in various parts of the plant and comparing those predictions to measurements of particulate matter. The validation found that,

1. for compartments larger than 39,000 m^3, the model predicted the observed concentration reasonably well, with error rates of 60% or less, and
2. for compartments greater than 39,000 m^3 that contained particulate sources, the error was no greater than 29.5%.
3. The model overpredicted particulate concentration in only one compartment greater than 39,000 m^3. In that compartment, the model's prediction was precisely equal to the input value used for particulate matter in the ambient air outside the plant. Ambient outdoor concentrations of contaminants modeled to evaluate the pollution prevention program are negligible. This means that the model's estimated concentration of contaminants of concern for evaluating the P2 program are not likely to be overestimates.

4. The predictive value of the concentration model was severely limited for compartments less than 5 m^3. However, in the P2 evaluation, the smallest compartment used was more than 300 times that size. While it is an important finding that the model is of limited utility for small compartments, this finding is not surprising and has few implications for the evaluation of the impact of the plant's P2 program on occupational exposures.

Once validated, the model was used to evaluate the impact of the plant's pollution prevention program on occupational exposures. The primary finding of this evaluation indicates that

5. workers benefited from the elimination of TCE, even though occupational health was not the primary reason for which TCE was eliminated.

A secondary finding was that

6. a subset of workers experienced moderately increased exposure severity, due to a substitution made to accommodate the impact of P2 on the manufacturing process.

Usefulness of Findings

The research presented here validated a model, which can be used to estimate historical contaminant concentrations in industrial facilities. This will allow other researchers to use the model to estimate the impact on occupational exposures of pollution prevention programs in other industrial facilities. In addition, this research is the first to offer a pre-post analysis of the impact on occupational exposures of a P2 program based on irreversible (as opposed to experimental) manufacturing process changes. The findings suggest that other plants may be able to reduce occupational exposures while implementing P2 programs to reduce environmental releases. In addition, they indicate that modifications designed to accommodate production processes to pollution prevention (e.g. increased volatility of metal press lubricants) can increase the exposure of some workers. Plant personnel who are responsible for designing and implementing pollution prevention would be well-advised to look for both potential occupational exposure reductions and potential new workplace hazards when projects are still in the planning stage. Policy makers should design and implement pollution prevention policies with explicit incentives for incorporating occupational health at the planning stage.

Scientific Report

Chapter 1

Introduction

A Neglected Question: The Impact of Pollution Prevention on Occupational Exposure

Environmental health policy in the United States is shifting from the paradigm of control to that of prevention. Under the control paradigm, harmful substances are dealt with only after their production or acquisition. In contrast, the prevention paradigm seeks to change the processes by which goods or services are produced in order to achieve the same product, while reducing the generation and use of environmentally harmful substances. In 1989, Massachusetts and Oregon became two of the first states to pass laws implementing the prevention paradigm. In each state a toxics use reduction (TUR) act was passed. TUR focuses on reducing the generation of waste by reducing toxic chemicals used in the production process (Geiser, Kenneth, 1995). By the following year, ten states and the federal government had passed pollution prevention (P2) or waste minimization statutes. The Federal Pollution Prevention Act of 1990 (PPA) established the reduction or prevention of pollution "wherever feasible" as a national goal, but gave the U.S. Environmental Protection Agency no new authority in relation to the private sector. By 1994, twenty-nine states had passed such statutes (Burnett, Miles L., 1998).

Intuitively, it would seem that programs that are designed to reduce the use of toxic substances and the generation of waste are likely to reduce occupational exposure to toxic chemicals as well. For example, some dry cleaning facilities have adopted a new process called "wet cleaning" which replaces the carcinogen perchloroethylene ("perc") with water under high pressure, thereby avoiding both environmental release and occupational exposure to perc (USEPA, 1995). However, pollution prevention is not always beneficial to workers. Mirza *et al.* (2000) documented worker exposure to trichloroethylene, as evidenced by eye irritation and dry skin, resulting from the elimination of trichloroethane, due to its ozone depleting properties.

Unfortunately, there is a scarcity of scientific knowledge as to the conditions under which pollution prevention increases or reduces occupational exposures. It is important to develop a base of scientific knowledge on the impact of pollution prevention on occupational exposure in order to provide decision-makers with a sound basis for action. In the private sector, this would facilitate the selection in a variety of occupational settings of programs that benefit both workers and the environment. In the public sector, policy makers could design regulations and incentives aimed at steering firms toward forms of pollution prevention that reduce both environmental and occupational exposures. Similarly, understanding of the circumstances under which pollution prevention has exacerbated toxic occupational exposures would make it possible to design policies that discourage those forms of pollution prevention that merely shift risk to workers. The research presented here is an attempt to contribute to scientific knowledge in this area.

Study Goal and Objectives

The overall goal of this study is:

> *To demonstrate the value of considering occupational exposures in the design, implementation, and evaluation of pollution prevention programs.*

To achieve this goal, the impact of pollution prevention on occupational exposures at an industrial facility was examined. Finding an unintentional occupational benefit would suggest that additional opportunities for preventing worker exposure could be found and exploited if occupational considerations are fully integrated into pollution prevention programs. Alternatively, a finding that worker exposures increased as a result of the P2 program could serve as a cautionary example demonstrating that if occupational exposures are not explicitly considered in planning P2, the result could be risk shifting, rather than overall benefit.

In pursuit of the goal, there were two major objectives:

1. *To develop and validate a model that is capable of making use of the data available from the study facility to estimate airborne concentrations of chemical contaminants before and after the implementation of a P2 program.*
2. *To apply that model to investigate the impact of pollution prevention on occupational exposures at the study facility.*

This chapter presents a brief introduction and overview of the research project. In Chapter 2, federal and state pollution prevention legislation is presented and published works that address the impact of P2 on occupational exposure are examined. In addition, Chapter 2 reviews literature related to the theoretical development of the model validated in the first phase and applied in the second phase. Finally, it discusses literature related to weighting chemical exposures by toxicity. This last is necessary for the purpose of comparing cumulative exposures before and after pollution prevention.

Chapter 3 presents the validation of the of the airborne contaminant concentration model. The validation method is to compare model results to indoor measurements of particulate matter (PM) in the facility. The model is presented, followed by a brief description of the use of Monte Carlo analysis to deal with variability and uncertainty in model inputs. The facility to be modeled is described as is the method for measuring particulate matter. This is followed by a description and tabulation of the model inputs. Results are presented and their implications are discussed.

Chapter 4 presents the application of the model to investigate the impact of pollution prevention on occupational exposures. As with the model validation, Monte Carlo analysis was used to deal with variability and uncertainty in model inputs. In order to weight exposure by toxicity, exposure severity scores were calculated for each job title in each department for each year and season in the study. Analysis of variance (ANOVA) models were used to estimate the impact of the pollution prevention program on occupational exposure. Results are presented and their implications are discussed. Chapter 5 reviews the study goal and objectives. It examines the relationship of the findings to the study goal and objectives and discusses the policy implications of the findings as well as avenues for additional research.

Scientific Report

Chapter 2

Research Needs for Investigating the Impact of Pollution Prevention on Occupational Chemical Exposures

A Literature Review

Abstract

This review discusses literature relevant to researching the impact of pollution prevention (P2) on occupational exposures. It begins with a brief discussion of federal and state P2 statutes. This is followed by a discussion of literature that addresses the relationship of P2 to occupational health. Subsequently, literature addressing the models used in this research to estimate worker exposure are reviewed. Finally, we discuss literature dealing with the question of comparing exposures to different combinations of chemicals. Such comparisons are necessary in order to evaluate the impact of pollution prevention on occupational exposure.

Introduction

Environmental policy in the United States is shifting from the paradigm of control to that of prevention. Under the control paradigm, harmful substances are dealt with only after their production or acquisition. In contrast, the prevention paradigm seeks to change the processes by which goods or services are produced in order to achieve the same product, while reducing the generation and use of environmentally harmful substances. In 1989, Massachusetts and Oregon became two of the first states to pass laws implementing the prevention paradigm. In each state a toxics use reduction (TUR) act was passed. TUR focuses on reducing the generation of waste by reducing toxic chemicals used in the production process (Geiser, 1995.). That same year, the New Jersey Department of Environmental Protection (NJDEP) established an Office of Pollution Prevention (OPP) whose charge was to assist industries in comprehensively evaluating manufacturing processes to identify opportunities for reducing the use of hazardous materials (Schuler, Susan W., 1992). By the following year, ten states and the federal government had passed pollution prevention (P2) or waste minimization statutes.

The Federal Pollution Prevention Act of 1990 (PPA) defined source reduction, the preferred form of P2 as

> "Any practice which reduces the amount of any hazardous substance, pollutant , or contaminant, entering any waste stream or otherwise released into the environment (including fugitive emissions) prior to recycling, treatment or disposal; and reduces the hazards to public health and the environment associated with the releases of such substances, pollutants or contaminants (PPA cited in Burnett, 1998)."

The Act established the reduction or prevention of pollution "wherever feasible" as a national goal. It authorized EPA to develop a standard method of measuring source reduction and to promote P2 policies in other federal agencies and state governments as well as within the agency. However, the Act gave the agency no new authority in relation to the private sector. It contained no substantive standards and none of the compliance or action forcing mechanisms included in previous environmental legislation (Burnett, 1998). The use of the phrase "wherever feasible" in combination with the lack of enforcement authority means that, as legislation, the act was little more than a pious wish. In 1991, New Jersey passed a Pollution Prevention Act (NJ P2 Act) as did Arizona, Connecticut, Florida, Iowa and Texas. By 1994, twenty-nine states had passed such statutes (Burnett, 1998).

Intuitively, it would seem that reducing the use of toxic substances and the generation of waste would be likely to reduce occupational exposure to toxic chemicals as well. The purpose of the research presented here is to develop and apply a method for estimating the impact of pollution prevention on occupational exposures so as to provide evidence that would support or cast doubt on this intuitive conjecture. In this review, literature that deals with the impact of pollution prevention on worker exposure is presented and evaluated in order to identify research needs in this area. Subsequently, literature addressing the models used in this research to estimate worker exposure are reviewed. Finally, we discuss literature dealing with the question of comparing exposures to different combinations of chemicals. Such comparisons are necessary in order to evaluate the impact of pollution prevention on occupational exposure.

Literature that Addresses the Impact of Pollution Prevention on Occupational Exposure

There is anecdotal evidence that pollution prevention has lessened the severity of occupational exposure. For example, some dry cleaning facilities have adopted a new process called "wet cleaning" which replaces the carcinogen perchloroethylene ("perc") with water under high pressure, thereby avoiding both environmental release and occupational exposure to perc (USEPA, 1995). However, pollution prevention is not always beneficial to workers. Mirza *et al.* (2000) identified a case in which internationally mandated pollution prevention, designed to protect the environment may have exposed workers to a more toxic substitute. In 1996, the Montreal Protocol banned the ozone-depleting chemical 1,1,1-Trichloroethane (TCA), which had been used as a spot remover in the textile industry. As a result, some textile companies switched to trichloroethylene (TCE), which is classified by the International Agency for Research on Cancer (IARC) as probably carcinogenic to humans.

In addition, according to the *Toxicological Profile for Trichloroethylene*, published by the Agency for Toxic Substances and Disease Registry (ATSDR, 1997), TCE causes depression of the central nervous system and irritation of the skin, eyes and respiratory tract. The same source indicates that chronic TCE exposure has been associated with liver damage. Mirza *et al.* were asked by a Quebecois woolen manufacturing company to identify a substitute for TCE after workers engaged in spot removing complained of eye irritation and dry skin. Unfortunately, the authors were unable to find a suitable substitute, in part because the manufacturer indicated that any substitute that would require an investment in process changes was unacceptable.

Ochsner (2001) interviewed 33 individuals responsible for pollution prevention activities at industrial facilities in New Jersey, Illinois, and Texas. She found frequent mention of occupational health and safety as an incentive for undertaking P2 and as a benefit of P2. Unfortunately, further questioning appeared to undermine that claim. Only two interviewees identified occupational health and safety as a reason for undertaking their 'largest or most important' projects. One environmental manager indicated that he had a sign on his desk stating 'I.H. I ain't.[1]' In addition, Ochsner states, "Participation [in pollution prevention] by industrial hygienists also appears to be very limited." Ochsner's research did not include an attempt to evaluate the intentional or unintentional impact of P2 on occupational exposures at any of these facilities.

Roelofs *et al.* (2000) perceived the Massachusetts Toxics Use Reduction Act (TURA) as an opportunity for enhanced prevention of occupational injuries and illnesses. They sought to learn the extent to which companies had taken advantage of that opportunity. To that end, they asked two questions:

- To what extent have companies and technical assistance providers consciously integrated worker safety and health into their TUR activities?
- In what ways have TUR activities had an impact on the work environment?

The authors argued that measuring the impact in terms of lives saved or injuries prevented is not possible at this time. For this reason they chose to "scrutinize descriptions of TUR projects to discover probable reductions in exposure to toxics..." or new problems created while solving old ones.

To do this, Roelofs *et al.* reviewed studies, written by the governor's Office of Technical Assistance (OTA) for TUR, that discussed technical and financial aspects of TUR projects undertaken in 35 Massachusetts companies between 1989 and 1997. After reviewing the studies, they interviewed 5 OTA employees. In addition, the authors investigated three of the 35 projects by visiting the sites where they were undertaken and conducting interviews with key company personnel. The reviews, interviews and investigations found what the authors describe as potential safety and health benefits of TUR projects and also potential new hazards. Most of the benefits listed by the authors involved the removal of chemical hazards such as solvents. The potential new hazards included physical hazards, such as pressurized gas and explosion risk. They also included unknown hazards of chemical substitutes about which little research has been done. Roelofs *et al.* reported that in 17 of 35 cases, improved worker safety and health was mentioned as a benefit of the project. In nine of these, it was mentioned as a motive for undertaking the project. However, according to the authors, interviews with OTA staff indicated that compliance with environmental regulations, rather than worker safety and health, was the primary motivation for most companies. In discussing their results, Roelofs *et al.* stated that the lack of deliberate attention to occupational safety and health means that there is a potential for missed opportunities for worker exposure benefits or

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[1] I.H. stands for industrial hygienist.

for risk shifting to workers.

Roelofs *et al.* have done well in showing us what is on the minds of government and corporate employees who work for TUR and what is, too often, not on their minds, namely occupational safety and health. In addition, they may have paved the way for hypothesis testing research. Each facility in which they identified a potential benefit, a potential new hazard, or both, might also be a locus for research that would scientifically establish whether or not the potential benefits and hazards were realized. Such research would quantitatively estimate exposure to hazards before and after each TUR project. Although the authors are probably correct that it is not possible to measure lives saved or injuries prevented, methods of exposure estimation do exist and some of these can be applied retrospectively.

The identification of potential occupational impacts of TUR underscores the need for research that uses quantitative exposure estimates to investigate the degree to which hazards are present before and after the implementation of P2. As such research begins to produce a body of literature that documents cases in which P2 has reduced harmful worker exposures and those in which P2 has exacerbated such exposures, it will become increasingly possible to draw general lessons as to the conditions under which P2 can benefit workers and those under which it can harm workers. These lessons can be applied in the private sector to facilitate the selection, in a variety of occupational settings of P2 interventions that benefit both the environment and workers. They can steer investment away from P2 interventions that benefit the environment while shifting risk to workers. In the public sector, these lessons can be applied to aim regulations and incentives at steering firms toward forms of pollution prevention that reduce worker exposure and away from forms of pollution prevention that shift risk to workers.

One of the few studies that begins to build such a literature was conducted by Bartlett *et al.* (1999). It is a quantitative study of a pollution prevention intervention that gave explicit advance consideration to both occupational exposure and environmental impacts. The authors evaluated vegetable-based cleaning agents (VCA) as a possible substitute for organic solvents to clean presses in the lithographic printing industry. According to the authors, the search for substitutes was driven by several factors. These included the worker health impact of some solvents, the contributions of some to the formation of ground level ozone and the role played by some in the depletion of stratospheric ozone. They compared solvent use and VCA use at four print works. In three of these, the authors measured solvents in the workplace air. Airborne concentrations were significantly lower in two of the locations when (low-volatility) VCA was used than when organic solvents were used. One of the locations was a small print room where the use of solvents was associated with airborne concentrations of perchloroethylene that spiked as high as 1.2 times the short term exposure limit (STEL)[2] and concentrations of petroleum distillate spiked as high as 1.6 times the supplier's recommended STEL. When VCA was used in a print school, measurements of isopropyl alcohol were 92 % lower and measurements of petroleum distillate were 88% lower than when the organic solvent was used. The solvent exposure that remained during use of VCA was due to ink and format solution. The authors concluded that both the environmental and occupational hygiene benefits of substituting VCA for organic solvents are clear.

However, they expressed concern about the impact of this substitution of the risk of musculoskeletal disorders and slips, trips or falls. They stated that, due to their low volatility, VCAs remain on the floor if spilled, creating a slippery environment. In addition, if used in excessive quantities, VCA's could force workers to exert more force and repeat motions more often in press cleaning. Unfortunately, they provided no data on ergonomic hazards nor on slips, trips or falls associated with VCA's. The Bartlett study benefited from the fact that it was possible temporarily to substitute VCA for solvent without disrupting the rest of the printing process. As a result the authors were able to study organic solvents and VCA substitutes under substantially similar conditions.

In sum, not much research has been done on the impact of P2 on occupational exposure. Mirza et *al.* (2000) identified a case in which workers were exposed to a probable human carcinogen as a result of a P2 mandate, designed to protect the ozone layer. Ochsner (2001) and Roelofs *et al.*(2000) found that government and corporate personnel who are responsible for P2 pay lip service to occupational health, but they found little evidence that occupational health considerations play an important role in the design or implementation of P2 programs. In addition, Roelofs *et al.* identified, but did not collect data on potential occupational health benefits and potential new hazards associated with toxics use reduction programs. Only Bartlett *et al.* (1999) compared worker exposure measurements before and after P2, finding that P2 reduced occupational exposures. Bartlett *et al.* did so under conditions in which the intervention was entirely reversible. Because no equipment or process changes were necessary in order to

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[2] The authors do not indicate whether the STEL to which they refer was established by a governmental or non-governmental agency. However, since the study was undertaken in the United Kingdom, the authors may have used the 100 ppm STEL established by the British Health & Safety Executive(SKC Inc, 2002).

substitute VCA for organic solvents, it was relatively easy for the authors to measure worker exposure under initial conditions, and measure again after the substitution. It was equally easy for the print shops to return to the use of organic solvents after the authors left, should they have chosen to do so. Unlike the substitution of VCA in a print works, many pollution prevention programs require expensive investment in process changes. Such changes cannot be made temporarily for the purpose of research, nor can they be easily reversed if the impact on product quality, environmental release or occupational exposure is undesirable. In order to measure the impact of these more capital intensive P2 programs on occupational exposure, researchers must either collect data before the changes are made or model exposures retrospectively. In the research reported here, exposures were modeled retrospectively. The next section reviews literature that presents the exposure models used in this research.

Well-Mixed Compartment Models

In the present study, occupational exposures were modeled before and after P2. Model results from before and after were compared to determine the impact of P2 on occupational exposure, while controlling for seasonal effects and production levels. Before the model was used to estimate the impact of P2 on occupational exposure, it was validated by using it to predict contemporary particulate concentrations at the study facility. These results were compared with measurements taken at the facility. The model used in this study belongs to a category of models known as 'well-mixed' compartment models. In what follows, we show that it is possible to develop a well-mixed model with sufficient complexity, in theory, to capture vertical and horizontal variations in concentration within a facility and to implement such a model using a computer application developed by Zemba and Luis (1993).

The U.S. EPA well-mixed compartment model states that, during a time interval of interest, the concentration of a contaminant in a compartment of workroom air is equal to the mass of contaminant entering the compartment minus the contaminant mass leaving the compartment divided by the volume of the compartment. This assumes that the concentration at the beginning of the interval was zero. Mathematically, it is represented by the following differential equation (Jayjock, Michael A, 1988):

$$VdC = Gdt - QCdt \qquad \text{(I)}$$

where

V= compartment volume

C = mass/unit volume

G = contaminant generation rate

Q = ventilation rate

(mixing volume of air/unit time) Jayjock states that the model assumes perfect and instantaneous mixing of all the air in the compartment with the incoming air, which does not exist in the real world. To account for imperfect mixing, Q' is used as follows:

$$Q' = Qp \qquad \text{(II)}$$

where

Q' = effective ventilation (air volume/ unit time) into and out of the compartment

p = dimensionless mixing factor ($0 \le p \le 1$)

At equilibrium, ($dC/dt = 0$; G, Q, and p all constant), equations I and II can be combined and simplified to

$$C_{eq} = G/(Qp) \qquad \text{(III)}$$

According to Jayjock, equation III is independent of volume, but the amount of time it takes to reach equilibrium increases with volume. Equation III can be used to estimate the equilibrium concentration of a contaminant in any compartment of workroom air if the general ventilation rate and the source rate are known.

Nicas (1996) showed that the use of a model with only one well-mixed compartment may underestimate exposure. He posited a room in which contaminant is released at or near the floor and the ventilation intakes and outtakes are at or near the ceiling. Then he compared a model in which air was exchanged between an upper compartment and a lower compartment, where the worker's breathing zone was located, to a model that used one compartment for the whole room. The predicted concentrations in the worker's breathing zone were 40% greater in the two compartment model than in the one compartment model, suggesting that the latter often underestimates worker exposures.

Zemba and Luis (1993) developed a computer application, called "modeling elements," which permit the user to divide the modeled space into as many compartments as are appropriate for the space modeled. The modeling elements use the following equation for contaminant concentrations within a single well-mixed compartment:

$$d(cV)/dt = E - \alpha c + (Q_{in})(c^{*}) \qquad \text{(IV)}$$

where c is the contaminant concentration in the user-defined compartment

V is the volume of the user-defined compartment

t is the time

E is the contaminant emission rate within the compartment

α is the rate of chemical loss from the compartment [3]

Q_{in} is the rate of air transfer into the compartment from external sources

c^* is the average chemical concentration in external sources weighted by rates of volume flow

Equation IV is similar to equation I, but equation IV accounts for the possibility that air concentration could be diminished by deposition or chemical reaction in addition to ventilation. Equation IV accounts, as well, for the possibility that the modeled contaminant could enter a compartment from an adjacent compartment or from the outdoors. Equation I can be viewed as a special case of equation IV in which k_{bulk}, k_{surf}, and c^* are set to zero (see footnote 2 above).

In order to allow for modeling of multiple boxes, the authors modified equation IV as follows:

$$d(c_jV_j)/dt = E_j - \sum_{\substack{i=1\\ i\neq j}}^{n} Q_{i\leftarrow j}\, c_j + \sum_{\substack{i=1\\ i\neq j}}^{n} Q_{i\rightarrow j}\, c_i \qquad \text{(V)}$$

where c_j is the contaminant concentration in compartment j

V_j is the volume of compartment j

E_j is the emission rate from a source into compartment j

n is the number of compartments that exchange air with compartment j

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[3] For Zemba and Luis $\alpha = Q_{out} + k_{bulk}\, V + k_{surf}\, A$

where Q_{out} is the rate at which air exits the compartment

k_{bulk} is the rate of chemical reaction within the compartment

k_{surf} is the rate of surface reaction or contaminant deposition within the compartment

i is the subscript that refers to one of the n compartments that border compartment j

$Q_{i \rightarrow j}$ is the rate at which air passes from compartment i to compartment j (where compartment i can be either a virtual compartment within the modeled space or an external source)

c_i is the contaminant concentration in compartment i

$Q_{i \leftarrow j}$ is the rate at which air passes from compartment j to compartment i (where compartment i can be either a virtual compartment within the modeled space or an external sink)

In Nicas's model, the zone occupied by the worker comprises the entire lower portion of the space under consideration. However, in many cases, including the facility in this study, it is necessary to identify horizontal as well as vertical differences in concentration. This is because exposure varies inversely with horizontal distance from a source. Cherrie (1999) presented evidence for this intuitive proposition by compiling which showed that, for several contaminants, workers in close proximity to a source were more highly exposed than those further away. This difference can be simulated by drawing a virtual compartment to include a contaminant source and the workers close to that source.

The "source proximate effect" (SPE) model of Furtaw *et al.* (1996) does exactly this. In the SPE model, a space is described by exactly two compartments, one inside the other. The inner compartment is called the "source proximate zone" (SPZ) and is chosen to represent a small virtual area around the source of a contaminant, which is believed to be the area of greatest concentration. Furtaw *et al.* present the following equation for the contaminant concentration of the SPZ:

$$V_s\,(dC_s/dt) = S + (C_r\,Q_s) - (C_s\,Q_s) \qquad \text{(VI)}$$

and this for the remainder of the space:

$$V_r\,(dC_r/dt) = (C_i\,Q_r) + C_s\,Q_s - C_r\,(Q_r + Q_s) \qquad \text{(VII)}$$

where

V_s = volume of SPZ

V_r = volume of remainder of the space

C_s = contaminant concentration in SPZ

C_r = contaminant concentration in remainder of space

C_i = contaminant concentration in SPZ

S = pollution source emission rate into the outdoor air coming into the space

Q_s = air exchange rate between the SPZ and the remainder of the space

Q_r = air exchange rate between the remainder of the space and outdoors

t = time

If it can be shown that the SPE model represents a special case of equation 5 above, the Zemba and Luis modeling elements can then be used to implement the SPE model. Let us assign the subscript '1' to the SPZ, the subscript '2' to the remainder of the space and the subscript '3' to the outside air. It follows that

$$c_1 = C_s \qquad c_2 = C_r \qquad c_3 = C_i \qquad V_1 = V_s \qquad \text{and} \qquad V_2 = V_r$$

where c_i and V_i are defined as for equation V and C_i, V_s and V_r are defined as for equations VI and VII. Since the only contaminant source is in the SPZ,

$$E_1 = S \qquad \text{and} \qquad E_2 = 0$$

where E_j is defined as for equation V and S is defined as for equation VI. Because the

SPZ exchanges air only with the remainder of the space

$$Q_s = Q_{1\rightarrow 2} = Q_{1\leftarrow 2} \qquad \text{and} \qquad Q_r = Q_{2\rightarrow 3} = Q_{2\leftarrow 3}$$

where $Q_{i\rightarrow j}$ and $Q_{i\leftarrow j}$ are defined as for equation V and Q_s and Q_r are defined as for equations VI and VII. These equivalencies yield the following equation for the contaminant concentration of the SPZ:

$$V_1\,(dc_1/dt) = E_1 + (c_2\, Q_{1\leftarrow 2}) - (c_1\, Q_{1\rightarrow 2}) \qquad \text{(VIII)}$$

and this for the remainder of the space:

$$V_2\,(dc_2/dt) = (c_3\, Q_{2\leftarrow 3}) + c_1\, Q_{1\rightarrow 2} - c_2\,(Q_{2\rightarrow 3} + Q_{1\leftarrow 2}) \qquad \text{(IX)}$$

These two equations can be rendered together as follows:

$$d(c_j V_j)/dt = E_j - \sum_{\substack{i=1 \\ i\neq j}}^{3} Q_{i\leftarrow j}\, c_j + \sum_{\substack{i=1 \\ i\neq j}}^{3} Q_{i\rightarrow j}\, c_i \qquad \text{(X)}$$

which is clearly a special case of equation V in which n = 3. Hence the Zemba and Luis modeling elements can be used to implement the SPE model.

Using Toxicity Weights to Compare Exposures that Vary by Time, Location and Job

In the research presented here, it will be seen that workers in different jobs were exposed to different combinations of the chemicals in the plant and that workers in any given job were exposed to different combinations of chemicals before and after pollution prevention. In order to evaluate the overall impact of pollution prevention on occupational exposure, it is necessary to have some means of saying that exposure to one combination of chemicals is better or worse than exposure to another combination. In this study, the concept of 'exposure severity' is used to make such comparisons.

‘Exposure severity’ is not intended to measure cumulative risk. It is intended only to capture the following intuitive propositions:

(1) Overall exposure becomes worse if exposure to one potentially toxic agent is increased or exposure to a new potentially toxic agent is introduced while exposure to all other agents remains unchanged.

(2) Overall exposure becomes better if exposure to one potentially toxic agent is reduced or eliminated while exposure to all other agents remains unchanged.

For the purpose of this research, it was decided to use the time weighted average exposure divided by the NIOSH recommended exposure limit (REL) as an index of exposure severity. For chemicals that do not have RELs, threshold limit values (TLVs), designated by the American Conference of Governmental Industrial Hygienists (ACGIH) are used. Exposure severity is calculated by the following formula:

$$S_i = \sum_{j=1}^{n} \frac{E_{ij}}{OEL_j} \qquad \text{(XI)}$$

where S_i is the exposure severity score for occupational title i, E_{ij} is the TWA exposure of workers in occupational title i to chemical j, and OEL_j is the occupational exposure limit for chemical j, either a REL or a TLV.

Equation X is similar to the method recommended by the ACGIH (2001) to determine whether exposure to a mixture has exceeded the occupational for that mixture. If the sum

$$(C_1/TLV_1) + (C_2/TLV_2) + \ldots + (C_n/TLV_n)\ ^{\spadesuit} \qquad \text{(XII)}$$

♠ Where C_1 to C_n are airborne concentrations of compounds 1 to n and TLV_1 to TLV_n are the TLVs of compounds 1 to n exceeds unity, the TLV of the mixture is exceeded. The AGGIH states and some toxicologists (Wilkinson, Chris F. et al., 2001) have argued that the dose additivity of this formula is appropriate only when the chemicals involved share a common mechanism of toxicity. This argument makes sense in the context of quantitative risk estimation because there may not be a meaningful way to aggregate an exposure to a liver toxicant with an exposure to a respiratory toxicant to produce a single quantitative estimate of risk. However, if the goal is not to estimate risk, but simply to provide an index of severity of exposure, the argument is less powerful. It is not counterintuitive to state that exposure to moderately neurotoxic substance *and* to a potent liver toxicant is more severe than exposure to either one of these alone.

Whaley *et al.* (1999) incorporated an occupational term into a hazard score designed to measure the effectiveness of pollution prevention efforts. For the toxicity component of this term, they used a formula similar to the one above and they aggregated across mechanisms of toxicity as well as target organs and tissues. In calculating the total hazard score, they aggregated across species and ecosystems as well. Their purpose was not to predict the level of risk that any specific ecosystem, or any population of any given species was subject to before or after pollution prevention. Rather they wished to estimate the overall net impact of P2 interventions. Applying their scoring system to interventions in 16 processes and on entire facility (Whaley, David A. & Barrett, Shayla S., 2000), they found that pollution prevention efforts had produced net benefits in 15 of 17 cases. Unfortunately for our purposes, they did not report disaggregated scores that would have separated out the occupational impact. Following Whaley, the study presented here aggregates exposure severity across different kinds of toxic effects, while recognizing that exposure severity is not a numerical index of any particular risk.

Discussion

Our review has briefly presented the increasing importance of pollution prevention to U.S. environmental policy. We have discussed a case in which the elimination of TCA, due to its ozone depleting properties, resulted in worker exposure to TCE, as evidenced by eye irritation and dry skin (Mirza, Touseef, Gerin, Michel, Begin, Denis, & Drolet, Daniel, 2000). We have seen that both Ochsner and Roelofs *et al.* found that occupational health is not prominent in the thinking of those who implement pollution prevention in New Jersey, Texas, Illinois and Massachusetts. The latter authors identified a number of potential hazards and benefits to workers associated with specific TUR programs.

Taking this research to the next step requires comparing quantitative estimates of exposure before and after P2. Bartlett *et al.* provide quantitative exposure comparisons for a case in which substitution could be undertaken temporarily for the purpose of study. In many cases, the required investment and changes to the physical plant are such that exposure data must either be collected before the implementation of P2 or modeled after the fact. In the present study, we do the latter using an application developed by Zemba and Luis (1993). Finally, in order to evaluate the impact of P2 on occupational exposure, the toxicity of different combinations of chemicals must be compared. In this study, an exposure severity score is used which sums exposure to each chemical divided by the REL. While such a procedure cannot be used a method for quantitatively estimating risk, we have chosen to follow Whaley *et al.* in using it as an index of exposure severity.

In this research, exposure modeling and evaluation of exposure severity are used to used to evaluate the impact on occupational exposure of a P2 program at an air conditioner manufacturer. It is hoped that the publication of this research will inspire others to undertake similar investigations, eventually leading to the development of a body of literature that identifies conditions under which P2 has reduced harmful worker exposures and those under which P2 has exacerbated them. This can lead those who work on P2 in both the public and private sectors to steer there efforts toward those interventions that benefit workers as well as the environment and away from those forms of P2 that can harm workers.

Scientific Report

Chapter 3

Validation of a Model for Estimating Contaminant Concentrations in Industrial Facilities

Abstract

This chapter presents a validation of a mathematical model that estimates indoor contaminant concentrations in an industrial facility. The validation method is to compare model results to indoor measurements of particulate matter (PM) in the facility. Because information about many of the input parameters in the model is incomplete and/or the phenomena they describe are inherently variable, Monte Carlo simulations were run to account for random error. For the purpose of modeling, the facility was divided into virtual compartments. Data were obtained for the following model inputs necessary to estimate particulate concentration in each compartment: compartment volumes, the concentration of particulate matter in outdoor air entering the facility, the rates of emission of particulate matter from sources within each compartment, and the rates at which air is exchanged between compartments and between each compartment and the outdoors. Predicted particulate concentrations for each compartment were compared to measured concentrations in each. Particulate sampling was conducted with a personal data-logging real-time aerosol monitor (personal DataRAM™) model pDR-1000AN manufactured by Monitoring Instruments for the Environment (MIE), Inc. Modeled values for large compartments (> 39,000 m^3) differ from measured values by 25-60%. The results are worse for small compartments (< 5 m^3) indicating that the model is unreliable for these. One potential reason for this is that the consequences of random deviations from model assumptions may be much greater over a small volume. Random deviations from the well-mixed assumption that are spread throughout a large volume compartment may cancel each other out, having little impact on the mean concentration. However, it may be that deviations which could be shown to be

randomly distributed over a population of small compartments, produce a systematic effect on each one of them.

Introduction

This chapter presents a validation of a mathematical model that estimates indoor contaminant concentrations in an industrial facility. Once validated, this model can provide researchers with a valuable tool for estimating historical occupational exposures when the data measuring such exposures are inadequate. In the next chapter, this model is used to the evaluate the impact of a pollution prevention program on occupational exposures. It is important to undertake such an evaluation because environmental policy is moving increasingly toward the paradigm of pollution prevention, but the impact of pollution prevention on occupational exposures has not been well studied.

Pollution prevention seeks to change the processes by which goods or services are produced in order to reduce the generation and use of environmentally harmful substances while producing goods and services of the same quality. Several statutes at the federal and state levels are designed to promote these goals. Among these are the Massachusetts Toxics Use Reduction Act of 1989, the federal Pollution Prevention Act of 1990 and the New Jersey Pollution Prevention Act of 1991. Each of these acts is designed to promote pollution prevention without mandating specific changes in industrial processes. Each has achieved some documented success(Helms, Susan C., Sullivan, Jennifer A., & White, Allen N., 2000; Massachusetts Toxics Use Reduction Program, 1996; Mazurek, Janice, Gottleib, Robert, & Roque, Julie, 1995).

Intuitively, it would seem that programs designed to reduce the use of toxic substances and the generation of waste are likely to reduce occupational exposure to toxic chemicals as well. For example, some dry cleaning facilities have adopted a new process called "wet cleaning" which replaces the carcinogen perchloroethylene ("perc") with water under high pressure, thereby avoiding both environmental release and occupational exposure to perc. However, pollution prevention is not always beneficial to workers. For example, 1,1,1-trichloroethane (TCA) was banned internationally in 1996, due to its ozone depleting potential. As a result, some textile manufacturers reintroduced trichloroethylene (TCE) as a spot remover. TCE is an acute central nervous system depressant, an irritant, a chronic liver toxicant, and it is classified by the International Agency for Research on Cancer (IARC) as a probable human carcinogen (Mirza, *et al,* 2000).

The scarcity of good historical occupational exposure data has received considerable attention in occupational epidemiology (Seixas, Noah S. & Checkoway, Harvey, 1995; Smith, Thomas J., Hammond, S. Katharine, Hallock, Marilyn, & Woskie, Susan R., 1991; Stewart, Patricia A. & Herrick, Robert F., 1991). As a result of the shortage, there are few published studies that examine the conditions under which pollution prevention increases or reduces the severity of occupational exposures. It is difficult to determine the impact of many pollution prevention programs on occupational exposure because adequate baseline exposure data are rarely available. The model presented here provides a method for estimating occupational exposures that can be used to evaluate the impact of pollution prevention on occupational exposures for cases in which industrial hygiene monitoring data are unavailable or inadequate.

Model to be Validated

In the preceding chapter, it was shown, through a review of the relevant literature, that the model implemented by Zemba and Luis (1993) in their 'modeling elements' is sufficiently complex to capture vertical and horizontal variations in contaminant concentration within a facility. The modeling elements can be used to model a facility either by placing compartments side by side or by placing compartments one inside another. The Zemba and Luis model is as follows:

$$d(c_j V_j)/dt = E_j - \sum_{\substack{i=1 \\ i \neq j}}^{n} Q_{i \leftarrow j}\, c_j + \sum_{\substack{i=1 \\ i \neq j}}^{n} Q_{i \rightarrow j}\, c_i \qquad \text{(I)}$$

where	c_j	is the contaminant concentration in compartment j
	V_j	is the volume of compartment j
	E_j	is the emission rate from a source into compartment j
	n	is the number of compartments that exchange air with compartment j
	i	is the subscript that refers to one of the n compartments that border compartment j
	$Q_{i \rightarrow j}$	is the rate at which air passes from compartment i to compartment j (where compartment i can be either a virtual compartment within the modeled space or an external source)
	c_i	is the contaminant concentration in compartment i
	$Q_{i \leftarrow j}$	is the rate at which air passes from compartment j to compartment i (where compartment i can be either a virtual compartment within the modeled space or an external sink)

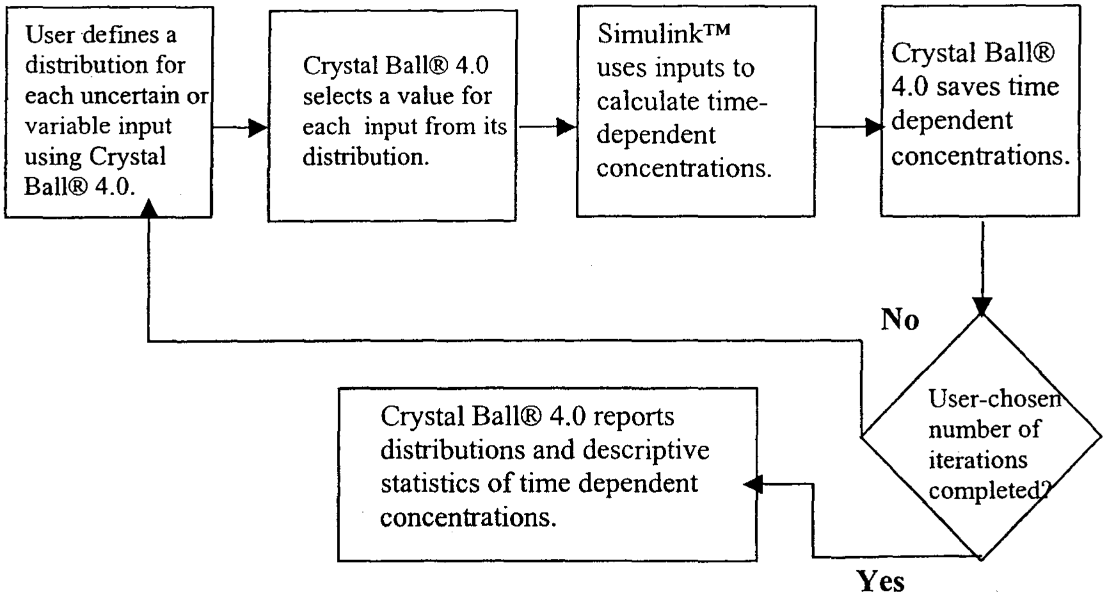
The modeling elements are a set of programming subroutines that allow a user to define all the parameters for Equation I and to calculate the time-dependent concentration in each compartment using the Simulink™ and MATLAB® software packages. A detailed description of the modeling elements and a brief description of Simulink™ and MATLAB® may be found in the Zemba and Luis publication cited above. For more complete descriptions of Simulink™ and MATLAB® see (The Mathworks, 2000a) and (The Mathworks, 2000b).

Variability and Uncertainty

Because information about many of the input parameters in Equation I are incomplete and/or the phenomena they describe are inherently variable, choosing a single value for each model input and running the model only once could produce results whose difference from the measured concentration in each compartment might be due to random error rather than model properties. To account for random error, Monte Carlo simulations were run using the Crystal Ball® 4.0 software (Decisioneering, 2000), an Excel© macro. In a Monte Carlo simulation, a probability distribution is defined, based on the best available information, for each input that is characterized by uncertainty or inherent variability. Models are run multiple times. On each iteration of a model, one value is selected from the user-defined distribution. The selected values are used as inputs in a Simulink™ application to calculate the time-dependent concentrations of particulate matter for each compartment in a model. After each iteration, Crystal Ball® 4.0 saves the results and selects new values for the variable or uncertain inputs. The process is repeated until a user-specified number of iterations is reached. Upon completion, Crystal Ball® 4.0 presents the distributions and descriptive statistics for the time-dependent concentration of particulate matter in each compartment. Figure 3-1 is a flowchart that describes this process.

Figure 3-1:

Flowchart of Monte Carlo Analysis of Time-Dependent Particulate Matter Model

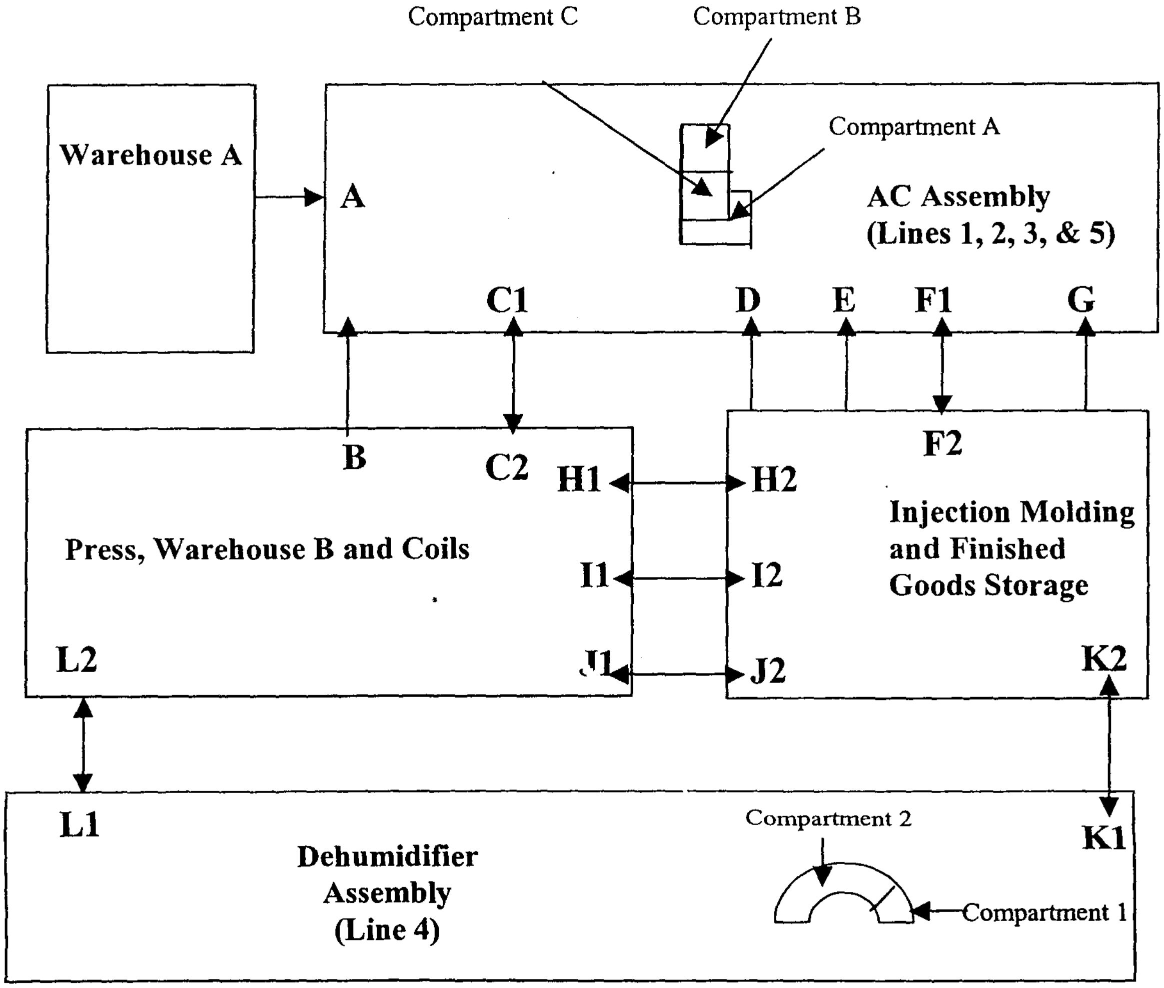


The method by which input values are selected is known as latin hypercube sampling. In this form of sampling, the probability distribution of a model input is divided into non-overlapping segments of equal probability and one value is selected from each segment. This means that, even for a small number of iterations, input values are well-distributed across the range of each model input (Decisioneering, 2000). For a small number of iterations, it is improbable that input values would be well-distributed across the range if the values were randomly selected from the entire distribution without first dividing it into segments. Because each iteration took a long time to run, it was not practical to perform a large number of iterations.

The Facility to be Modeled

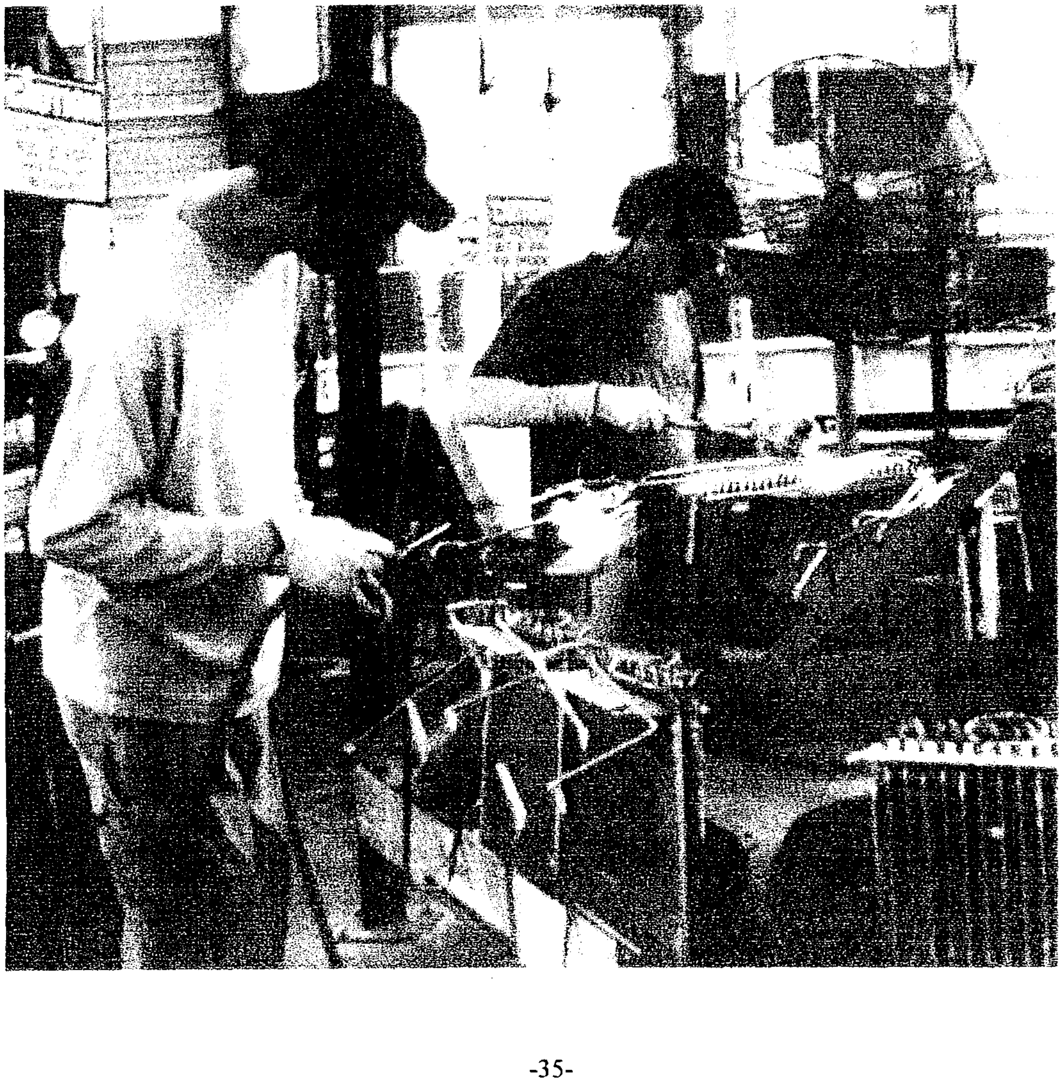
Figure 3-2 is a schematic representation of the facility to be modeled, an air conditioner (AC) and dehumidifier manufacturing plant. In this figure, the facility has been divided into five large compartments, based on observable separations, such as walls or inventory stacked almost to the ceiling. In addition, there are five smaller compartments. Two of them, Compartments 1 and 2, are within the compartment labeled 'Dehumidifier Assembly (Line 4).' Three of the smaller Compartments, A,B, and C are within the compartment labeled 'AC Assembly (Lines 1, 2, 3, & 5).' A compartment is a volume of space within the facility that is treated as well-mixed (i.e. uniform contaminant concentration) for the purpose of modeling. Connections, such as doorways, between large compartments are indicated by arrows showing the locations and directions of air exchange. The representation of a connection with an arrow in one direction only and labeled by a letter unaccompanied by a number indicates that all measurements of air velocity at the represented connection showed air blowing in the same direction. The representation of a connection by two arrows in opposite directions labeled by the same letter accompanied by different numbers indicates that measurements at the represented connection showed air sometimes blowing in one direction and sometimes in the opposite direction.

Figure 3-2: Schematic Representation of the Study Facility



Within Compartments 1 and 2 and within Compartments A, B and C, there are workers who operate brazing torches that are sources of particulate matter. Other workers who operate brazing torches are within the Dehumidifier Assembly and AC Assembly compartments. The purpose of the brazing operation is to seal the copper tubes of air conditioner or dehumidifier evaporators and condensers using a molten copper alloy. Figure 3-3 shows workers engaged in brazing. Within the Press, Warehouse B and Coils compartment there is a machine called a Selas brazer that performs a similar operation. It is also a source of particulate matter.

Figure 3-3: Workers Engaged in Brazing



The validation for Model 1 compares modeling results to measured particulate concentrations in warehouse A, AC assembly, injection molding / finished goods, dehumidifier assembly, Compartment 1 and Compartment 2. The four named compartments are over 39,000 m^3 in volume. The two numbered compartments are under 5 m^3. The validation of Model 2 was undertaken in order to provide additional information on the model's performance for compartments under 5 m^3. For this reason, no additional measurements were taken in any of the large compartments named in figure 3-2. Instead, measurements of particulate concentration in Compartments A & B were compared to model estimates of particulate concentration in those compartments. It was not possible to measure particulate concentration in Compartment C with interfering with work or threatening the safety of the workers or the researcher. As a result, no measurements were taken in Compartment C.

Model 1

Model 1 estimates particulate concentrations in the compartments labeled Warehouse A, AC Assembly, Press, Warehouse B and Coils, Injection Molding and Finished Goods Storage, Dehumidifier Assembly Compartment 1 and Compartment 2. Figure 3-4 is a cross-sectional depiction of Compartments 1 and 2. Compartment 1 is labeled (1) and Compartment 2 is labeled (2). In this figure, everything outside the perimeter of the unit formed by the two contiguous compartments is within the Dehumidifier Assembly compartment. The arrows labeled with letters indicate the direction of airflow. As indicated in the figure, air flows from Dehumidifier Assembly into one of the smaller compartments, from Compartment 1 to Compartment 2, or from one of the smaller compartments into dehumidifier assembly.

Figure 3-4: Cross-section of Compartments 1 & 2

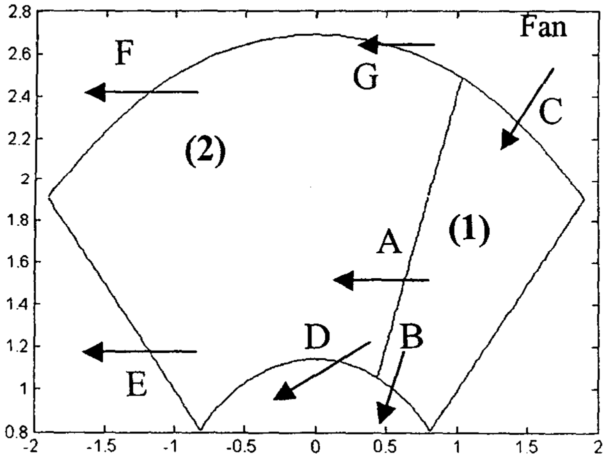
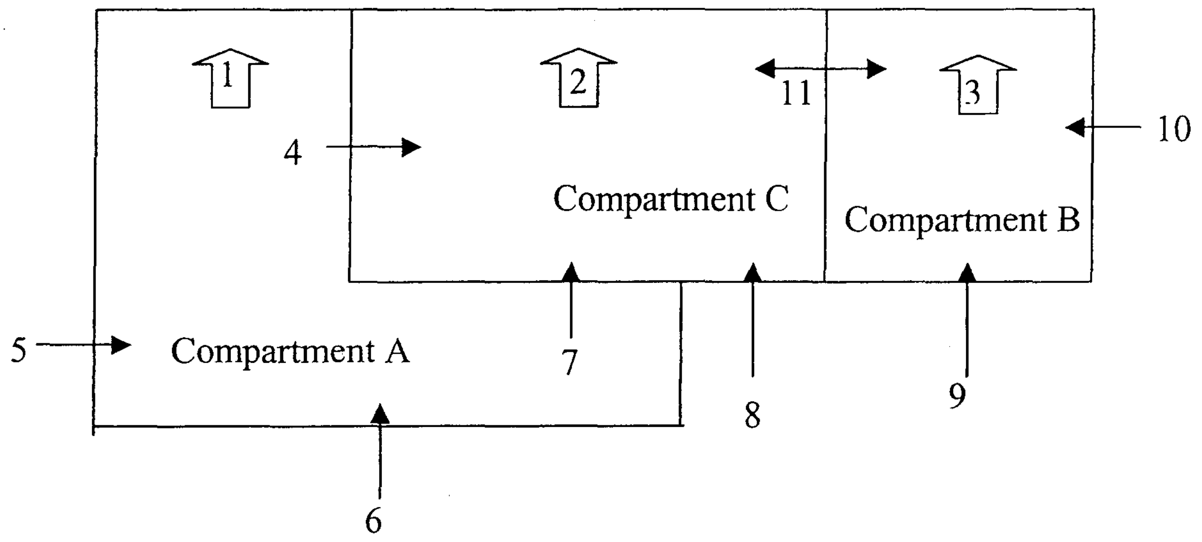


Figure 3-5: Cross-section of Compartments A, B & C



Model 2

Model 2 estimates particulates concentrations near a brazing station within the AC assembly compartment. The model uses three Compartments A, B and C, shown cross-sectionally in figure 3-5. In this figure, everything outside the perimeter of the unit formed by the three contiguous compartments is within the AC Assembly compartment. Thin arrows represent north-south or east-west air movement. Wide outlined arrows represent air movement up from each small compartment into the AC assembly compartment.

Monitoring

In order to validate these models, it was necessary to compare modeled results to particulate concentrations measured within the facility. To this end, sampling was conducted on 17, 18, 19 April and 14 May 2001. In this time, particulate matter concentrations were measured in warehouse A, AC assembly, injection molding / finished goods, dehumidifier assembly, Compartment 1, Compartment 2, Compartment A, and Compartment B. Due to physical constraints, it was impossible to conduct air monitoring in Compartment C. No air monitoring was conducted in the warehouse B / press / coil compartment. Table 3-I indicates the volume and number of measurements taken in each of the compartments sampled.

Table 3-I:
Volumes and Numbers of Samples per Compartment

Compartment (date of sampling)	**Volume (m^3)**	**# of measurements**
Warehouse A (April, 2001)	39,450	27
AC Assembly, Lines 1, 2, 3 & 5 (April, 2001)	153,752	31
Injection Molding / Finished Goods	97,225	23
Dehumidifier Assembly, Line 4 (April, 2001)	53,662	27
Compartment 1 (April, 2001)	1.63	5
Compartment 2 (April, 2001)	4.9	15
Compartment A (May, 2001)	2.04	11
Compartment B (May, 2001)	0.56	4

Particulate sampling was conducted with a personal data-logging real-time aerosol monitor (personal DataRAM™) model pDR-1000AN manufactured by Monitoring Instruments for the Environment (MIE), Inc. The device samples passively. DataRAM™ is a photometric monitor whose light scattering sensing configuration has been optimized for the measurement of the respirable fraction of airborne particulate matter. Its measurement range is (0.001 mg/m^3, 400 mg/m^3) and its particle size range of maximum response is (0.1 μm, 10 μm). This does not correspond precisely either to PM_{10} or to $PM_{2.5}$. For this reason, when it was necessary to account for particulate in air coming from outside the plant, it was unclear *a priori*, as to whether it was better to use an outdoor monitoring station's report of PM_{10} or $PM_{2.5}$.

Each day before sampling, the DataRAM was zeroed. This was done as follows. Dust was removed from the outside surface and the DataRAM was placed in a low-particle pouch that comes as a standard accessory. The pouch was sealed and air was pumped into it through a filter that prevented particle from entering. The DataRAM was turned on and a sequence of keys was pressed instructing it to zero itself. The DataRAM sampled air in the pouch for two minutes and then indicated 'CALIBRATION:OK.' If the DataRAM had ever indicated 'BACKGROUND HIGH' or 'MALFUNCTION,' the zeroing would have been redone. However, this never happened.

Outputs and Inputs

The model outputs of interest are the time-dependent particulate concentrations in each compartment. The inputs necessary to produce these outputs are:

- the volumes of each of the seven compartments (V_j in Equation I),
- the concentration of particulate matter in outdoor air entering the facility (one of the c_i's in Equation I),
- the rates of emission of particulate matter from sources within each compartment (E_j in Equation I),
- the rates at which air passes into a compartment from each adjacent compartment and from the outside ($Q_{i\rightarrow j}$ in Equation I), and
- the rates at which air passes out of each compartment to each adjacent compartment and to the outside ($Q_{i\leftarrow j}$ in Equation I).

Distributions (or constant values) of each of the inputs were determined by the following means:

Volume: The volumes of the five large compartments were calculated using facility plans, which report their dimensions. The dimensions of the small virtual compartments in each of the two models were chosen on the basis of a judgment that they represent well-mixed zones in close proximity to brazing torches, which are sources of particulate matter. Table 3-II indicates the volumes of the virtual compartments used in Model 1 and in Model 2.

Table 3-II: Compartment Volumes in Models 1 & 2

Compartment	Volume in Model 1 (m^3)	Volume in Model 2 (m^3)
AC Assembly	153752*	153748*
Dehumidifier Assembly	53662**	53675**
Compartment 1	1.63	N/A
Compartment 2	4.9	N/A
Compartment A	N/A	2.04
Compartment B	N/A	0.56
Compartment C	N/A	1.3
Warehouse B / Press / Coils	183702.17	183702.17
Volume of Warehouse A	39450	39450
Volume of injection molding/ finished goods	97225	97225

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[*] In Model 1, AC Assembly is modeled as one compartment. In Model 2, the source proximate zones, compartments A, B, & C, are cut out of AC Assembly reducing the volume.

[**] In Model 2, Dehumidifier Assembly is modeled as one compartment. In Model 1, the source proximate zones, compartments 1 & 2, are cut out of Dehumidifier Assembly reducing the volume.

Particulate concentration in outdoor air: The measurements taken in the plant to validate the Model 1 were made on 17, 18, and 19 April 2001 between 9:00 AM and 3:00 PM. In order to account for particulate matter entering the plant in air from outside, it was necessary to acquire data for outdoor particulate concentration that were collected as close possible to the dates and times at which the sampling in the plant was done. Data received from the Department of Environmental Protection (NJDEP, 2001), indicated that the particulate monitoring station closest to the study facility reported an average PM_{10} concentration for 19 April of 30.16 $\mu g/m^3$. NJDEP did not report an average PM_{10} concentration for 17 April or 18 April. However the Department did report hourly average $PM_{2.5}$ concentrations for 17, 18, and 19 April. Table 3-III indicates hourly average concentrations by date and time. Model 1 was run twice . The first time, particulate concentration in outdoor air was assigned a value of 30.16 $\mu g/m^3$ for all 36 iterations. The second time, one of the values indicated in table 3-III was selected at random on each iteration. The reason the model was run both ways is that, as indicated above, the instrument used to make the measurements that were compared to the modeling results is not designed precisely to measure either PM_{10} or

Table 3-III:
Hourly Running $PM_{2.5}$ ($\mu g/m^3$)Averages for Days and Times During which Sampling to Validate Model 1 Took Place

	17 April	**18 April**	**19 April**
9:00 AM	4	6	6
10:00 AM	5	5	6
11:00 AM	4	5	7
12:00 noon	5	5	6
1:00 PM	6	6	8
2:00 PM	7	6	9
3:00 PM	8	7	10

$PM_{2.5}$. It was, therefore, uncertain *a priori* which inputs to the model would better predict the measurements. For Model 2, four measurements of air outside the facility were taken with the DataRAM used to measure particulate matter inside the facility. The average of these four measurements, 7.4 $\mu g/m^3$, was used in Model 2 as the value of the particulate concentration in outdoor air.

Emission of particulate matter from sources within each compartment: Particulate matter from sources within the facility was accounted for in the models if a number of conditions were met. First, the source had to be operating at the time of the sampling. For example, the facility reports that the regrinding of bad plastic parts from the injection molding process is a source of particulate matter. However, particulate from this source was set to zero in the model because it was not operating at the time of sampling. The second condition required that the source not ventilate outside the facility through a completely closed system. For example, particulate emissions from the injection molding machines were not modeled because they are exhausted through a system that is entirely closed in order to prevent occupational styrene exposure. Thirdly, for a source to be modeled, it was necessary that the facility collect and/or report data for the source. For example, any contribution to particulate from trucks at loading docks was not included in the model because these emissions are not reported by the facility.

All the sources of particulate matter that met the above criteria were brazing operations. In addition to the hand-held brazing torches, depicted in figure 3-3, the facility has two large Selas brazing machines, used to attach short copper return bends to evaporator and condenser coils. The machines are located in the warehouse B / press / coils compartment. The hourly emission rate for particulate matter was calculated by plugging data from the plant's 1999 emissions report to the DEP[1] into to the following equation:

$$PM = (NGEF \times NG + PEF \times P + AEF \times A) / OH \qquad (II)$$

where PM = particulate matter emission rate (lbs./hr)

$NGEF$ = natural gas emissions factor = 13.7 lbs./million metric standard cubic feet

NG = quantity of natural gas consumed in year of report

PEF = propylene emissions factor = 4×10^{-3} lbs./gallon

P = quantity of propylene consumed in year of report

AEF = brazing alloy emissions factor = 5×10^{-3} lbs. PM/lb.

A = quantity of brazing alloy consumed in year of report

OH = total number of operating hours in year of report

According to engineering specifications, ninety-eight percent of particulate emissions are captured by the hood on the brazing machines. Hence, workers are potentially exposed to 2% of particulate emissions attributed by the plant to the brazing machines. For this reason, the emission rate for the brazing machines is calculated from the emissions report by multiplying the result of Equation II by 0.02.

In dehumidifier assembly and AC assembly, the sources of particulate matter are the individual brazing torches depicted in figure 3-3. For Model 1, emissions from all torches in AC assembly were treated in aggregate. For dehumidifier assembly it was necessary to estimate aggregate emissions for all torches except those in Compartments 1 and 2, which were treated separately. In Model 2, on the other hand, emissions from all torches in dehumidifier assembly were treated in aggregate, while in AC assembly, it

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[1] At the time this analysis was performed, the 1999 report was the most recent available report.

was necessary to estimate aggregate emissions for all torches except those in Compartments A, B & C, which were treated separately. Emission rates for torches were calculated from the same 1999 report used to calculate emission rates for the Selas brazing machines. The plant reports its emissions to the DEP in English system units. For this research, all computation was performed in metric system units. Table 3-IV indicates particulate emission rates used as inputs in Models 1 and 2. The rates were translated into metric system units after they were calculated from the 1999 emissions report.

Table 3-IV:
Particulate Emission Rates Used as Inputs in Models 1 & 2

Compartment / Emissions	Model 1 Value (mg/hour)	Model 2 Value (mg/hour)
Particulate emissions into Warehouse B / Press / Coils Compartment from methane combustion in Selas brazing machines	317	317
Particulate emissions into Warehouse B / Press / Coils Compartment from propylene combustion in Selas brazing machines	4.54	4.54
Particulate emissions into Warehouse B / Press / Coils Compartment from brazing alloy in Selas brazing machines	3075	3075
Particulate emissions into Injection Molding / Finished Goods Compartment from plastic grinders	0	0

Table 3-IV: Particulate Emission Rates Used as Inputs in Models 1 & 2		
Compartment / Emissions	**Model 1 Value (mg/hour)**	**Model 2 Value (mg/hour)**
Particulate emissions from sources within Warehouse A	0	0
Particulate emissions into AC assembly compartment from brazing torches	13200[†]	12060[†]
Particulate emissions into line 4 from brazing torches.	3710[‡]	5760[‡]
Emissions from brazing torches into box 1	515	N/A
Emission into box 2	1535	N/A
Emissions from brazing torch 1 into boxes A & C	N/A	570
Emissions from brazing torch 2 into Compartments B& C	N/A	570

The rates at which air passes into a compartment from each adjacent compartment: These rates are expressed in volume of air per unit time. They are calculated by measuring the velocity at which air passes from one compartment to the next and multiplying by the area through which the air passes. Air velocity was measured using an Alnor ® Compuflow ® Thermoanemometer, model 8525. The probe on the anemometer was pointed perpendicular to the direction of airflow. Direction of airflow was determined using Dräger air current tubes. The light-emitting diode (LED)

[†] Emissions for torches in compartments A, B, & C treated separately from the rest of AC assembly in Model 2.
[‡] Emissions for torches in compartments 1 & 2 treated separately from the rest of Dehumidifier Assembly in Model 1.

indicating the speed of airflow was watched for several seconds, Maximum and minimum values were recorded. Each measurement was assigned a value according to the following formula:

$$value = \sqrt{\min \times \max} \qquad \text{(III)}$$

This formula was chosen because a survey of wind speeds in 55 indoor workplaces by Baldwin & Maynard (1998) found that they tend to be lognormally distributed. Hence, the geometric mean is a better measure of central tendency than the arithmetic mean.

Distributions of air speed, used as model inputs in Monte Carlo simulations, were chosen on the basis of air velocity measurements. Where there were enough measurements to fit a distribution, a lognormal distribution was fit because of Baldwin and Maynard's findings. If there were fewer than three measurements, the geometric mean of the input distribution was chosen to be the geometric mean of the measurements (or the value of the measurement, if there was only one). Similarly, if there were three or fewer measurements, a value of 1.96 m/s was assigned to the GSD of the input distribution in the Monte Carlo simulation. This value was chosen because it was equal to the GSD of the windspeeds in the Baldwin & Maynard (1998) survey. Table 3-V indicates air velocity inputs that are common to both models. Table 3-VI indicates air velocity inputs used exclusively in Model 1. Table 3-VII indicates air velocity inputs used exclusively in Model 2.

Table 3-V:
Air Velocity Input Distributions
Common to Both Model 1 and Model 2

Origin and Destination of Air Movement	Number of Measurements	Distribution of Input Assumption in Monte Carlo Simulation (m/s)[¥]
Velocity of air movement from warehouse A to AC assembly compartment (Figure 3-2, Arrow A)	9	Geometric Mean: 0.21 GSD: 1.86
Velocity of air passing from warehouse B/ press / coils to AC assembly through west opening (Figure 3-2, Arrow B)	7	Geometric Mean: 0.58 GSD: 3.09
Velocity of air passing from warehouse B/ press / coils to AC assembly through east opening (Figure 3-2, Arrow C1)	6	Geometric Mean: 0.82 GSD: 2.45
Velocity of air passing from AC assembly to warehouse B/ press / coils through east opening (Figure 3-2, Arrow C2)	1	Geometric Mean: .43[¥¥] GSD: 1.96 m/s[¥¥¥]
Velocity of air movement from injection molding / finished goods to AC assembly at far west door (Figure 3-2, Arrow D)	7	Geometric Mean: 0.82 GSD: 1.91
Velocity of air movement from injection molding / finished goods to AC assembly at west door (Figure 3-2, Arrow E)	5	Geometric Mean: 0.85 GSD: 1.27
Velocity of air movement from injection molding / finished goods to AC assembly at conveyor belt opening (Figure 3-2, Arrow F1)	5	Geometric mean: 0.45 GSD: 1.69
Velocity of air movement from AC assembly to injection molding / finished goods at conveyor belt opening (Figure 3-2, Arrow F2)	2	Geometric Mean:0.22[¥¥¥¥] GSD: 1.96[¥¥¥]

[¥] All distributions are lognormal because a survey of wind speeds in 55 indoor workplaces by Baldwin & Maynard (1998) found that they tend to be lognormally distributed. Distributions are fit from measurements using χ^2 test for goodness-of-fit unless otherwise indicated.

[¥¥] This is the value of the single measurement assigned according to Equation III.

[¥¥¥] This value was chosen because it was equal to the GSD of the windspeeds in the Baldwin & Maynard (1998) survey.

[¥¥¥¥] The geometric mean of the measurements was assigned as the value of the input distribution.

Table 3-V:
Air Velocity Input Distributions
Common to Both Model 1 and Model 2

Origin and Destination of Air Movement	Number of Measurements	Distribution of Input Assumption in Monte Carlo Simulation (m/s)$^{\text{¥}}$
Velocity of air movement from injection molding / finished goods to AC assembly at east door (Figure 3-2, Arrow G)	7	Geometric Mean: 0.58 GSD: 2.22
Velocity of air movement from injection molding / finished goods to warehouse B / press / coils at north door (Figure 3-2, Arrow H1)	5	Geometric Mean: 0.6 GSD: 1.13
Velocity of air movement from warehouse B / press / coils to injection molding / finished goods at north door (Figure 3-2, Arrow H2)	2	Geometric Mean:0.61$^{\text{¥¥¥}}$ GSD: 1.96$^{\text{¥¥}}$
Velocity of air movement from injection molding / finished goods to warehouse B / press / coils at center door (Figure 3-2, Arrow I1)	5	Geometric Mean: 0.23 GSD: 1.26
Velocity of air movement from warehouse B / press / coils to injection molding / finished goods at center door (Figure 3-2, Arrow I2)	2	Geometric Mean: 0.3$^{\text{¥¥¥}}$ GSD: 1.96$^{\text{¥¥}}$
Velocity of air movement from injection molding / finished goods to warehouse B / press / coils at south door (Figure 3-2, Arrow J1)	2	Geometric Mean: .13$^{\text{¥¥¥}}$ GSD: 1.96$^{\text{¥¥}}$
Velocity of air movement from warehouse B / press / coils to injection molding / finished goods at south door (Figure 3-2, Arrow J2)	5	Geometric Mean: 0.36 GSD: 1.83
Velocity of air movement from injection molding / finished goods to dehumidifier assembly (Figure 3-2, Arrow K1)	1	Geometric Mean: 0.09$^{\text{¥}}$ GSD: 1.96$^{\text{¥¥}}$
Velocity of air movement from dehumidifier assembly to injection molding / finished goods (Figure 3-2, Arrow K2)	6	Geometric Mean: 0.22 GSD: 1.74
Velocity with which air enters line 4 from warehouse B / press / coils (Figure 3-2, Arrow L1)	2	Geometric Mean: 0.18$^{\text{¥¥¥}}$ GSD: 1.96$^{\text{¥¥}}$

Table 3-V: Air Velocity Input Distributions Common to Both Model 1 and Model 2		
Origin and Destination of Air Movement	**Number of Measurements**	**Distribution of Input Assumption in Monte Carlo Simulation (m/s)[¥]**
Velocity with which air enters warehouse B / press / coils from line 4 (Figure 3-2, Arrow L2)		Not a stochastic variable. After each of the other values is randomly selected from its distribution, this value is determined by the necessity that air flows balance.

Table 3-VI:
Air Velocity Input Distributions Used in Model 1, Compartments 1 & 2

Origin and Destination of Air Flow	Number of Measurements	Distribution of Input Assumption in Monte Carlo Simulation (m/s)[¥]
Velocity of air movement from Compartment1 to Compartment 2 (Figure 3-4, arrow A)	1	Geometric Mean: 0.18[¥¥] GSD: 1.96[¥¥¥]
Velocity of air movement from Compartment 1 to dehumidifier assembly (Figure 3-4, arrow B)	1	482857[Ω] (constant)
Velocity of air movement from dehumidifier assembly to Compartment 1 (Figure 3-4, arrow C)		Not a stochastic variable. After each of the other values is randomly selected from its distribution, this value is determined by the necessity that air flows balance.
Velocity of air movement Compartment 2 to dehumidifier assembly, inside curve (Figure 3-4, arrow D)	1	Geometric Mean: 0.13[¥¥] GSD: 1.96[¥¥¥]
Velocity of air movement from Compartment 2 to dehumidifier assembly outside curve + side panel (Figure 3-4, arrows E & F)	1	Geometric Mean: 0.10[¥¥] GSD: 1.96[¥¥¥]
Velocity of air movement from dehumidifier assembly to Compartment 2 outer curve east (Figure 3-4, arrow G)	1	Geometric mean: 0.18[¥¥] GSD: 1.96[¥¥¥]
Velocity of air movement from Compartment 2 to dehumidifier assembly via top of compartment	1	Geometric Mean: 0.24[¥¥] GSD: 1.96[¥¥¥]
Velocity of air movement from dehumidifier assembly to Compartment 2 via bottom of compartment		Chosen so that air entering Compartment 2 = air leaving Compartment 2

[¥] All distributions are lognormal because a survey of wind speeds in 55 indoor workplaces by Baldwin & Maynard (1998) found that they tend to be lognormally distributed. Distributions are fit from measurements using χ^2 test for goodness-of-fit unless otherwise indicated.

[¥¥] This is the value of the single measurement assigned according to Equation III.

[¥¥¥] This value was chosen because it was equal to the GSD of the windspeeds in the Baldwin & Maynard (1998) survey.

[Ω] Measurement in excess of anemometer maximum (input value chosen so that air entering compartment 1 = air leaving compartment 1)

Table 3-VII: Air Velocity Input Distributions Used in Model 2, Compartments A, B & C

Input	Number of Measurements	Distribution of Input Assumption in Monte Carlo Simulation (m/s)
Velocity of air movement from AC assembly to Compartment A (Figure 3-5, arrow 5)	2	Geometric Mean: 0.21[¥¥¥] GSD: 1.96[¥¥]
Velocity of air movement from AC Assembly to Compartment A (Figure 3-5, arrow 6)	2	Geometric Mean: 0.21[¥¥¥] GSD: 1.96[¥¥]
Velocity of air movement from Compartment A to lines via top of compartment (Figure 3-5, arrow 1)	4	Geometric Mean: 0.2[¥¥¥] GSD: 1.96[¥¥]
Velocity of air movement from Compartment A to Compartment C (Figure 3-5, arrow 4)	2	Geometric Mean: 0.49[¥¥¥] GSD: 1.96[¥¥]
Velocity of air movement from Compartment A to Compartment C (Figure 3-5, arrow 7)	1	Geometric Mean: 0.3[¥] GSD: 1.96[¥¥]
Velocity of air movement from AC assembly to Compartment B (Figure 3-5, Arrow 9)	2	Geometric Mean: 0.24[¥¥¥] GSD: 1.96[¥¥]
Velocity of air movement Compartment B to AC assembly via top (Figure 3-5, Arrow 3)	3	Geometric Mean: 0.82[¥¥¥] GSD: 1.96[¥¥]
Velocity of air movement from AC assembly to Compartment B north (Figure 3-5, Arrow 10)	2	Geometric Mean: 0.28[¥¥¥] GSD: 1.96[¥¥]
Velocity of air movement between Compartment B and Compartment C (Figure 3-5, Arrow 11)	2	Geometric mean: 0.15[¥¥¥] GSD: 1.96[¥¥]

[¥] This is the value of the single measurement assigned according to Equation III.

[¥¥] This value was chosen because it was equal to the GSD of the windspeeds in the Baldwin & Maynard (1998) survey.

[¥¥¥] The geometric mean of the measurements was assigned as the value of the input distribution.

The rates at which air is exchanged between each compartment and the outdoors are calculated on the basis of information provided in two ventilation reports conducted for the plant. One from 1991 and the other from 1997. These rates are the same for both models. Table 3-VIII indicates the input distributions used for rates of air exchange between compartments within the facility and the outdoors.

Table 3-VIII: Air Exchange Between Each Compartment and the Outdoors	
Compartment	**Rate of Air Exchange (m^3/hour)**
Outdoor air entering AC assembly	Uniform Distribution (210000, 312000) Endpoints chosen to be equal to minimum (winter) and maximum (summer) capacity of air handlers
Air from dehumidifier assembly ventilated to the outdoors	0[*]
Air from warehouse B / press / coils ventilated to the outside	Triangular Distribution Minimum: 500,000 Maximum: 632,177 (total capacity of exhaust fans in compartment). Likeliest value: 568,960 (based on ventilation survey of September 1991 in which exhaust in this compartment operated at approximately 90% capacity)
Outdoor air entering warehouse B / press / coils	Uniform Distribution Minimum: 158,130 (winter capacity of nine air blowers) Maximum: 234,644 (summer capacity of nine air blowers)
Air from warehouse A ventilated to the outdoors	Triangular Distribution Minimum: 30,000 Maximum: 45,000 (capacity of exhaust fan) Likeliest: 40500 (based on ventilation survey of September 1991 in which exhaust in this compartment operated at approximately 90% capacity)
Air from injection molding / finished goods ventilated to the outside	Triangular Distribution Minimum: 284,000 Maximum: 355,000 (capacity of exhaust fan) Likeliest: 319,500 (based on ventilation survey of September 1991 in which exhaust in this compartment operated at approximately 90% capacity)

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[*] Dehumidifier Assembly has no exhaust fans.

Results

The results are presented in two parts. First the results for large volume compartments are presented. Then the results for small volume compartments are presented. Within each part, a spatial analysis of particulate concentration data is presented first, in order to test the assumption that the compartments are well-mixed. This followed by an examination of time trends in the concentration data in order to determine whether or not the results are confounded by temporal phenomena that may influence particulate concentration. Finally, the performance of the model is examined by direct comparison of measured and modeled data.

Large Compartments

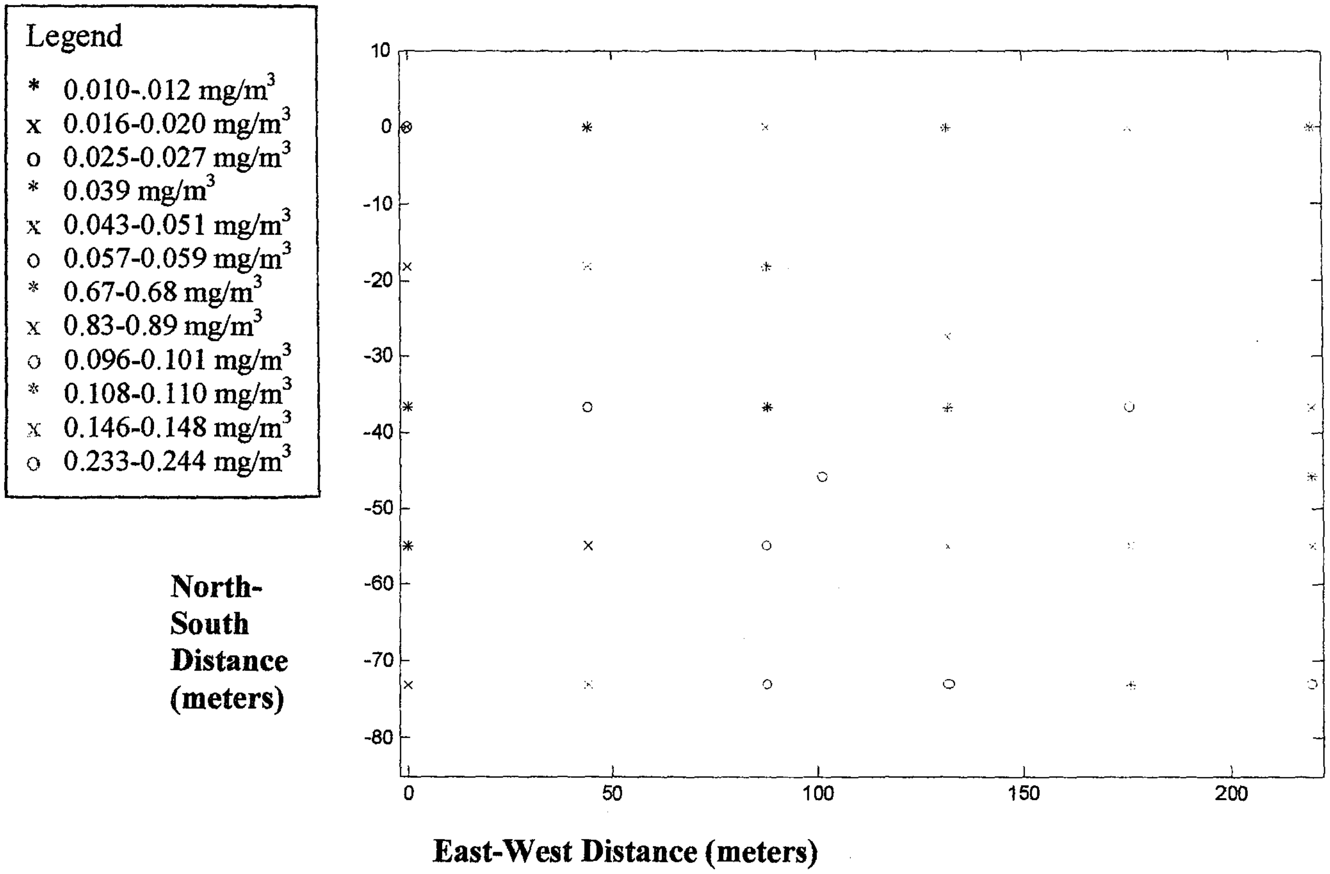
Testing the Well-Mixed Assumption in Large Compartments

As discussed above, the model assumes that compartments are well-mixed. The assumption is that each compartment has a concentration that is approximately uniform. Figures 3-6 through 3-9 present the spatial variation of measurements taken in each large compartment in order to examine how well the well mixed assumption is satisfied in each compartment. Concentration ranges are represented by color-coded symbols to make it relatively easy to determine upon visual inspection where measurements of similar concentration were located.

Figure 3-6 indicates the location and magnitude of measurements in the air conditioner assembly compartment. There is some trend toward increasing concentrations as one moves from west to east within the compartment. This trend is consistent with the observation that air within the compartment was moving west to east.

Figure 3-6:

Location and Magnitude of PM Concentration Measurements in AC Assembly



However, concentration falls off towards the far eastern part of the box. The probably reflects the fact that there are no brazing torches that far east. The compartment is not very well mixed.

Figure 3-7 indicates the location and magnitude of measurements in the dehumidifier assembly compartment. In figure 3-7, the southern row of measurements records a higher concentration than the northern row. These measurements are somewhat closer to the brazing torches than the northern row. In addition the measurements are generally consistent with the fact that air movement in the compartment is from east to west. The measurement of 0.094 mg/m^3 at approximately (120,20) is very close to a brazing station. This compartment, too, is not very well mixed.

Figure 3-7:
Location and Magnitude of PM Concentration Measurements in Dehumidifier Assembly

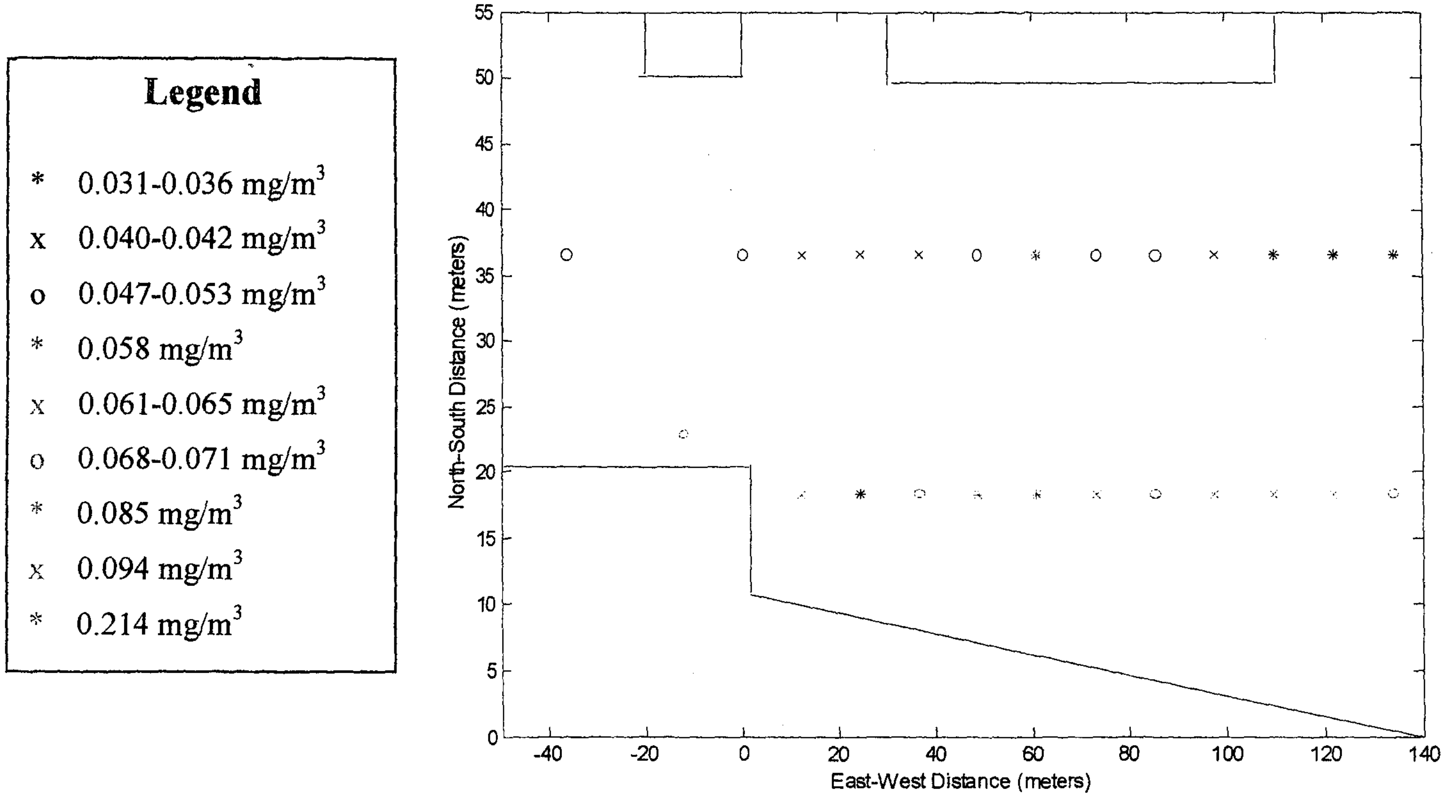


Figure 3-8 indicates the location and magnitude of particulate concentration measurements in warehouse A. This compartment appears closer to being well-mixed, possibly due to the fact that there are no particulate sources within the compartment. The highest measurement 0.123 mg/m^3 at approximately (-16, -80) is at a location where trucks load and unload.

Figure 3-8:
Location and Magnitude of PM Concentration Measurements in Warehouse A

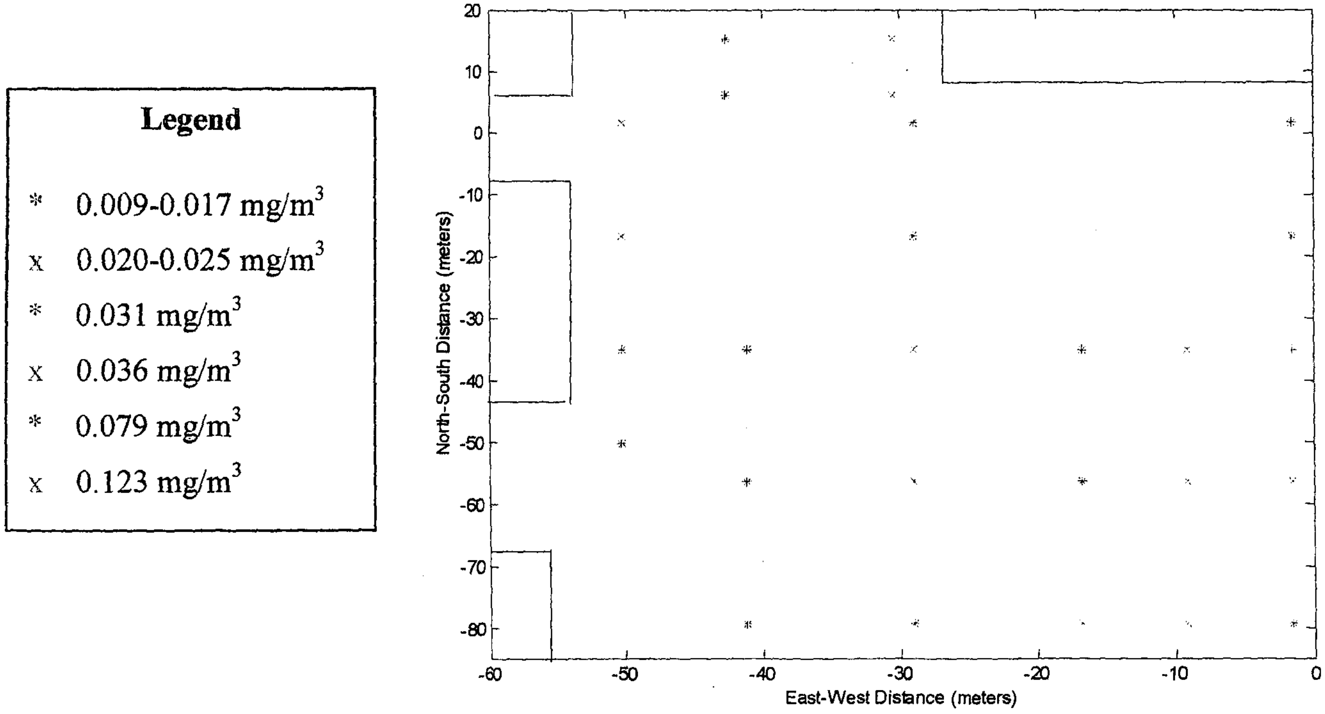


Figure 3-9:
Location and Magnitude of PM Concentration Measurements in Injection Molding / Finished Good

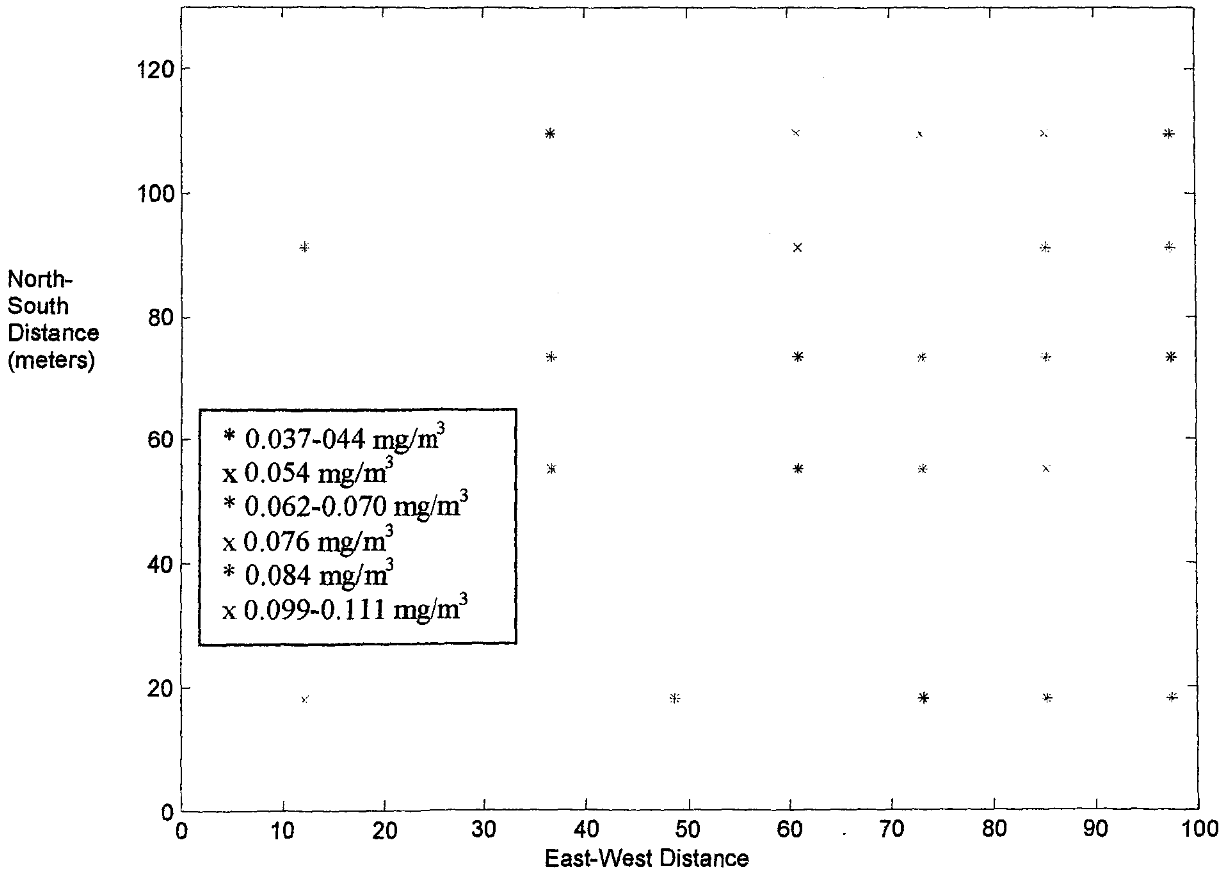


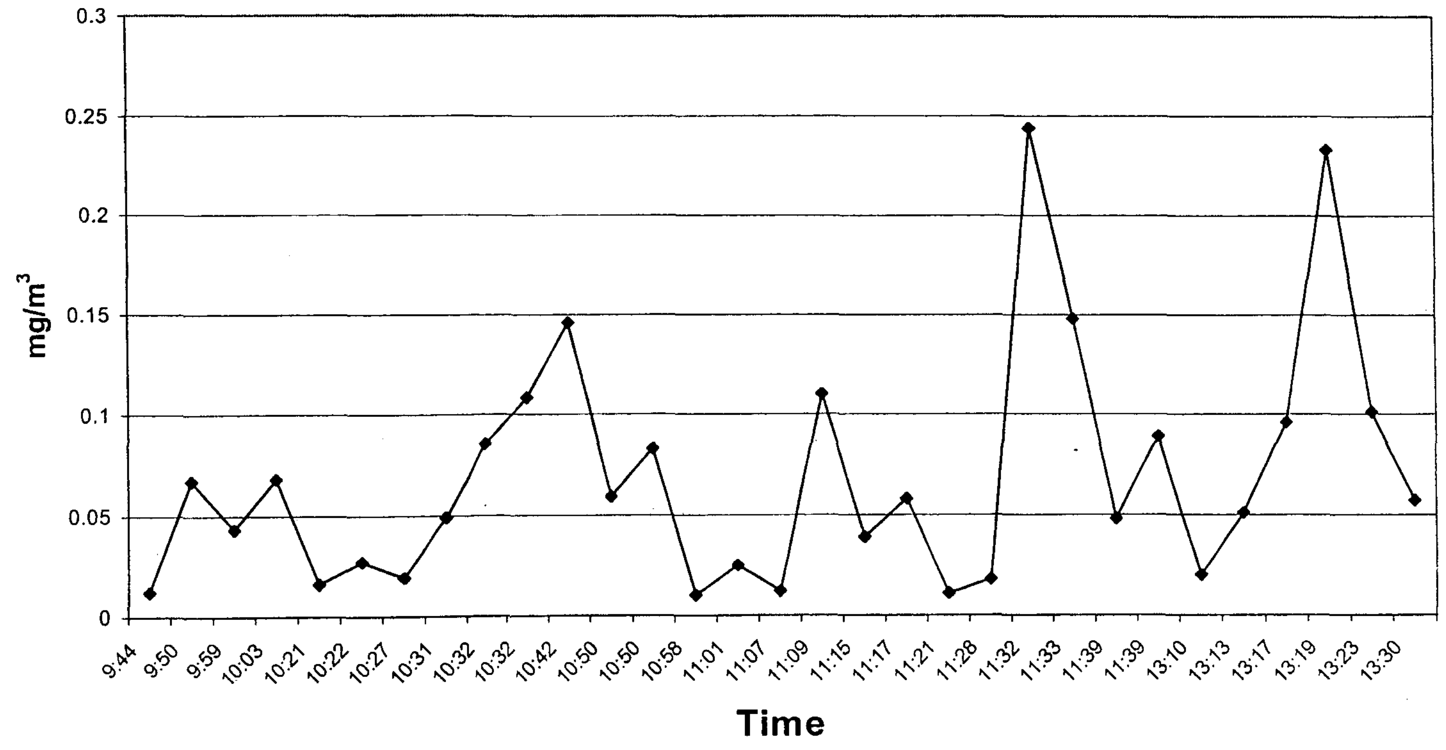
Figure 3-9 indicates the location and magnitude of PM concentration measurements in the injection molding / finished goods compartment. This compartment, too, is not very well-mixed. There is no readily apparent cause of the observed pattern. Since three of the four large compartments in this validation are not very well mixed, the exercise will test the robustness of model predictions to violations of the well-mixed assumption.

Examinations of Time Trends in Large Compartments

Since the particulate concentration measurements in large compartments, whose spatial variation is presented in figures 3-6 through 3-9 above, were made sequentially rather than simultaneously, an examination of time trends was undertaken in order to determine whether apparent spatial variation might be an artifact, reflecting instead an increasing or decreasing concentration of particulate matter over time. As indicated in figures 3-10 through 3-13 and the accompanying presentations of Pearson and Spearman correlation coefficients, only one of the large compartments, dehumidifier assembly, exhibits a significant correlation between time and magnitude of measurement. Dehumidifier assembly exhibits a decreasing trend. This means that it is possible that the apparent spatial variation observed in dehumidifier assembly is an artifact resulting from a decline in concentration of the whole compartment over time. However, the measurements were taken one after another with relatively little time between them. Some measurements were even taken simultaneously because two DataRAMs were used. It seems more likely that the apparent time trend is due to movement from locations of higher concentration to locations of lower concentration when the measurements were taken.

Figure 3-10:

Graph of Measured Particulate Concentration in AC Assembly against Time of Measurement

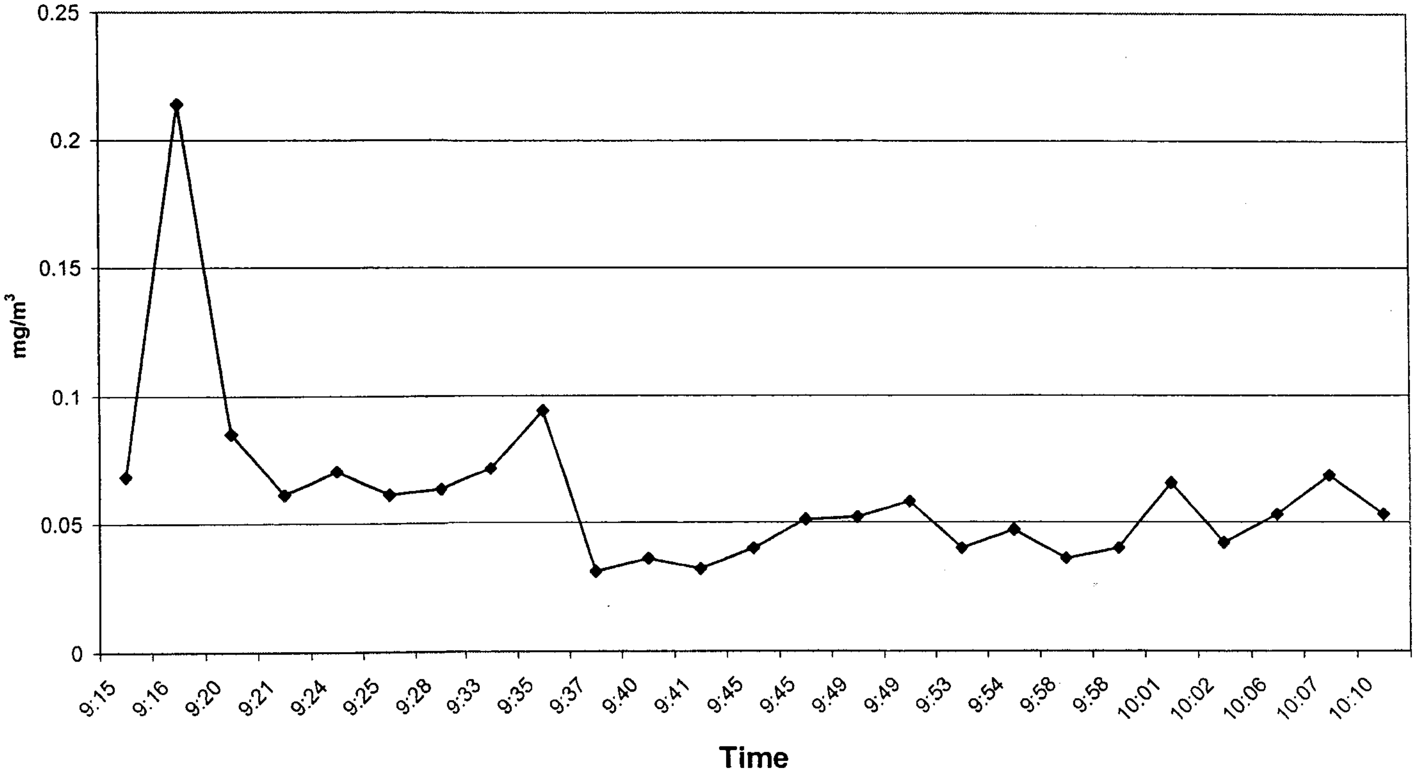


Coefficients for Correlation of Concentration with Time

Pearson Correlation: 0.28 (p=0.12)
Spearman Correlation: 0.28 (p=0.12)

Figure: 3-11

Graph of Measured Particulate Concentrations in Dehumidifier Assembly against Time of Measurement

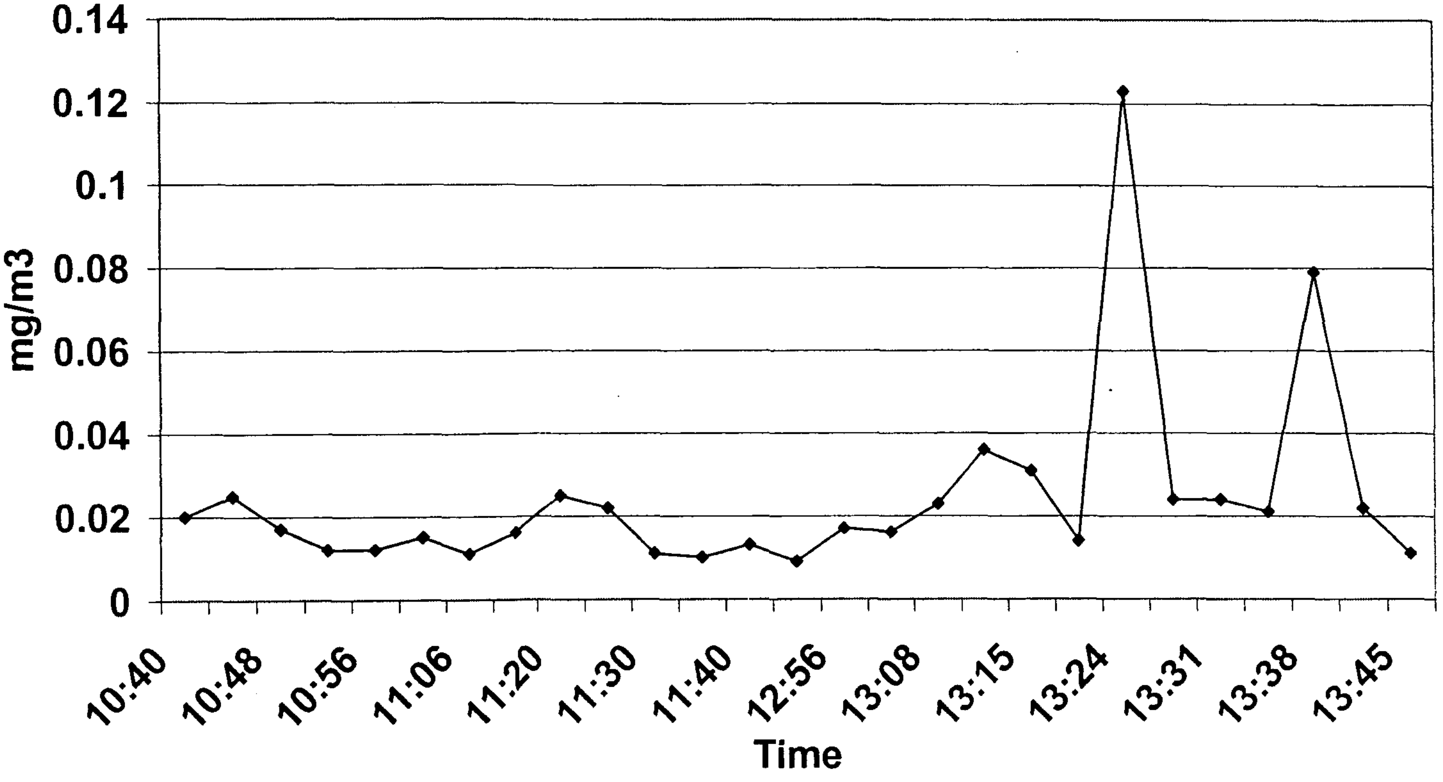


Coefficients for Correlation of Concentration with Time

Pearson Correlation: - 0. 47 (p=0.02)
Spearman Correlation: - 0.44 (p=0.03)

Figure 3-12:

Graph of Measured Particulate Concentrations in Warehouse A against Time of Measurement

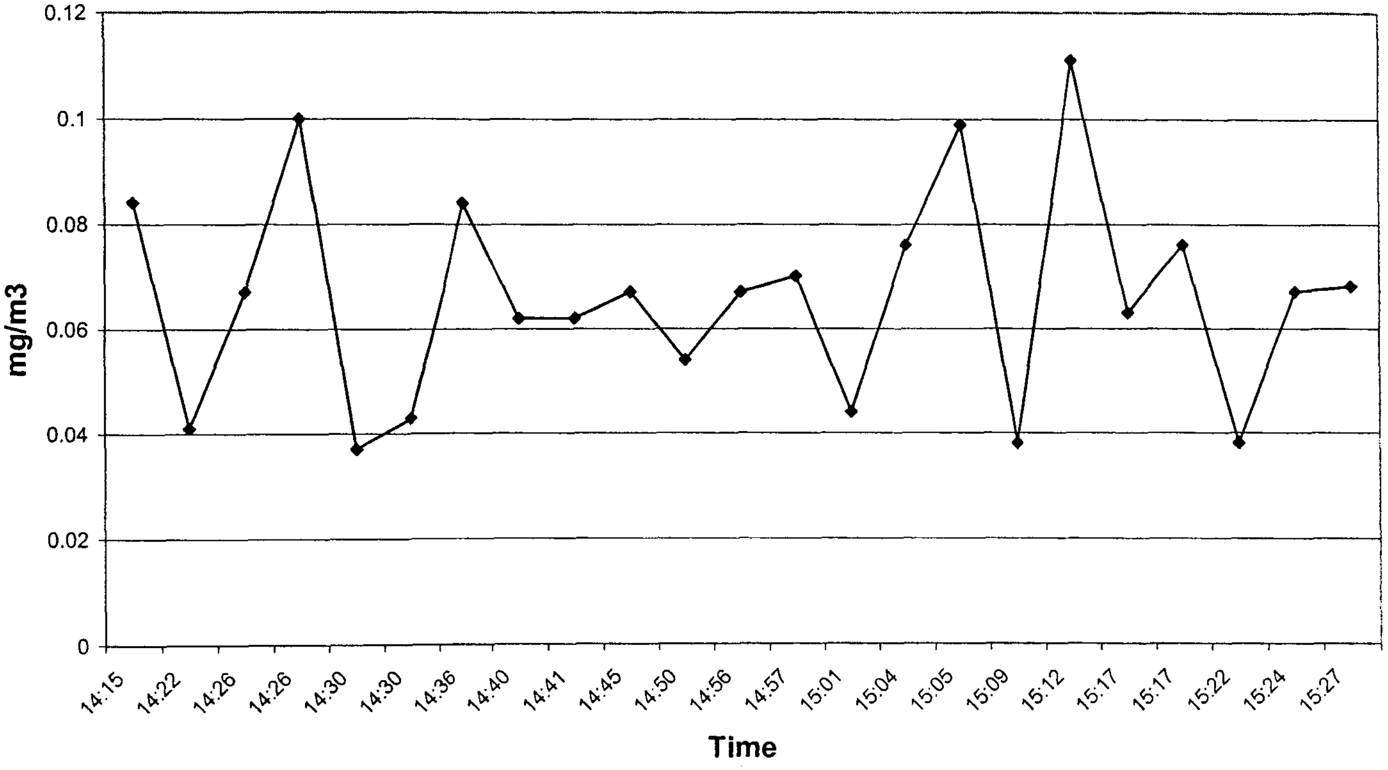


Coefficients for Correlation of Concentration with Time

Pearson Correlation: 0.36 (p=0.066)
Spearman Correlation: 0.30 (p=0.13)

Figure 3-13:

Graph of Measured Particulate Concentrations in Injection Molding / Finished Goods against Time of Measurement



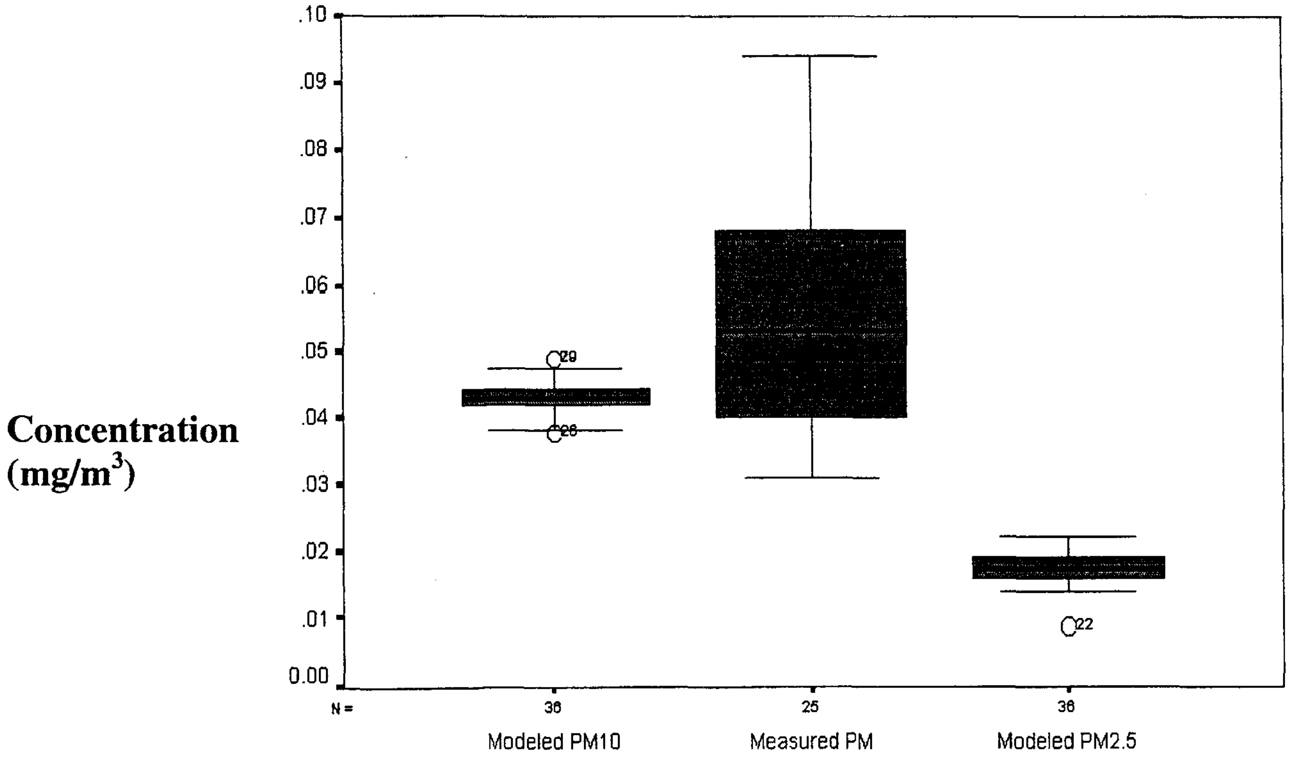
Coefficients for Correlation of Concentration with Time

Pearson Correlation: 0.04 (p=.87)
Spearman Correlation: 0.06 (p=0.79)

Model Performance for Large Compartments

Figures 3-14 through 3-17 compare DataRAM-measured particulate concentrations in each of the large compartments with modeled particulate concentrations. As previously indicated, Model 1 was run once each using outdoor PM_{10} and $PM_{2.5}$ concentrations at the time of sampling. Each of the four figures shows a boxplot of particulate concentrations modeled using outdoor PM_{10} on the left, a boxplot of DataRAM-measured particulate concentrations in the center and a boxplot of particulate concentrations modeled using outdoor $PM_{2.5}$ on the right. Variability in modeled PM reflects variability in the input distributions presented in tables 3-III through 3-VIII above. Figures 3-XIV through 3-XVII show that when outdoor $PM_{2.5}$ concentration was used, Model 1 consistently under-predicted particulate concentrations in large compartments. When outdoor PM_{10} concentration was used, the model performed well for dehumidifier assembly and air conditioner assembly, not badly for warehouse A, and poorly for injection molding / finished goods.

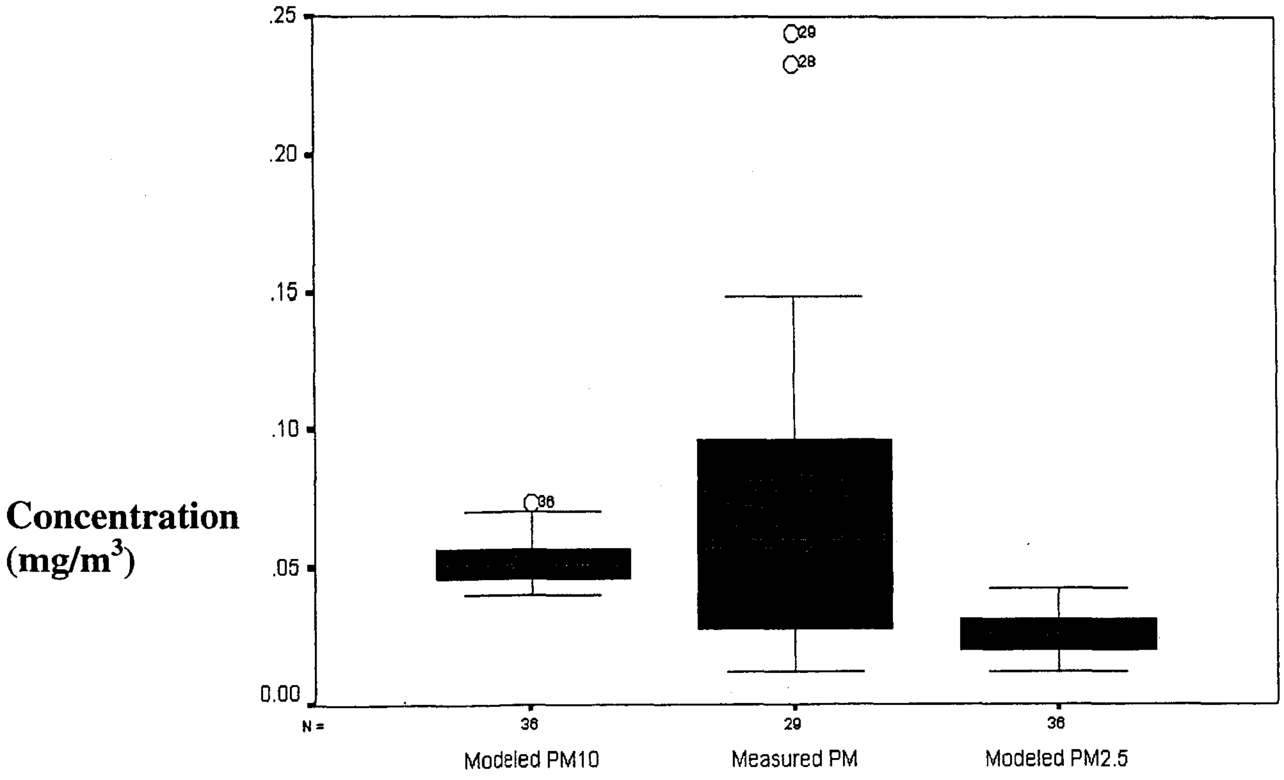
Figure 3-14



Dehumidifier Assembly:

Comparison of Measured and Modeled PM

Figure 3-15



Air Conditioner Assembly:

Comparison of Measured and Modeled PM

Figure 3-16

Warehouse A:

Comparison of Measured and Modeled PM

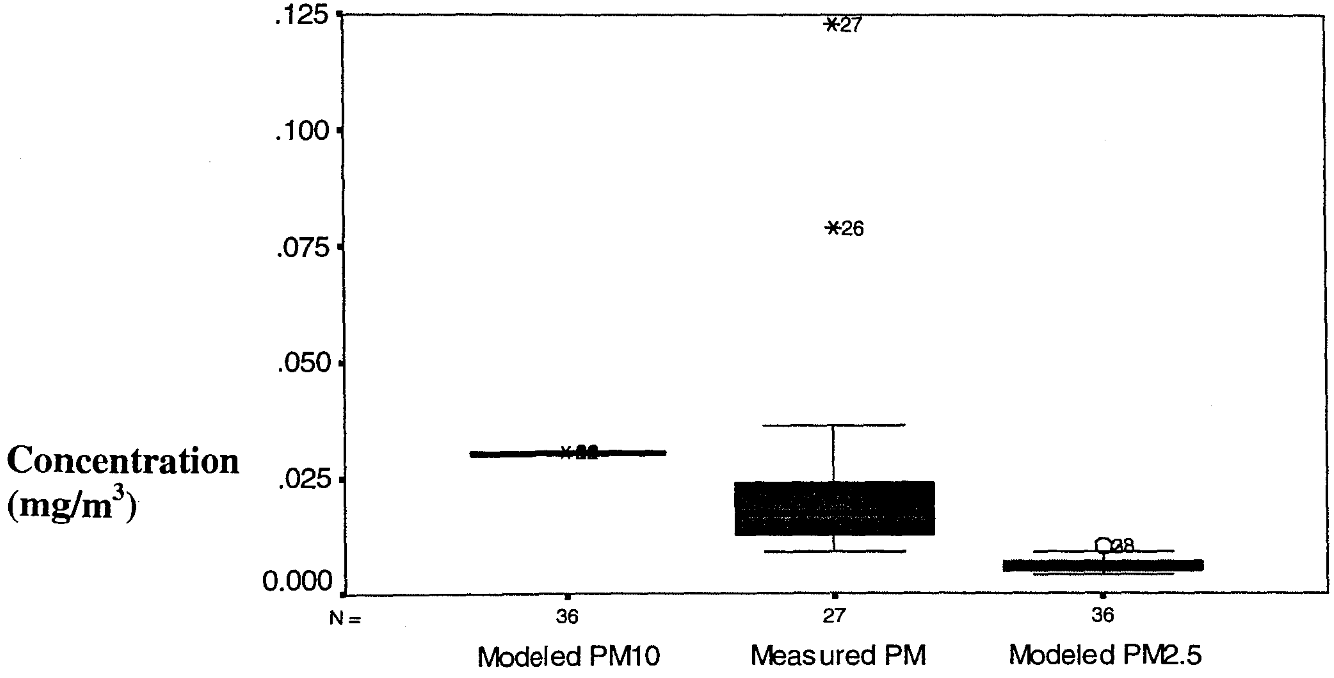


Figure 3-17

Injection Molding / Finished Goods:

Comparison of Measured and Modeled PM

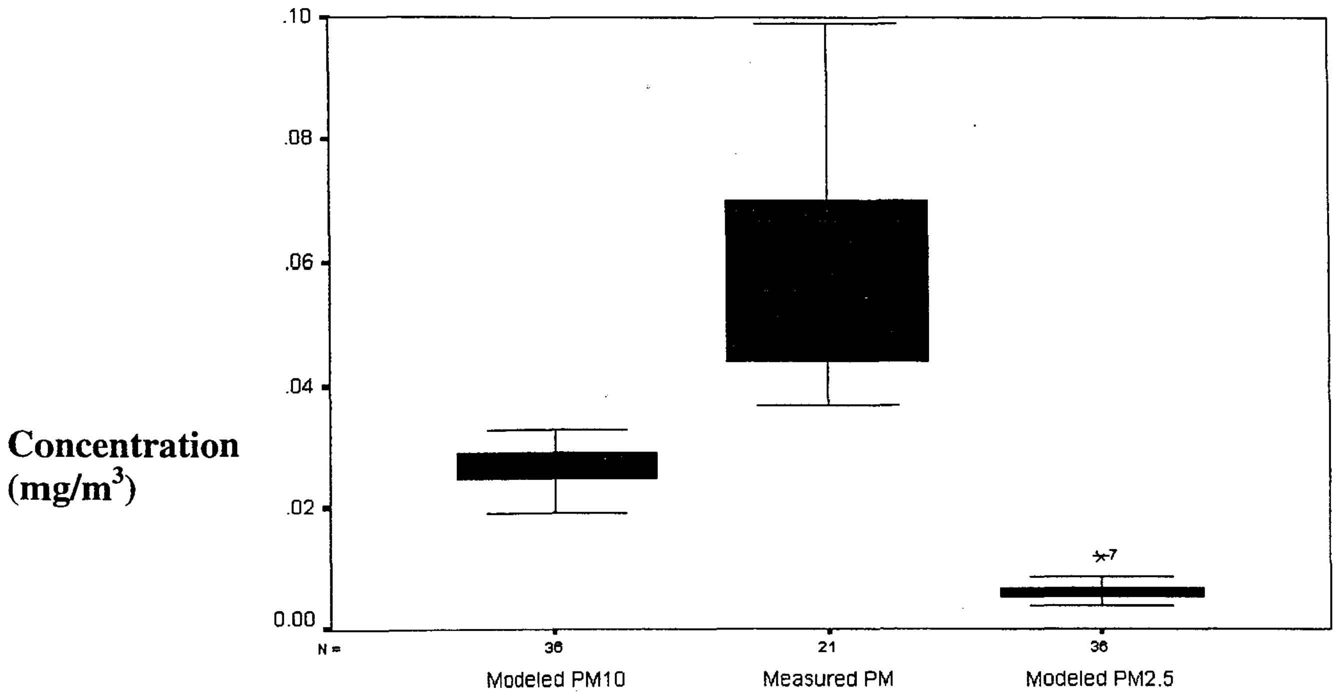


Table 3-IX is based on the same data used to construct figures 3-14 to 3-17. The table compares Model 1 predictions for four large compartments within the plant to the particulate measurements made in those parts of the plant on 17,18 and 19 April 2001. The relatively low coefficients of variability of the simulations (the standard deviation is less than 16% of the mean for all four compartments) indicate that the variability present in the model input distributions has only a moderate impact on the model's estimate of particulate concentrations. Additionally, it reflects the fact that, for some inputs, no estimate of variability was available. For example, particulate emissions from brazing were calculated by dividing estimated total annual emissions by the annual number of operating hours. There were no available data that would permit an estimation of the variation in emission rates over time. PM concentration measurements for three of four compartments have coefficients of variability in excess of 50%, indicating that they are not very well mixed. Absolute difference / measured mean can be understood as measure of the size of the model's error in predicting the measured mean. The size of the error ranges from 25% to 59% of the measured mean. For three of the four compartments, the model underpredicted the measured mean. Only in warehouse A did it overpredict.

Model 1's predicted particulate concentration for warehouse A was 0.03 mg/m^3. This is equal to the input value for outdoor PM_{10} concentration and higher than the measured result It may be that the outdoor particulate concentration in the immediate vicinity of the facility was lower than that reported by the monitoring station. Some support for this explanation can be found in the fact that on 14 May, the average of four measurements taken outside the facility was 0.0074 mg/m^3, while the report from the monitoring station for 13 May was 0.0224 mg/m^3. Data for 14 May were not available.

Table 3-IX: Comparison of Particulate Concentrations that Were Modeled Using Outdoor PM_{10} to PM Concentrations Measured in Large Compartments within the Plant
(17, 18, 19 April 2001)

	Dehumidifier Assembly (line 4)	**AC Assembly** (lines 1, 2, 3 & 5)	**Warehouse A**	**Injection Molding / Finished Goods**
Volume (m^3)	53,662	153,752	39,450	97,225
# of simulations	36	36	36	36
# of measurements	25	31	27	23
modeled mean (mg/m^3)	0.043	0.052	0.03	0.027
coefficient of variability of simulations	0.058	0.154	7.3×10^{-5}	0.11
measured mean (mg/m^3)	0.061	0.069	0.024	0.066
coefficient of variability of measurements	0.56	0.86	0.96	0.31
absolute difference	0.018	0.017	0.006	0.039
absolute difference / measured mean	0.295	0.25	0.25	0.59
modeled rank	2	1	3	4
measured rank	3	1	4	2

Examining the ranks for dehumidifier assembly, AC assembly and warehouse A, we observe that the model predicted that particulate concentration in AC assembly would exceed that of dehumidifier assembly, which would, in turn, exceed that of warehouse A. Indeed, the measurements indicated that particulate concentrations in these three compartments ranked in that order. Unfortunately, the model did considerably less well in predicting particulate concentration in the injection molding / finished goods compartment. The model indicated that particulate concentration in that compartment would be lower than the concentration in the other three. In fact, it was higher than all but AC assembly. At the time of sampling, there was no apparent source of particulate matter in the injection molding / finished goods compartment. It is possible that worker activity in this compartment re-suspended particulate matter emitted previously by the plastic grinding machines located there or that particulate is carried into the injection molding compartment by forklifts delivering the finished goods or released into this compartment from trucks onto which the finished goods are loaded. At the time of measurement, there were many forklifts moving in and out of this compartment, but no truck with motor running was observed.

Small Compartments

Well-Mixed Assumption

Figures 3-18 through 3-20 indicate the magnitude and location of measurements made in Compartments 1, 2, A and B. As with figures 3-6 through 3-9, their purpose is to examine how well the well-mixed assumption is satisfied in each compartment. Concentration ranges are represented by symbols to make it relatively easy to determine upon visual inspection where measurements of similar concentration were located.

Figure 3-18 depicts Compartments 1 and 2. These are small compartments within dehumidifier assembly representing a place in which there were two workers, each with a brazing torch. The division between Compartment 1 and Compartment 2 was selected *a priori* because there was fan blowing air through the space east of the division. It was believed that dividing the space into two Compartments was more likely to render each one well-mixed. It was also believed *a priori*, that Compartment 2 would have a higher particulate concentration than Compartment 1 because air passed through Compartment 2 at a slower rate since it lacked a fan. As figure 3-18 indicates, the belief was incorrect. The highest concentration measurements are in Compartment 1. The most likely explanation is that air blown by the fan does not reach the part of Compartment 1 in which the three highest measurements were taken. Compartment 1 is not very well-mixed. The coefficient of variability of the measurements is 0.84. Compartment 2 appears closer to being well-mixed than Compartment 1. It exhibits a smaller range of particulate concentrations. and does not have a strong spatial pattern of particulate concentrations. However, it does appear that the center of the compartment has a somewhat higher concentration and than the periphery. This may indicate that the brazing torch operator spends more time near the center of the compartment.

Figure 3-18:

PM Measurements in Compartments 1 and 2 (Dehumidifier Brazers)

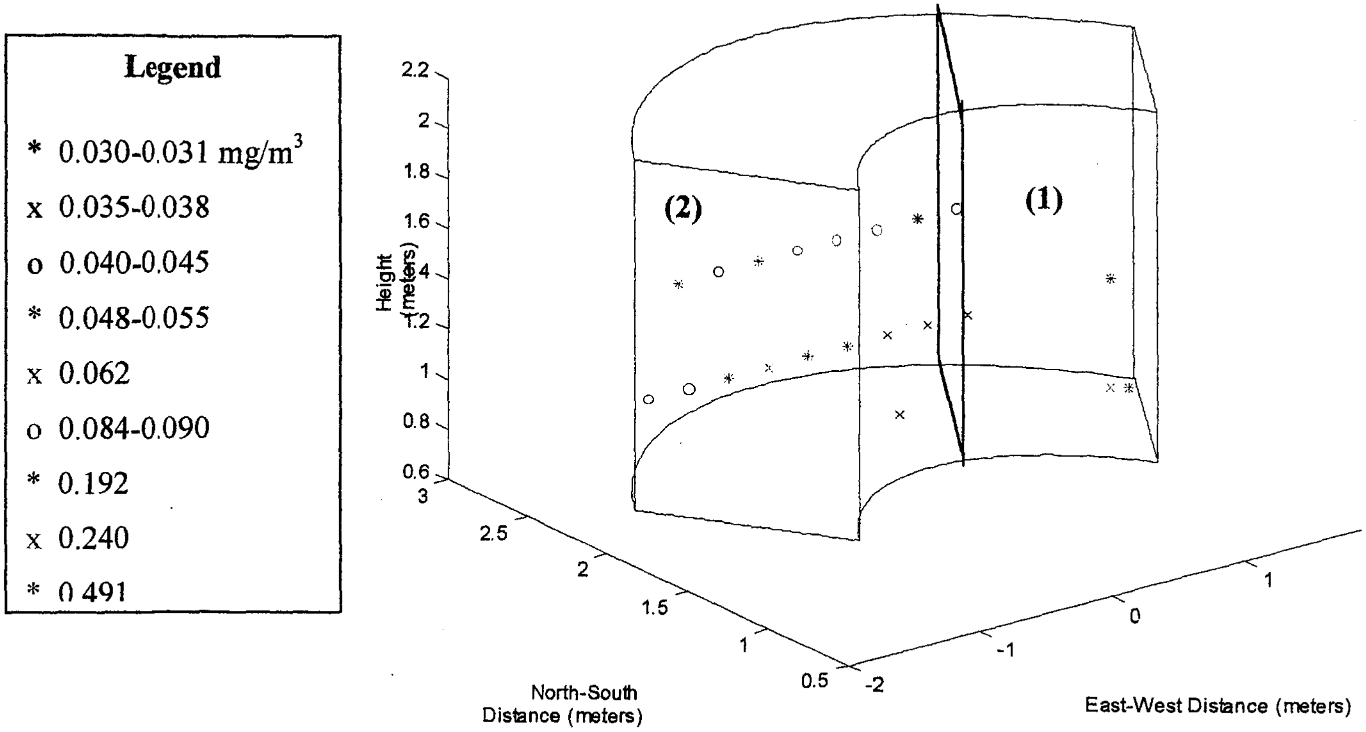
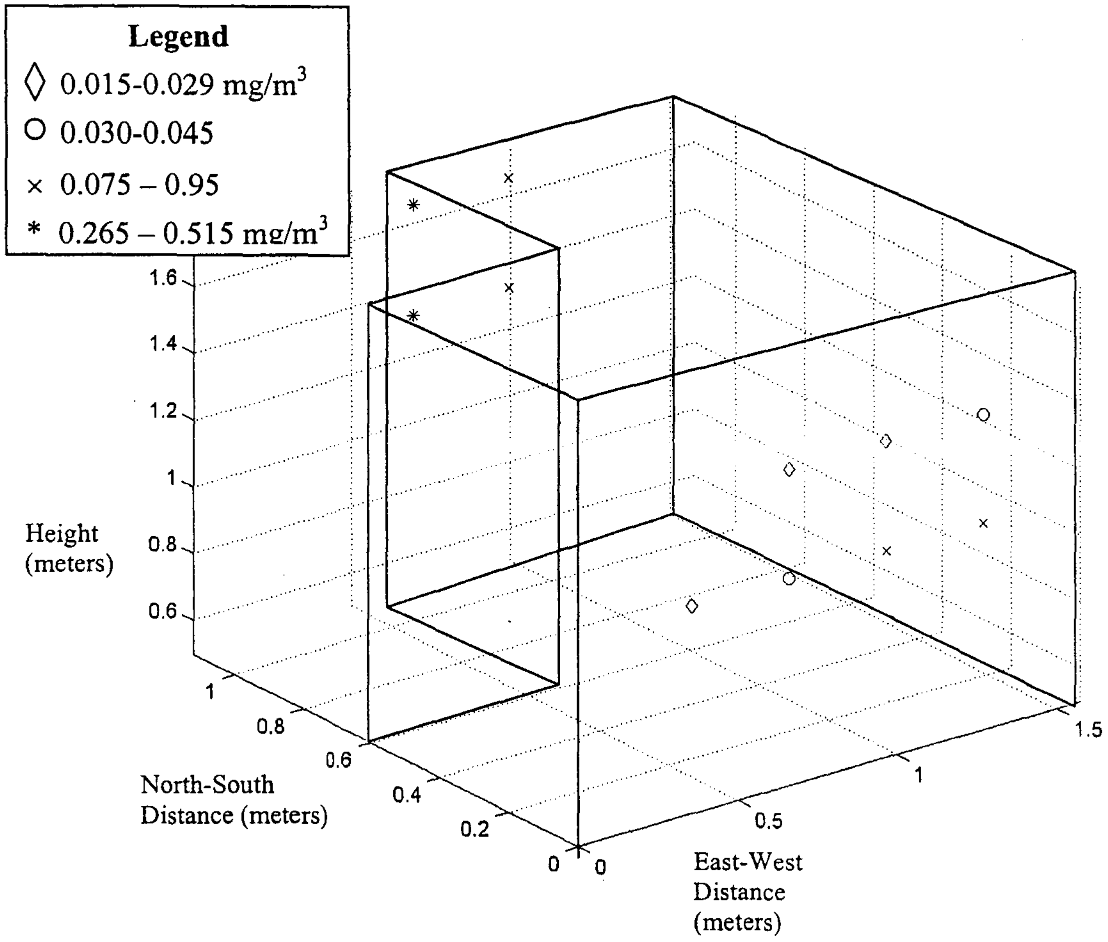
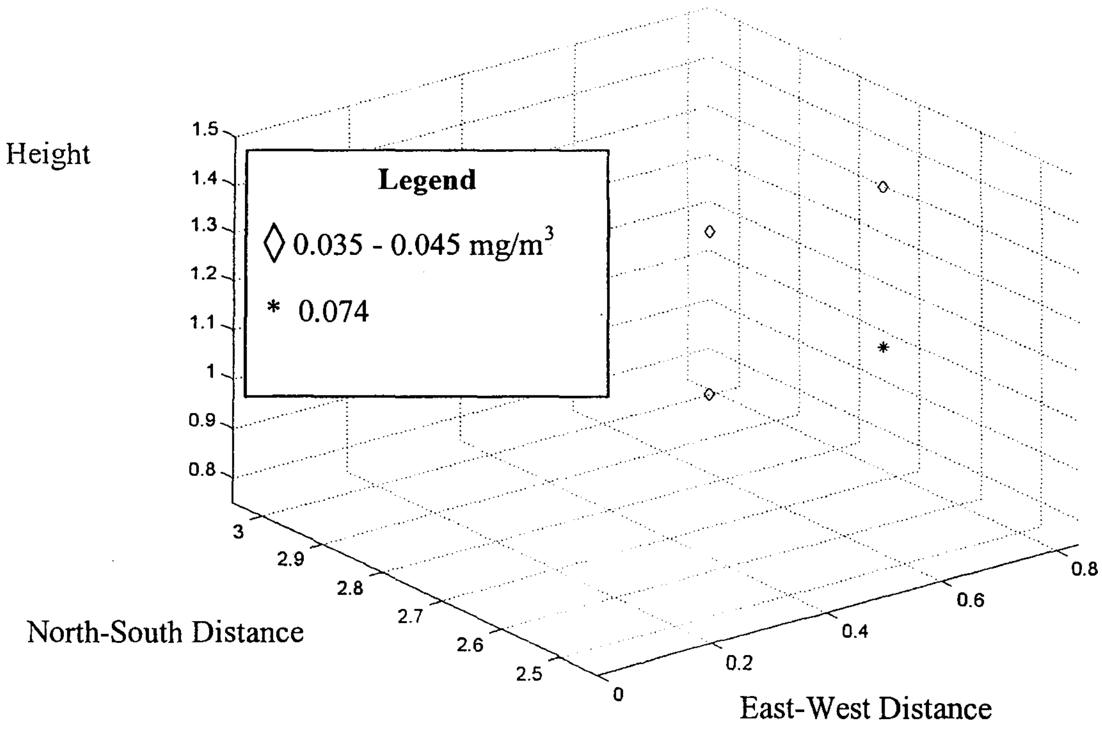


Figure 3-19: Magnitude and Location of Compartment A PM Measurements



Compartments A and B are small compartments within AC assembly. Similar to Compartments 1 and 2, they represent spaces where workers with brazing troches work. Figure 3-19 indicates the magnitude and location of concentration measurements in Compartment A. Observed concentration is considerably higher in the northern part of the compartment. This may indicate that the torch operator spends more time in this part of the compartment or it may be an artifact of a small number of observations. As can be seen in figure 3-20, the four measurements in Compartment B are fairly close in range. Compartment B may be fairly well mixed or this, too may be an artifact of a small number of observations. Since two of the four large compartments in this validation are not very well mixed, the exercise will test the robustness of model predictions to violations of the well-mixed assumption.

Figure 3-20: Magnitude and Location of Compartment B PM Measurements

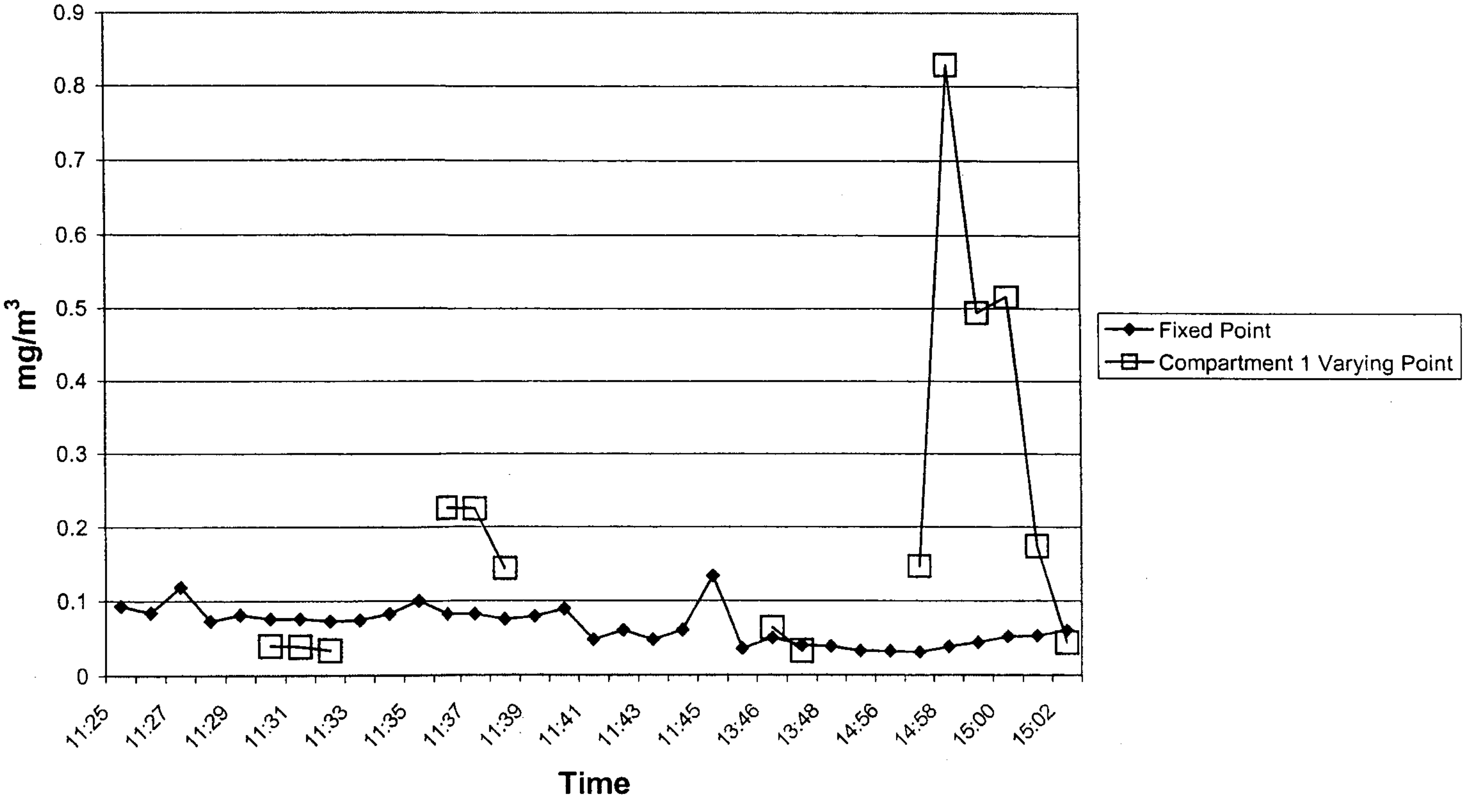


Time Trends in Small Compartments

Two DataRAMs™ were available for this research. In the large compartments both measuring devices were used to take the spatially varying measurements presented above. However, in small compartments, this task could be accomplished using one measuring device. The second one was placed at a fixed point in or near the compartments being measured. Any changes in concentration measured by the second device can be attributed to time because the second device did not move. Hence for the small compartments it was possible to examine, not merely whether there was a trend in the measurements over time, but also whether observed differences between measurements in different locations correlated with changes in measurements over time in a nearby fixed location. Figures 3-21 through 3-24 indicate the variation of fixed point and varying point measurements in each small compartment over time. In none of the four compartments does it appear that differences in spatially varying measurements reflect changes that occurred over time. Figure 3-22 indicates that the fixed point measurement exhibited much greater variability than the spatially varying measurements made in Compartment 2. Similarly, figure 3-24 indicates that the fixed point measurements exhibited much greater variability than the spatially varying measurements made in Compartment B.

Figure 3-21:

Comparison of Fixed Point Measurements with Simultaneous Spatially Varying Measurements in Compartment 1



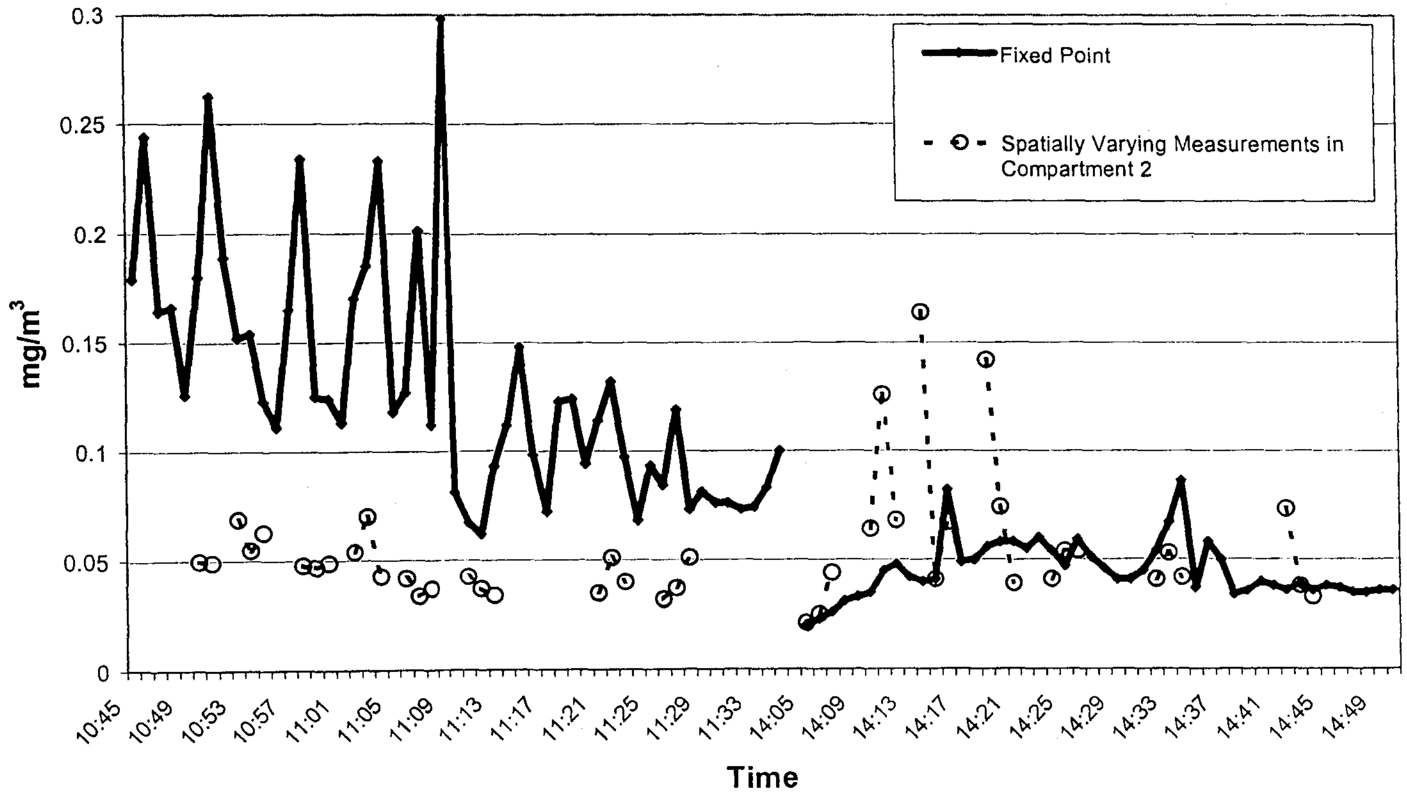
Correlation Coefficients between Fixed Point and Compartment 1 Varying Point Measurements

Pearson Correlation: -0.39 (p=0.16)

Spearman Correlation -0.17 (p=0.57)

Figure 3-22:

Comparison of Fixed Point Measurements with Simultaneous Spatially Varying Measurements in Compartment 2



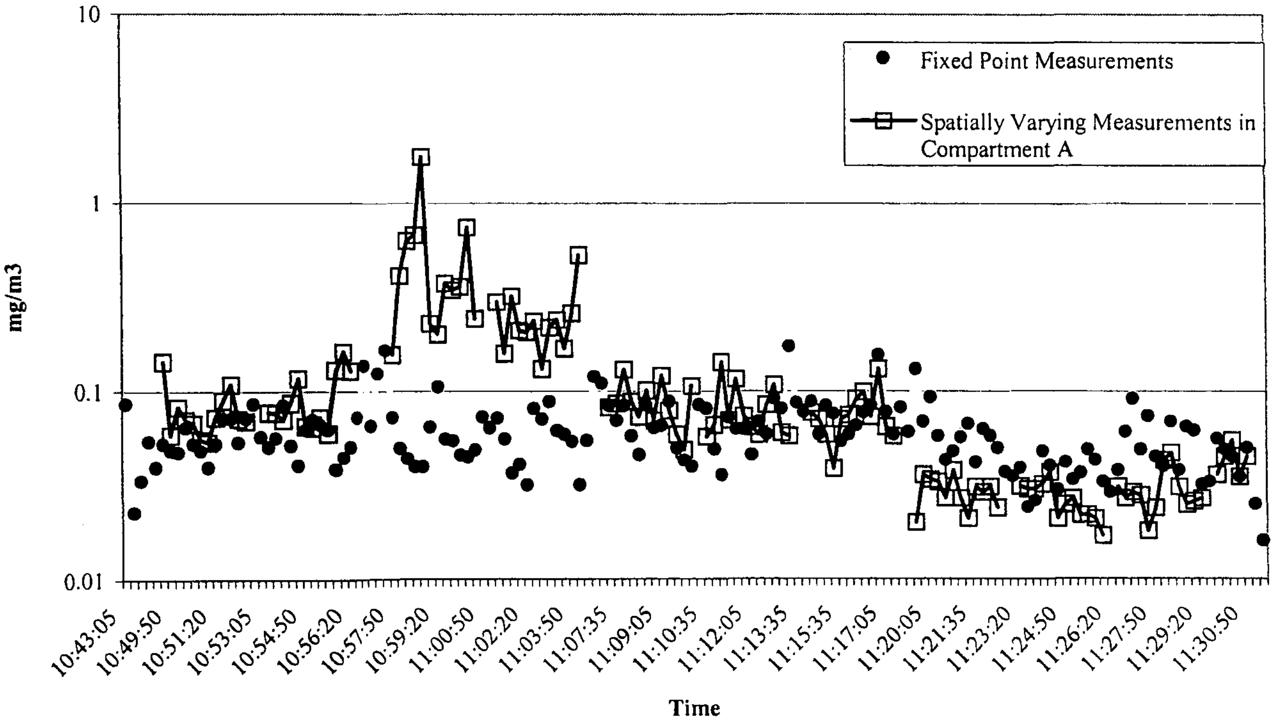
Correlation Coefficients between Fixed Point and Compartment 2 Varying Point Measurements

Pearson Correlation: - 0.14 (p = 0.37)

Spearman Correlation: - 0.05 (p=0. 78)

Figure 3-23:

Comparison of Fixed Point Measurements
with Spatially Varying Measurements in Compartment A



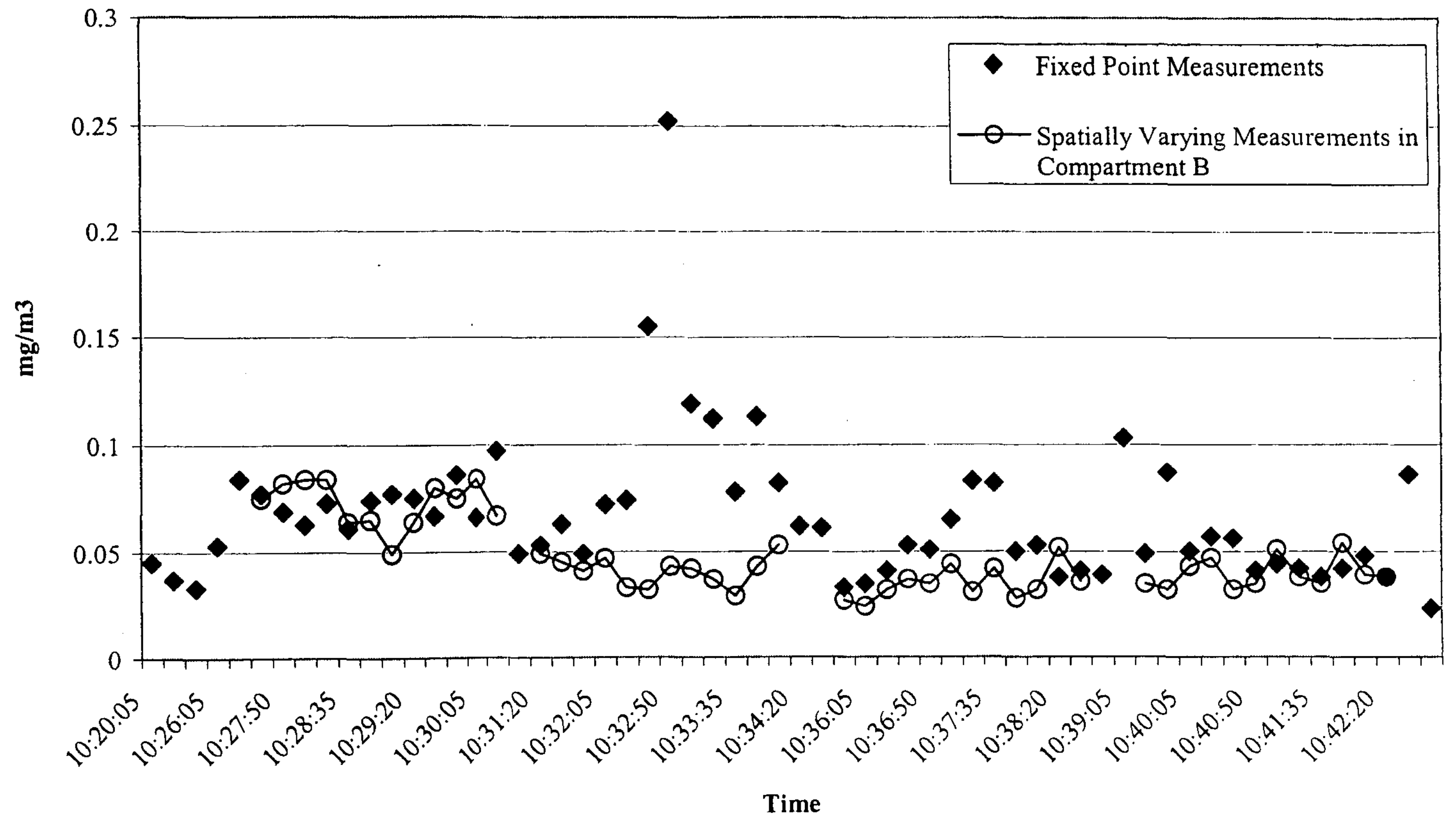
Correlation Coefficients between Fixed Point and Compartment A Varying Point Measurements

Pearson Correlation: - 0.122 (p=0.18)

Spearman Correlation: 0.13 (p=0.14)

Figure 3-24:

Comparison of Fixed Point Measurements with Spatially Varying Measurements in Compartment B



Correlation Coefficients between Fixed Point and Compartment B Varying Point Measurements

Pearson Correlation: 0.08 (p=0.67)

Spearman Correlation: 0.26 (p=0.07)

Model Performance for Small Compartments

Figures 3-25 through 3-28 compare DataRAM-measured particulate concentrations in each of the small compartments with modeled particulate concentrations. As previously indicated, Model 1, which was used to predict particulate concentrations in Compartments 1 and 2, was run once each using outdoor PM_{10} and $PM_{2.5}$ concentrations at the time of sampling. For this reason figures 3-25 and 3-26 each show a boxplot of particulate concentrations modeled using outdoor PM_{10} on the left, a boxplot of DataRAM-measured particulate concentrations in the center and a boxplot of particulate concentrations modeled using outdoor $PM_{2.5}$ on the right. Model 2 used outdoor concentrations measured with a DataRAM. Hence figures 3-27 and 3-28 present measured PM on the left and modeled PM on the right. Variability in modeled PM reflects variability in the input distributions presented in tables 3-III through 3-VIII above.

Figure 3-25

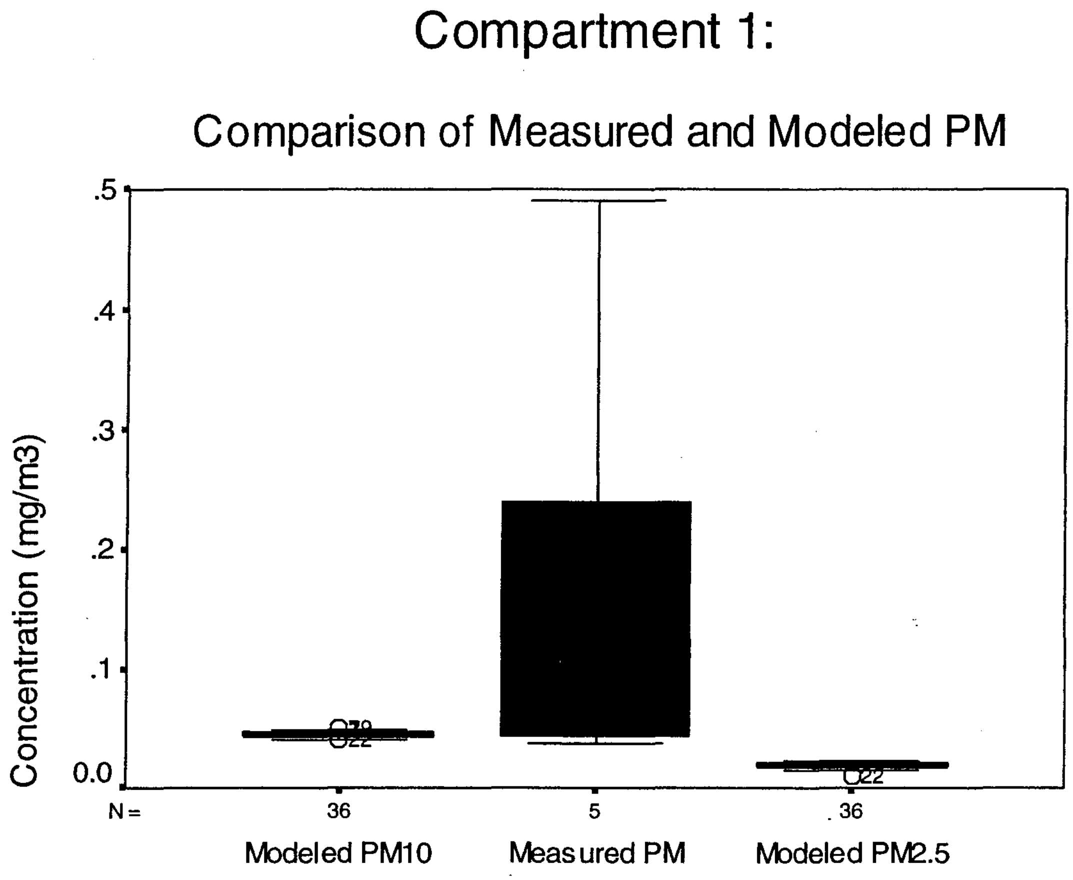

Compartment 1:
Comparison of Measured and Modeled PM
Concentration (mg/m3)
.5
.4
.3
.2
.1
0.0
N =
36
5
36
Modeled PM10
Measured PM
Modeled PM2.5
O19
O22
O22

Figure 3-26

Compartment 2:

Comparison of Measured and Modeled PM

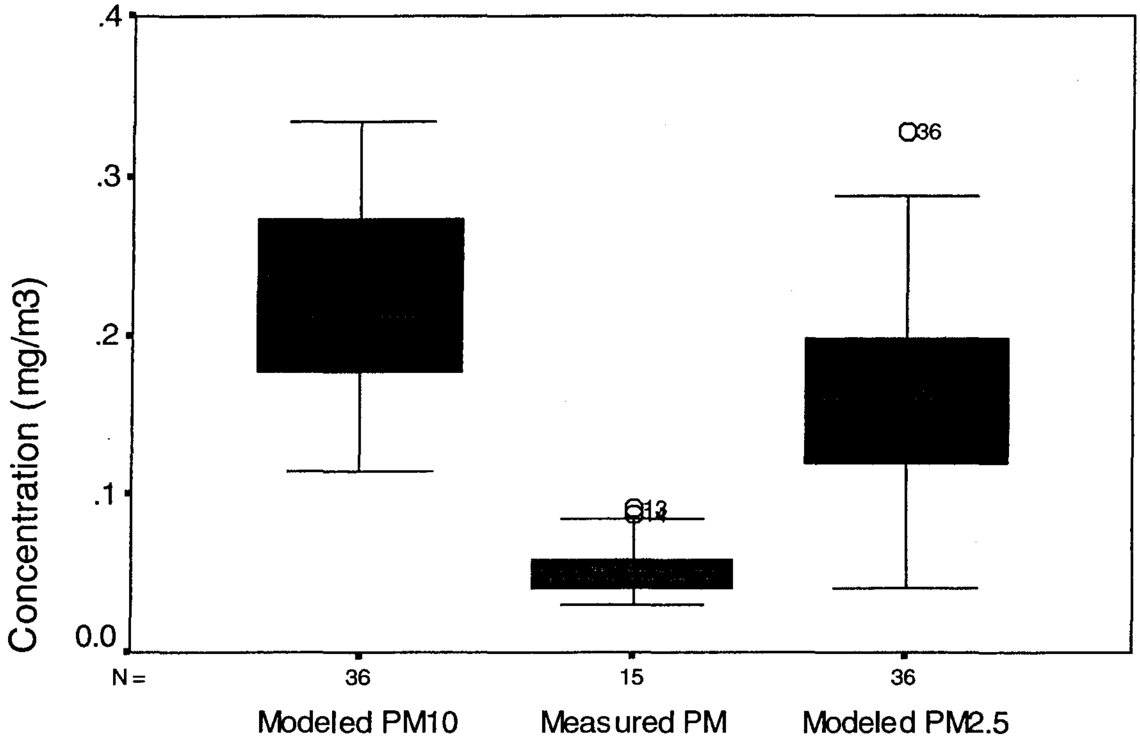


Figure 3-27

Comparison of Measured and Modeled PM

for Model 2, Compartment A

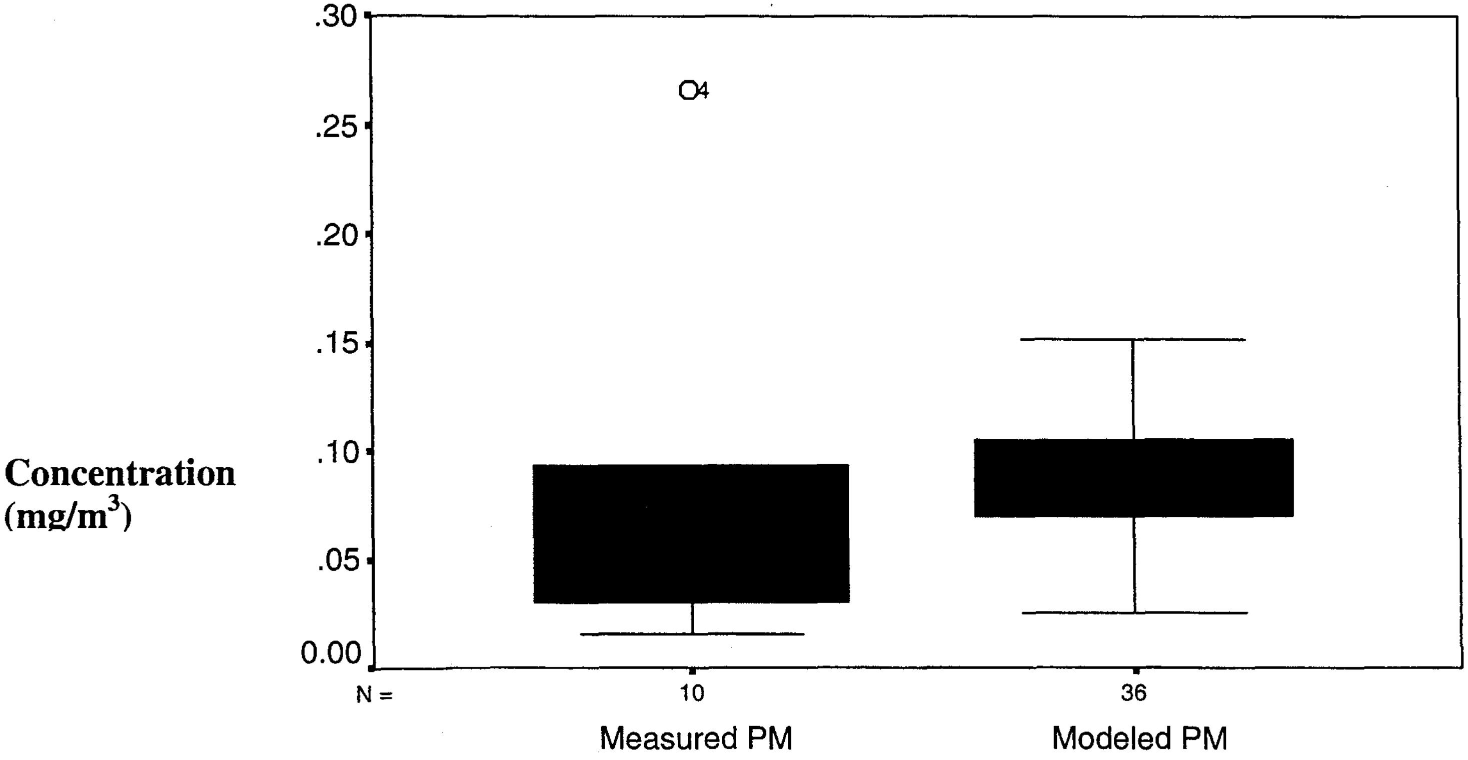


Figure 3-28

Comparison of Measured and Modeled PM

for Model 2, Compartment B

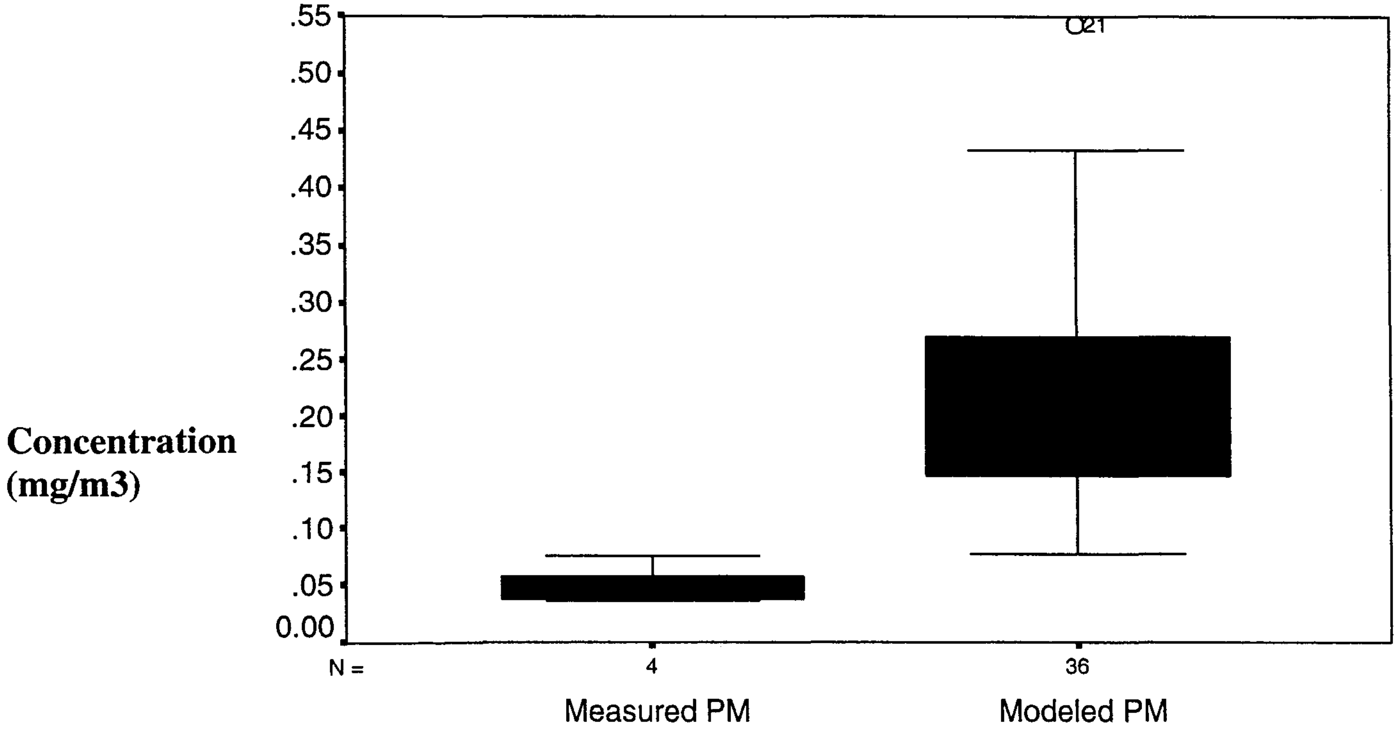


Table 3-X is based on the same data used to construct figures 3-25 to 3-28. The table compares model predictions for four small compartments within the plant to the particulate measurements made in those parts of the plant in April and May 2001. The coefficients of variability of the simulations are higher than for large compartments. Since the concentration of a small volume compartment has a small denominator by definition, it is not surprising that small volume compartments are more sensitive to variability in inputs that influence the numerator. The coefficients of variability of measurements of Compartment 1 and Compartment A indicate that these compartments are not very well mixed. Compartment 2 and Compartment B appear to be better mixed. However, in Compartment B, the low coefficient of variability of measured means could be an artifact of the small number of measurements. Absolute difference / measured mean can be understood as measure of the size of the model's error in predicting the measured mean. The size of the error ranges from 78% to 356% of the measured mean, a disappointingly high result.

A potential reason for the disappointing result is that the consequences of random deviations from model assumptions may be much greater over a small volume. In a large compartment, random deviations from the well-mixed assumption that are spread throughout the compartment may cancel each other out, having little impact on the mean concentration. For small compartments, it might be that deviations which could be shown to be randomly distributed over a large population of small compartments each produce a systematic effect on a particular compartment. For example, Compartment 1 was modeled as if air from the nearby fan was passing rapidly and uniformly throughout the entire compartment. As a result, the model predicted that the concentration in

Table 3-X: Comparison of Modeled PM Concentrations to PM Concentrations Measured in Small Virtual Compartments Selected to be Source Proximate Zones

	Compartment 1 (April, 2001)[•]	Compartment 2 (April, 2001)[•]	Compartment A (May, 2001)	Compartment B (May, 2001)
Volume (m^3)	1.63	4.9	2.04	0.56
# of simulations	36	36	24	24
# of measurements	5	15	11	4
modeled mean (mg/m3)	0.045	0.222	0.083	0.219
coefficient of variability of simulations	0.06	0.27	0.35	0.46
measured mean (mg/m3)	0.201	0.054	0.114	0.048
coefficient of variability of measurements	0.82	0.34	1.24	0.33
absolute difference	0.156	0.168	0.031	0.171
absolute difference / measured mean	0.78	3.11	0.272	3.56

[•] Model 1 (compartments 1 & 2), the table reports results calculated using outdoor PM_{10} as an input.

Compartment 1 (0.045 mg/m^3) would be slightly greater than the concentration in dehumidifier assembly (0.043 mg/m^3). In fact , the five measurements made in Compartment 1 exhibited an average (0.201 mg/m^3) that far exceeded the measured average for dehumidifier assembly (0.061 mg/m^3). Three measurements in the eastern part of Compartment 1 exceeded the measured average, while two measurements in the western part of Compartment 1 were near or below model predictions. It may be that Compartment 1 was not well mixed and that the fan influenced concentrations in only the western part of Compartment 1. Compartment 1, itself, had been separated from Compartment 2 because Compartment 1 and 2 together were unlikely to form a well-mixed compartment, due to the presence of the fan. Another potential reason for the failure of modeled means to match measurements in small compartments, is that it was not possible to make evenly spaced measurements within the compartments, precisely because the compartments were chosen to contain workers working with torches. Measurements had to be taken without putting the researchers or the workers in danger and without interfering with the work.

Conclusion

The results of this validation exercise are not encouraging for the use of small source-proximate zones, under 5 cubic meters, to estimate historical occupational exposures. Not surprisingly, the fact that the mean measurement for Compartment 1 is more than 3 times the mean measurement for dehumidifier assembly as whole (0.201 mg/m^3 vs. 0.061 mg/m^3) illustrates that exposures near a source may be considerably higher than average exposures for a workspace. However, this validation exercise has highlighted the difficulty of identifying small-well mixed, source proximate zones that can be modeled with confidence. One can imagine that, in the absence of time and resource constraints, one could conduct enough air velocity measurements to better identify well-mixed source proximate zones at the time of measurement. However, due to the inherent variability of air speed and direction, even such an investment of resources would not provide high confidence in the appropriateness of the same zones for estimation of historical exposure. Regrettably this limits the usefulness of this method and suggests that extensive ongoing industrial hygiene monitoring would be a preferable means of evaluating the impact of pollution prevention on occupational exposures. The performance of the model for larger compartments is more encouraging.

The model's ability to predict concentrations compartments greater than 39,000 m^3, though not perfect, is more encouraging. In three of the four compartments, including both of the compartments in which particulate sources were present, the size of the error was less than 30% of the observed mean concentration. In all but one compartment, the error was in the direction of under-prediction rather than over-prediction. The circumstances associated with over-prediction of particulate concentration in warehouse A may not apply when the contaminant modeled is not present in significant quantities in ambient outdoor air. Measured particulate matter reflected particulate generated in the plant plus particulate in the ambient air coming into the plant. The model had to include a term for such particulate. In warehouse A, the predicted concentration was exactly equal to the value used for particulate in the ambient air. The compartment contained no modeled sources of particulate generated in the plant. Hence, the over-prediction is likely to be due to greater particulate concentrations in the ambient air at the closest monitoring station than in the local ambient air near the plant. This means that, when modeling contaminants whose concentration in ambient air is negligible, the validation results suggest that under-prediction is more likely than over-prediction. This permits some confidence that when the modeling is used to estimate the impact of pollution prevention on occupational exposure, error is likely to be in the same direction for all contaminants and time periods modeled. As a result, the model can be used to compare relative contaminant concentration levels in a large compartments at different points in time. One reason that the model did not perform better may be that particulate matter is inherently more difficult to model than vapors because particulate is subject both to deposition and to re-entry into the air.

Scientific Report

Chapter 4

A Quantitative Assessment of the Impact of a Pollution Prevention Program on Occupational Exposures

Abstract

This chapter describes an evaluation of the impact of an industrial facility's pollution prevention (P2) program on occupational exposures. Due to the lack of adequate baseline exposure data, it was necessary to model exposures before and after P2 and to compare model results. The facility eliminated a trichloroethylene (TCE) degreaser and undertook other process changes that allowed it to produce air conditioners and dehumidifiers without degreasing parts with TCE. The study question is 'What was the impact of the elimination of TCE on occupational exposures during the period 1994-1997?'

In order to answer this question, workers were interviewed as to where in the plant they worked and how much time during a shift they spent in each location. Concentrations of TCE, petroleum naphtha and mineral spirits were modeled, using Monte Carlo simulations to account for uncertainty and variability in the input values. In order to compare cumulative exposures across job titles and across time, exposure severity scores, which weight exposures based on toxicity, were calculated for each job title in each department for each year and season in the study. Two different versions of the exposure severity score were calculated. One weights TCE by its non-cancer health effects. The other weights TCE by its cancer potency. Analysis of variance (ANOVA) models were used to estimate the impact of the elimination of TCE on toxic exposures.

Results indicated that the worker population in the plant experienced an overall reduction in exposure severity. Workers in the brazing department and in the immediate vicinity of the degreaser benefited most because they had the highest TCE exposures before P2. Metal press workers and tube making workers experienced statistically significant increases in exposure severity. They had very low TCE exposures before P2

and they experienced increased naphtha exposure afterward. The increase in naphtha exposure was due to the use of a more volatile metal press lubricant so that parts would arrive at the assembly line relatively free of lubricant even though they were not degreased. Policy makers and facility pollution prevention planners should note that this evaluation has shown both that P2 can reduce the severity of occupational exposures and that it can increase their severity. They should pay attention to occupational exposures in P2 planning. P2 options whose occupational exposure impacts are beneficial (or at least neutral) should be adopted, while those whose occupational exposure impacts are detrimental should be rejected.

Introduction

This chapter describes an evaluation of the impact of an industrial facility's pollution prevention (P2) program on occupational exposures. There are few published studies that examine the conditions under which pollution prevention increases or reduces the severity of occupational exposures. It is difficult to determine the impact of many pollution prevention programs on occupational exposure because adequate baseline exposure data are rarely available. The facility in this study was not atypical in this respect. Although the plant hired an industrial hygiene consultant periodically to sample contaminants of concern, the sampling was not intended to establish baseline data that could be used to evaluate the impact of process changes on exposure. As a result, it was necessary to model exposures before and after pollution prevention and to compare model results. This was done using a model validated by the author (see previous chapter). In this chapter, the pollution prevention program is presented, as are the methods for evaluating the impact of pollution prevention on exposure. Results are presented and the implications of the findings for pollution prevention planning are discussed.

The Pollution Prevention Program

The plant in this study is an air conditioner and dehumidifier manufacturer. The study period for which data are presented and analyzed here is 1994-1997. During period studied, the plant undertook a number of pollution prevention interventions :

- At the end of 1995, the plant eliminated a degreaser, putting an end to its use of trichloroethylene (TCE, CAS number 79-01-6), a probable human carcinogen (IARC, 1995). The degreaser had been used to remove lubricant from steel air conditioner and dehumidifier parts that were made by stamping them with a punch press.
- During 1995, the plant phased out its use of refrigerant 500 in air conditioners and dehumidifiers. By 1996, its use had been eliminated. Refrigerant 500 is a mixture of dichlorodifluoromethane (CAS number 75-71-8) and 1,1-difluororethane (CAS number 75-37-6). It was phased out because of its ozone-depleting properties.

As a result of these interventions the plant found it necessary to make the following process changes:

- Without the use of the degreaser, the plant found that it was unable to remove the lubricant it had been using from the stamped steel parts. The composition of that lubricant was 90-100% petroleum naphtha (CAS number 64741-65-7) with small amounts of mineral spirits (CAS number 8052-41-3). The plant ceased to use this lubricant after 1996.
- In 1996, the plant experimented with the use of another petroleum naphtha (CAS number 64741-65-7) based lubricant. That lubricant exhibited similar problems and its use was discontinued in the same year.
- In the same year, the plant introduced a third lubricant consisting of 90-100% petroleum naphtha (CAS number 64741-65-7) with small amounts of phosphate ester and animal lard as well as mineral spirits (CAS number 8052-41-3).

According to an engineer at the plant, this lubricant volatilized more completely and was thus, more easily removed without TCE.

- Before the elimination of refrigerant 500, the plant had made different coils for air conditioners and dehumidifiers. It had used mineral spirits (CAS number 8052 - 41-3) to lubricate the machines that made the dehumidifier coils. After the elimination of refrigerant 500, the plant decided to use the same coils for air conditioners and dehumidifiers. In 1997, it phased out the use of the dehumidifier coil machines and, with them, the mineral spirits.
- After the elimination of refrigerant 500, chlorodifluoromethane became the sole refrigerant used in the plant.

The Study Question

The question that this study attempts to answer is 'What was the impact of the elimination of TCE on occupational exposures during the period 1994-1997?' As discussed below, data that would have permitted a direct evaluation of the impact of the elimination of refrigerant 500 on occupational exposure are not available.

Methods

The following steps were taken to evaluate the impact of the elimination of TCE on occupational exposure:

1. Workers were interviewed in order to determine where in the plant they worked and how much time during a shift they spent in each location in the plant where they worked. This information was necessary in order to estimate time-weighted average (TWA) exposures for each job title within each department in the plant. Due to uncertainty of recollection, day-to-day and week-to-week variability of work performed by a given worker, and variability of work between workers with the same job title, time spent in each location was often expressed as a range of values rather than a given value.

2. The full-shift average concentrations of TCE, petroleum naphtha and mineral spirits were modeled for each location of interest in the plant using summer and winter data from 1994-1997. To reflect uncertainty and variability in the input values, Monte Carlo simulation was used to generate 36 modeled concentration values for each of the above chemicals each year and season for each location of interest in the facility.

3. In order to estimate TWA exposures for each job title within each department, a second Monte Carlo simulation was run 72 times. For each trial, an amount of time spent in each location was randomly selected for each job title within each department from the ranges reported in step 1 and a concentration for each chemical in each location was randomly selected from the results of step 2.

4. For each of the 72 runs, an exposure severity score (ESS) was calculated for each job title in each department for each year and season in the study. The purpose of the exposure severity score is to weight exposure by toxicity. It recognizes that not all chemical exposures are equally hazardous to health. Two different versions of the exposure severity score were calculated. One weights TCE by its non-cancer health effects. The other weights TCE by its cancer potency

5. Analysis of variance (ANOVA) models were used to estimate the impact on occupational exposure of the elimination of TCE.

Worker Interviews

(Step 1)

In order to calculate a TWA exposure for each job title in each department, it was necessary to know where in the plant employees worked and how much time during a shift they spent in each location. This information was obtained by administering a questionnaire to 292 current and former workers by telephone. The text of the questionnaire may be found on p. 190 of the Appendix. For each location in the plant where an interviewee worked, he or she reported the amount of time per week spent in that location. Locations were coded by translating each one into a compartment in each of the concentration models for TCE, petroleum naphtha and mineral spirits described below (step 2). The amount of time an employee with a given job title reported spending in a given location was coded as the amount of time employees with that job title were exposed to each of the three chemicals at concentrations modeled for the corresponding compartments. If two or more employees with the same job title reported spending different amounts of time at a given location or if a single employee reported a range of times, reflecting variability in the work or uncertainty in the employee's memory, the amount of time employees with a given job title spent in given location was treated as a range of values. In each of the 72 runs of the Monte Carlo simulation in step 3, a value for the amount of time that workers with that job title spent in that location was randomly selected from the range of values derived from the interviews. For job titles for which interviews could not be obtained, the research made use of answers in writing provided by a plant engineer and written standard job descriptions made available by the plant.

Modeling Full-Shift Average Concentrations for Locations of Interest in the Plant

(Step 2)

Contaminants Modeled

In this study, concentrations of TCE, mineral spirits, and petroleum naphtha were modeled. Concentrations of refrigerants were not modeled because there were no refrigerant emissions data to use as model inputs, due to the fact that the company reported no releases of refrigerants. The refrigerants were contained in closed systems, which means that, when everything functioned as it was supposed to, there were no refrigerant exposures. However, employees and management acknowledged that unidentified leaks and/or improper work practices may have resulted in some refrigerant releases. Unfortunately no reliable estimate of the quantity of such releases was available.

Although it cannot be demonstrated quantitatively, there are qualitative reasons to believe that the plant's P2 activities with regard to refrigerants may have reduced the severity of worker exposures. Table 4-I indicates the toxicity and annual use of each refrigerant. Reference concentrations established by the U.S. Environmental Protection Agency are used to compare toxicity because neither recommended exposure limits (RELs) established by the National Institute for Occupational Safety & Health (NIOSH), nor Threshold Limit Values (TLVs) established by American Conference of Governmental Industrial Hygienists (ACGIH) were available for 1,1-Difluoroethane. The rightmost column of the table indicates that the total use of refrigerants declined in each year of the study period. The columns for the individual refrigerants indicate that the use of each one of these declined in each year of the study period. If the level and probability of exposure are proportional to use, exposure is likely to have declined over the study period. Moreover, 1,1-Difluoroethane, the most toxic of these refrigerants as indicated by EPA reference concentration (RfC) was totally eliminated. Although this can not be considered a quantitative demonstration that P2 activities related to refrigerants reduced the severity of occupational exposure, it appears that they may have.

Table 4-I:
Refrigerant Use 1994-1997

	1,1-Difluoroethane (HFC-152a, CAS# 75-37-6)	**Dichloro-difluoromethane (CFC-12, CAS# 75-71-8)**	**Chloro-difluoro-methane (HCFC-22, CAS# 75-45-6)**	**Total**
RfC[1] (mg/m^3)	40	100	500	N/A
1994 Use (lbs.)	36,653	103,243	1,571,013	1,710,909
1995 Use (lbs.)	31,263	88,061	1,411,599	1,530,923
1996 Use (lbs.)	2,785	7,844	1,208,325	1,218,954
1997 Use (lbs.)	0	0	904,695	904,695

Mathematical Concentration Model

Contaminant concentrations were estimated using computer 'modeling elements' developed by Zemba and Luis (1993). The elements were used to implement a model that divides an indoor space into well-mixed compartments. An assumption that underlies the model is that, within each compartment, air movement produces a uniform

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[1] EPA reference concentration (Environmental Defense, 2001)

contaminant concentration. The model is flexible enough to permit the use of as many well-mixed virtual compartments as are necessary to capture important spatial variations in concentration. The following equation is used by Zemba and Luis to estimate contaminant concentrations in a given virtual compartment adjacent to others:

$$d(c_jV_j)/dt = E_j - \sum_{\substack{i=1\\ i\neq j}}^{n} Q_{i\leftarrow j}\, c_j + \sum_{\substack{i=1\\ i\neq j}}^{n} Q_{i\rightarrow j}\, c_i \qquad \text{(Equation 1: Concentration Model)}$$

where

c_j	is the contaminant concentration in compartment j
V_j	is the volume of compartment j
E_j	is the emission rate from a source into compartment j
n	is the number of compartments that exchange air with compartment j
i	is the subscript that refers to one of the n compartments that border compartment j
$Q_{i\rightarrow j}$	is the rate at which air passes from compartment i to compartment j (where compartment i can be either a virtual compartment within the modeled space or an external source)
c_i	is the contaminant concentration in compartment i
$Q_{i\leftarrow j}$	is the rate at which air passes from compartment j to compartment i (where compartment i can be either a virtual compartment within the modeled space or an external sink)

The literature discussing the theoretical development of the concentration model is presented above (Chapter 2) as is a validation of the model's predictions of air contaminant concentrations (Chapter 3).

Models for Each Contaminant

The contaminants of interest have sources that are physically located in different parts of the plant. For that reason, a different division of the facility into virtual compartments was necessary for each contaminant modeled in order best to identify important variations in concentration. Figure 4-1 presents the division of the facility into virtual compartments used to model concentrations of TCE in different parts of the plant. The only source of TCE was the degreaser that was eliminated after 1995. It was in the virtual compartment marked with an asterisk. The brazing machine space was divided into two virtual compartments (A and B) because it was believed *a priori*, based on the location of the source and the magnitude and direction of measured air velocity, that there would be a large concentration gradient within this space. A single virtual compartment contained the coil wash, expanding machines and fin presses. Another single compartment contained the tube making machines, hairpin bending machines, dehumidifier assembly, warehouse B and finished goods storage. One compartment contained metal presses. One contained warehouse A and all the AC assembly lines and the last one contained injection molding machines and the finished goods department.

Figure 4-1:

Division of the Plant Into Virtual Compartments for the Purpose of Modeling TCE

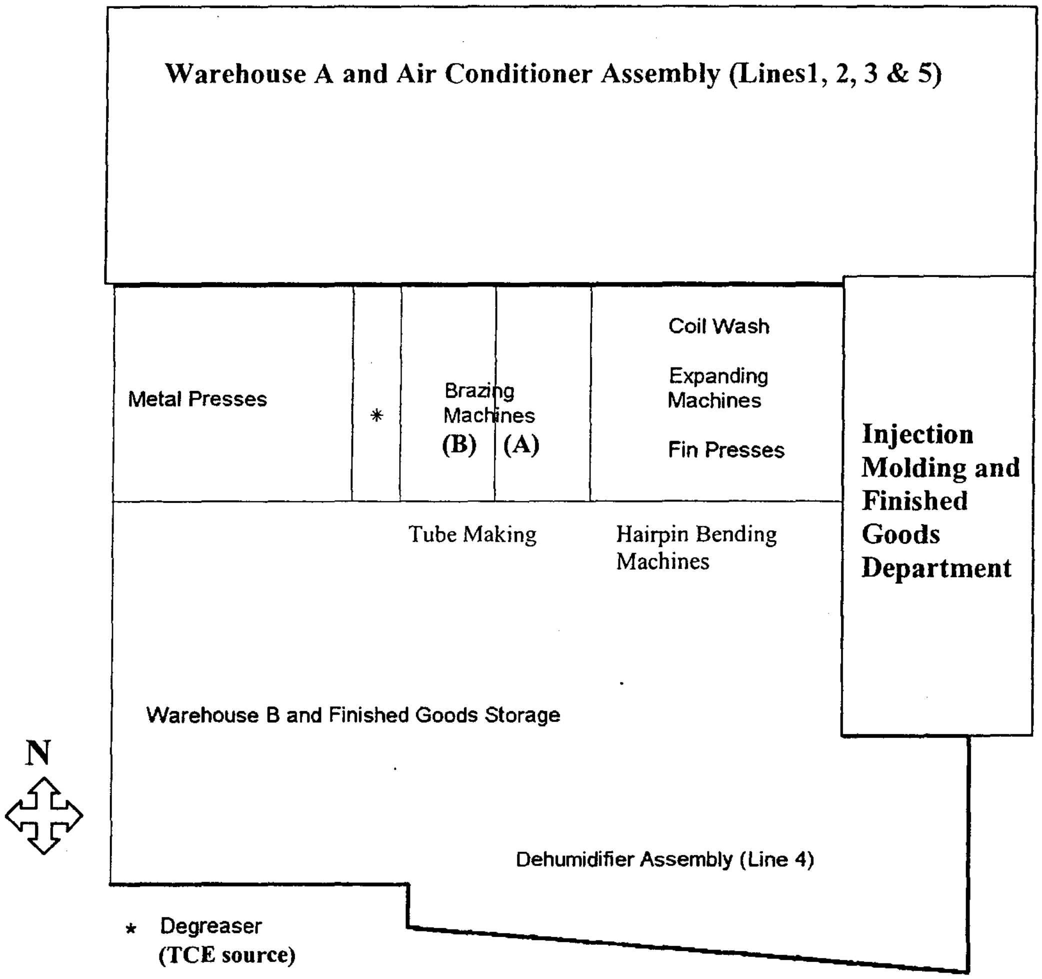
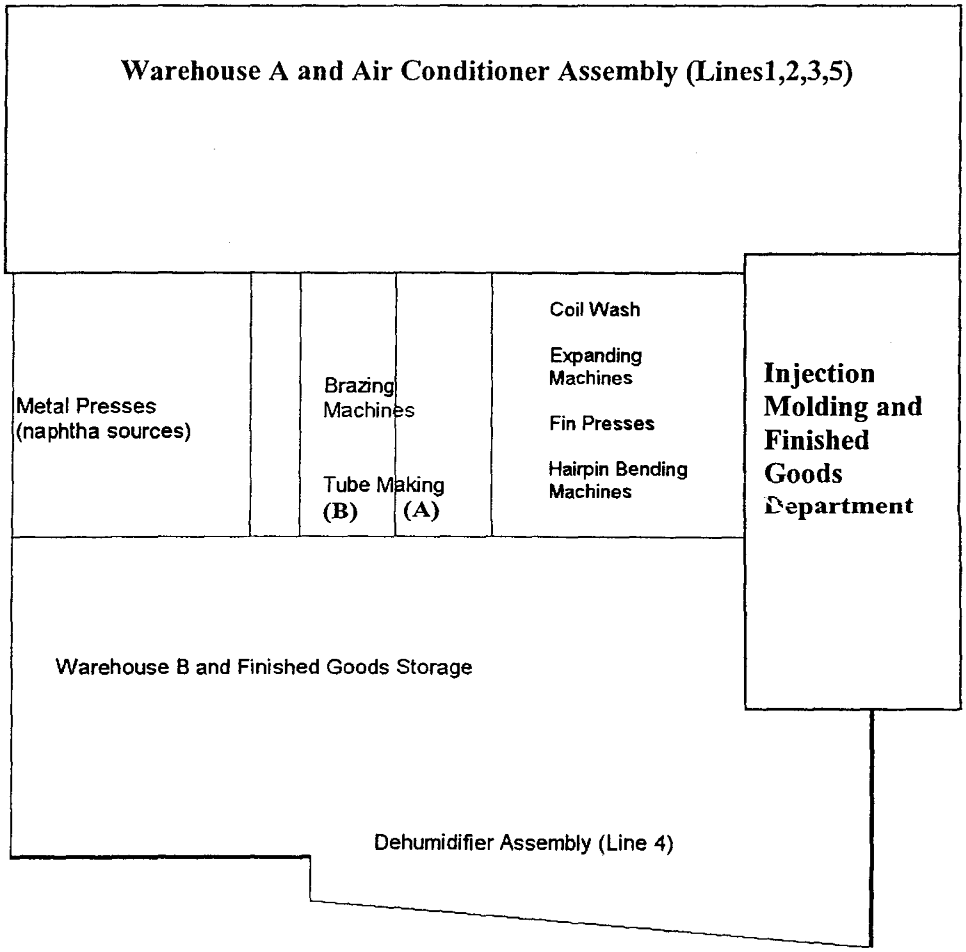


Figure 4-2 presents the division of the plant into virtual compartments for the purpose of modeling petroleum naphtha. It is similar to the division for TCE, but several compartments have been lengthened. The metal presses are the naphtha sources. For the TCE model, the compartment containing warehouse B and finished goods storage included the southernmost row of metal presses. Based on the location of the source and the magnitude and direction of air velocity, it was believed that the modeled

Figure 4-2:

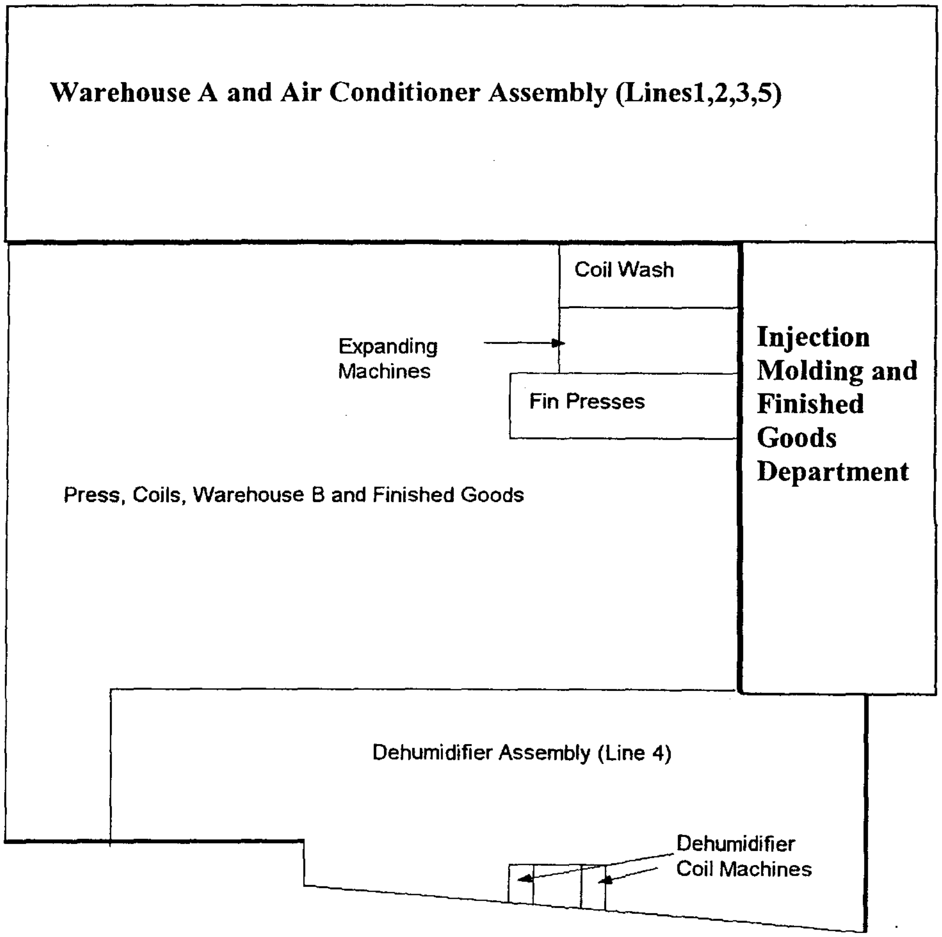
Division of the Plant Into Virtual Compartments for the Purpose of Modeling Petroleum Naphtha



concentration of TCE for this compartment would better reflect the concentration of TCE for the southernmost row of metal presses. Since the metal presses are the source of petroleum naphtha, when modeling petroleum naphtha, it made most sense to put all the metal presses in a single compartment. Since the air in that part of the plant blew from west to east, it made sense to lengthen the compartments located east of the metal

Figure 4-3:

Division of the Plant Into Virtual Compartments for the Purpose of Modeling Mineral Spirits



Coil Wash, Fin Presses and Dehumidifier Coil Machines are all sources of mineral spirits.

presses. Hence, the two compartments containing brazing machines were expanded to include tube making machines as well and the hairpin bending machines were placed in the compartment containing the coil wash, expanding machines and fin presses.

Figure 4-3 presents the division of the plant into virtual compartments for the purpose of modeling mineral spirits. The sources of mineral spirits are the fin presses, the coil wash and the dehumidifier coil machines. Because these sources have a very different location in relation to the magnitude and direction of air flow, the division is quite different. The compartment containing warehouse A and the AC assembly lines is identical to the similarly labeled compartment in the other two models as is the compartment containing the injection molding machines and the finished goods department. For this model, the metal presses and the coil department including the brazing and tube making machines are in the same compartment as warehouse B and finished goods storage. Dehumidifier assembly is now in its own compartment. Within dehumidifier assembly are two smaller compartments containing coil machines and another compartment that accounts for the space between the two dehumidifier coil machines. The fin presses and coil wash each have their own compartments because they are sources of mineral spirits. The expanding machines are given their own compartment to account for the space between the fin presses and coil wash.

Variability and Uncertainty in Concentration Estimates

Figure 4-4 is a flowchart that describes Monte Carlo Analysis of the concentration model. Because information about many of the input parameters in Equation 1 is incomplete and/or the phenomena they describe are inherently variable, choosing a single value for each model input and running the model only once could produce results whose deviation from the true concentration in each compartment is due to random error rather than model properties. To account for random error, Monte Carlo simulations were run using the Crystal Ball® 4.0 software (Decisioneering, 2000), an Excel© macro. In a Monte Carlo simulation, the user defines a probability distribution for each inherently variable input and for each input whose value is uncertain. Models are run multiple times. For this study, the latin hypercube method (Decisioneering, 2000) was used to select a value on each iteration from distributions assigned to each input that was variable or uncertain.

The selected values were used as inputs in Simulink™ applications, written using the Zemba and Luis modeling elements. The applications calculate the time-dependent contaminant concentrations for each compartment in each model. After each iteration, Crystal Ball® 4.0 saves the results and selects new values for the variable or uncertain inputs. The process is repeated until a user-specified number of iterations is reached. Upon completion, Crystal Ball® 4.0 presents the distributions and descriptive statistics for the time-dependent concentration of the modeled contaminant in each compartment. Each of the three concentration models, TCE, petroleum naphtha, and mineral spirits was run 36 times. Results were used as inputs for step 3, modeling TWA exposure.

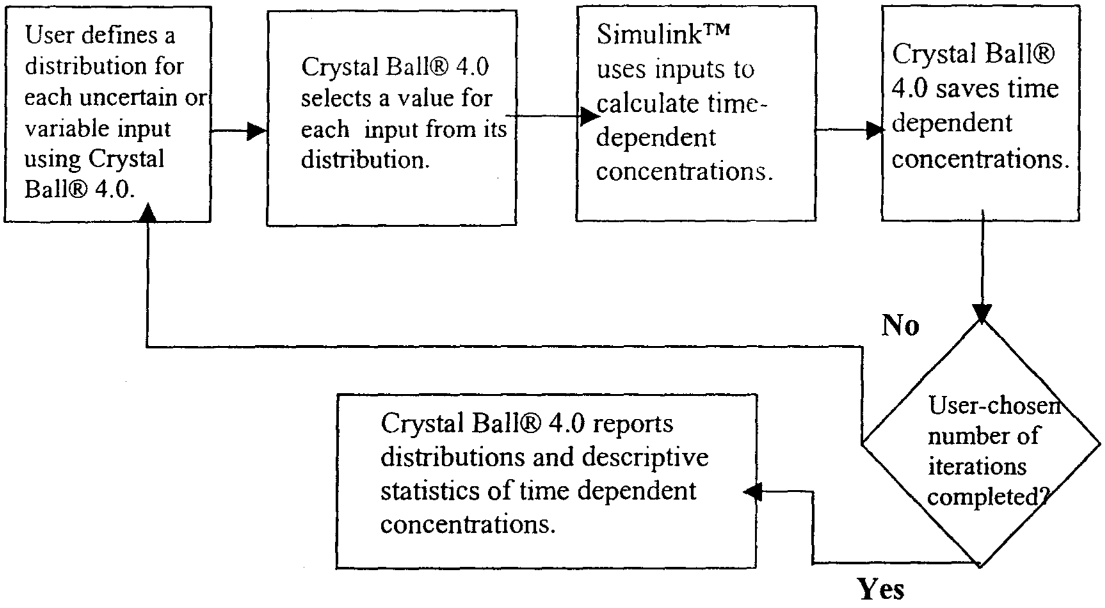


Figure 4-4:
Flowchart of Monte Carlo Analysis of Time-Dependent Air Contaminant Model

Model Inputs

In order to calculate time-dependent contaminant concentrations in each compartment, the following inputs are needed:

- the rate of emission of each contaminant within each compartment (E_j in Equation 1),
- the volume of each compartment (V_j in Equation 1),
- the rates at which air passes out of each compartment to each adjacent compartment and to the outside ($Q_{i\leftarrow j}$ in Equation 1), and
- the rates at which air passes into each compartment from each adjacent compartment and from the outside ($Q_{i\rightarrow j}$ in Equation 1).

Distributions (or constant values) of each of the inputs were determined as indicated below.

Emission of Chemical Contaminants: Table 4-II indicates annual average emission rates for chemical contaminants modeled in this study. For mineral spirits emitted from the dehumidifier coil machines, the plant provided the data indicating annual quantity of mineral spirits used by these machines and the annual number of hours of operation. Because the material safety data sheet indicates that mineral spirits are 100% volatile, emission rates were calculated by dividing the quantity used by the time of operation. Results were translated to mg/min.

For TCE, naphtha, and the larger sources of mineral spirits, located in the coil department, emission rates were taken from the plant's annual report to the New Jersey Department of Environmental Protection. From the annual emissions and the number of operating hours, it was possible to calculate average rates of emission of all three contaminants from each source. For petroleum naphtha only, the plant provided additional data that permitted a description of the variation in emission rates. Daily average rates of petroleum naphtha emissions from the metal presses (mg/min) were calculated for one day of each of the 76 weeks that the plant was operational between 15 March, 1999 and 22 December, 2000. This was done by dividing the total quantity emitted each day by the amount of time that the presses operated that day. Two pieces of information were derived from these 76 daily average emission rates. One was the shape of the distribution. Using Crystal Ball® 4.0, it was determined that a normal (mean = 61,421 mg/min, s.d. = 24,761) distribution was a better fit for the 76 daily average emission rates than a lognormal distribution (geometric mean = 55,931 mg/min GSD = 1.59). The χ^2 goodness of fit value for the normal distribution was 10.26 (p = 0.25). For the lognormal distribution, the χ^2 goodness of fit value was 17.21 (p = 0.03). The second piece of information was the coefficient of variability, which was 0.41. On the basis of these two pieces of information, distributions of petroleum naphtha emissions for the years 1994-1997 were constructed as follows. The mean of the distribution was calculated by dividing total annual emissions by total annual operating time. It was expressed in mg/min. The standard deviation of the distribution was calculated by multiplying the mean by 0.41. The distribution was assumed to be normal.

Table 4-II: Annual Average Emission Rates of Chemical Contaminants						
Process	**Pollutant**	CAS#	**1994 Emissions** (mg/min)	**1995 Emissions** (mg/min)	**1996 Emissions** (mg/min)	**1997 Emissions** (mg/min)
Degreaser	TCE	79-01-6	333,841 (no data available for fitting distribution)	322,340 (no data available for fitting distribution)	0	0
Fin Presses (Coil)	Mineral Spirits	64742-48-9	179784 (no data available for fitting distribution)	211823 (no data available for fitting distribution)	225188 (no data available for fitting distribution)	123317 (no data available for fitting distribution)
Dehumidifier Coil Machines	Mineral Spirits	8052-41-3	4567 (no data available for fitting distribution)	6418 (no data available for fitting distribution)	6481 (no data available for fitting distribution)	5304 (discontinued midyear)
Oil Separator (Coil Wash)	Mineral Spirits	64742-48-9	2242 (no data available for fitting distribution)	2242 (no data available for fitting distribution)	2242 (no data available for fitting distribution)	433 (no data available for fitting distribution)
Metal Presses	Petroleum Naphtha	64741-65-7	Mean: 53,629 s.d.: 73711 (normal distribution)	Mean: 62,737 s.d.: 25,722 (normal distribution)	Mean: 112,554 s.d.: 46,147 (normal distribution)	Mean: 102,850 s.d.: 42,168 (normal distribution)

Volume: The volumes of the part of the plant containing Warehouse A and AC Assembly and of the part of the plant containing injection molding and the finished goods department were calculated on the basis of the facility plans, which report their dimensions. The smaller compartments, indicated in Figures 4-1 through 4-3, were defined on the basis of professional judgment that contaminant concentrations were likely to vary significantly among the parts of the plant represented by each of the virtual compartments. Table 4-III indicates the volume of each compartments that is used in all three concentration models. Table 4-IV indicates the volume of each virtual compartment used in both the TCE and Naphtha models. Table 4-V indicates the volume of each the virtual compartment used only in the mineral spirits model. Compartment volumes ranged from 817 m^3 to 193,200 m^3. Interviews indicated that the smallest of these, between the two dehumidifier coil machines was rarely occupied by workers. The smallest compartment regularly occupied by workers was 1565 m^3, more than three hundred times as large as the compartment volume for which the validation (see previous chapter) indicated that the model was unreliable.

Table 4-III:
Volumes of Compartments
Common to All Three Concentration Models

Compartment	Volume (m^3)
Warehouse A / Air Conditioner Assembly	193,200
Injection Molding & Finished Goods	97,225

Table 4-IV: Volumes of Modeled Virtual Compartments in TCE and Naphtha Models (Refer to Figures 4-1 & 4-2)		
Compartment	**Volume (m^3) in Naphtha Model**	**Volume (m^3) in TCE Model**
Volume of virtual compartment containing metal presses	32646	24484
Volume of virtual compartment containing degreaser	6529	4896
Volume of western virtual compartment containing brazing machines.	13058	9793
Volume of eastern virtual compartment containing brazing machines.	6529	4896
Volume of virtual compartment containing coil wash, expanding machines and fin presses.	39175	29381

Table 4-V: Volumes of Modeled Virtual Compartments in Mineral Spirits Model (Refer to Figure 4-3)	
Compartment	**Volume (m^3)**
Press, Coils, Warehouse B & Finished Goods	237,364
Virtual compartment containing coil wash	5,713.06
Virtual compartment containing fin presses	4,896.91
Virtual compartment containing expanding machine	5,713.06
Dehumidifier Assembly (Line 4)	53,661.98
Virtual compartment containing first of two dehumidifier coil machines.	1,707.04
Virtual compartment containing second of two dehumidifier coil machines.	1,564.23
Virtual compartment between two dehumidifier coil machines	817.82

The rates at which air is exchanged between each compartment and the outdoors were calculated on the basis of information provided in two ventilation reports conducted for the plant. One is from 1991 and the other is from 1996. Table 4-VI reports the distributions used for ventilation rates that are common to all three models. Table 4-VII reports ventilation rates for compartments common to the TCE and Naphtha models. Table 4-VII reports ventilation rates for compartments unique to the mineral spirits model. Triangular distributions describe the ventilation rates for air leaving the injection molding / finished goods compartment (Table 4-VI), for all the compartments listed in Table 4-VII and for air ventilated out of the virtual compartments containing the presses, coils warehouse B and finished goods, containing the coil wash, containing the fin presses, and containing the expanding machines (Table 4-VIII). The number and capacity of the exhaust fans in each compartment is taken from the 1996 plant survey. The fact that the likeliest value of the ventilation rate is 90% of the total capacity comes from the 1991 plant survey.

Table 4-VI:
Ventilation Rates (m^3/min) for Compartments Common to All Three Models

Ventilated Space	Distribution or Value
Air ventilated out of injection molding / finished goods	*Maximum value:* 5915 *Likeliest value:* 5325 *Minimum value:* 5030
Outdoor air brought into Warehouse A / AC Assembly by air handling units	3953.24 (winter) 5866.09 (summer)

Table 4-VII: **Ventilation Rates (m^3/min) for Compartments Common to TCE and Naphtha Models**	
Ventilated Space	**Distribution**
Air ventilated out of virtual compartment containing degreaser	*Maximum value:* 85 *Likeliest value:* 76.5 *Minimum value: 65*
Air ventilated out of western virtual compartment containing brazing machines.	*Maximum value:* 740 *Likeliest value*: 666 *Minimum value:* 630
Air ventilated out of eastern virtual compartment containing brazing machines.	*Maximum value:* 455 *Likeliest value:* 410 *Minimum value:* 385
Air ventilated out of virtual compartment containing coil wash, expanding machines and fin presses.	*Maximum value:* 7400 *Likeliest value:* 6650 *Minimum value:* 6300
Air ventilated out of virtual compartment containing warehouse B and finished goods storage.	*Maximum value:* 1940 *Likeliest value:* 1745 *Minimum value:* 1650

Table 4-VIII: Ventilation Rates (m^3/min) for Compartments in Mineral Spirits Model
(Refer to Figure 4-3)

Ventilated Space	Distribution or Value
Outdoor air brought into Press, Coils, etc. by air handling units	2196.24 (winter) 3258.94 (summer)
Air ventilated out of Press, Coils, etc.	*Maximum value*: 4340 *Likeliest value:* 3905 *Minimum value:* 3690
Air ventilated out of coil wash compartment	*Maximum value:*3236 *Likeliest value:* 2912.4 *Minimum value:*2750.6.
Air ventilated out of fin press compartment	*Maximum value:* 740 *Likeliest value:* 630 *Minimum value:* 665
Air ventilated out of the expanding machine compartment	*Maximum value:* 2220 *Likeliest value:* 2000 *Minimum value:* 1885
Air from dehumidifier assembly (line 4) ventilated to outside[*]	0

The rates at which air passes into a compartment from each adjacent compartment: These rates are expressed in volume of air per unit time. They are calculated by measuring the velocity at which air passes from one compartment to the next and multiplying by the area through which the air passes. Air velocity was measured using an Alnor ® Compuflow ® Thermoanemometer, model 8525. The probe on the anemometer was pointed perpendicular to the direction of airflow. Direction of airflow was determined using Dräger air current tubes. The light-emitting diode (LED) indicating the

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[*] Line 4 has no exhaust fans.

speed of airflow was watched for several seconds, Maximum and minimum values were recorded. Each measurement was assigned a value according to the following formula:

$$value = \sqrt{\min \times \max} \qquad \text{(Equation 2)}$$

This formula was chosen because a survey of wind speeds in 55 indoor workplaces by Baldwin & Maynard (1998) found that they tend to be lognormally distributed. Hence, the geometric mean is a better measure of central tendency than the arithmetic mean.

Distributions of air speed, used as model inputs in Monte Carlo simulations, were chosen on the basis of air velocity measurements. Where there were enough measurements to fit a distribution, a lognormal distribution was fit because of Baldwin and Maynard's findings. If there were fewer than three measurements, the geometric mean of the input distribution was chosen to be the geometric mean of the measurements (or the value of the measurement, if there was only one). Similarly, if there were three or fewer measurements, a value of 1.96 m/s was assigned to the GSD of the input distribution in the Monte Carlo simulation. This value was chosen because it was equal to the GSD of the wind speeds in the Baldwin & Maynard (1998) survey.

Figure 4-5 is a graphic depiction of all the locations in the plant at which air velocity measurements were taken. In Figure 4-5, each arrow without a letter designation indicates a single air velocity measurement taken in May 2001. Each of these arrows points in the direction the air was moving at the time of measurement. The lengths of these arrows are proportionate to the velocities measured. It can be seen in the figure that almost of all of the arrows without letter designations point north, west, or northwest.

Figure 4-5: Air Movement within the Plant

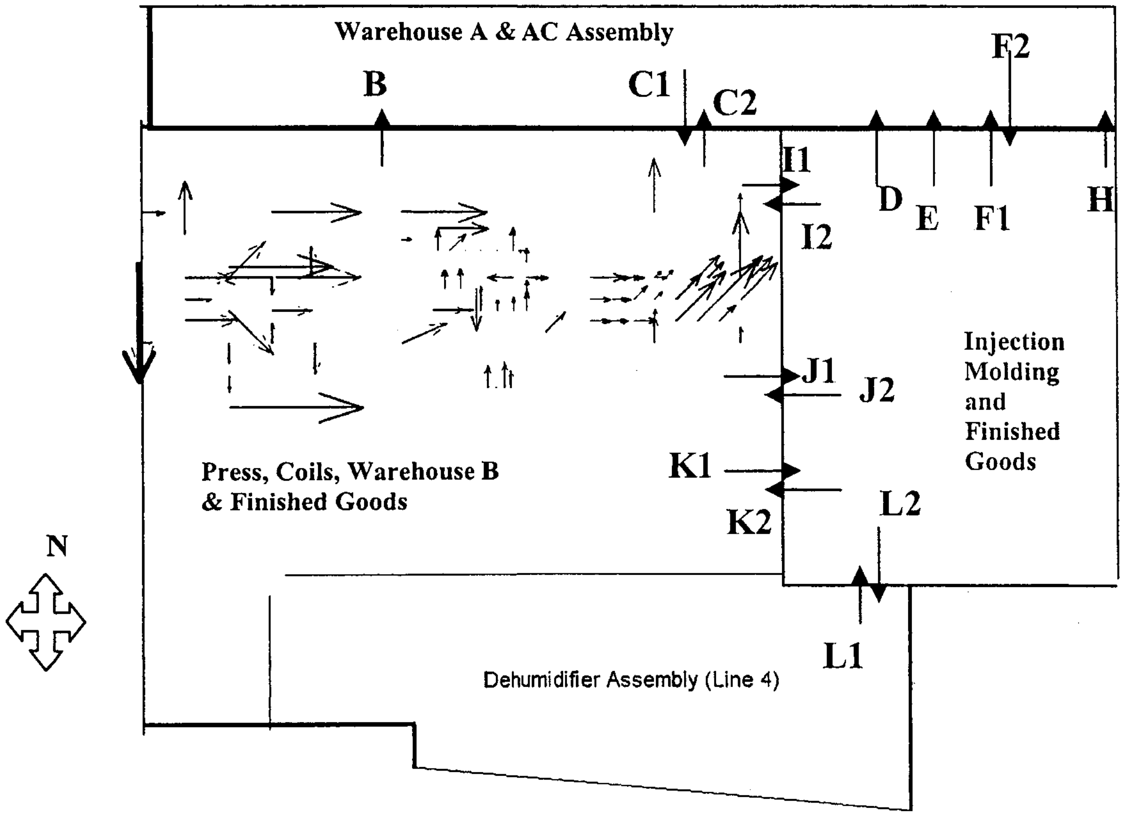

Table 4-IX:
Doorway Air Velocity Assumptions Used in All Three Models
(All distributions are lognormal)

Doorway: Direction (Doorway designations from Figure 4-4)	**Number of Measurements Taken**	**Geometric Mean of Input Distribution (m/s)**	**Geometric Standard Deviation of Input Distribution**
F1: injection molding to AC assembly	5	0.45*	1.69*
F2: AC Assembly to Injection Molding	2	0.22**	1.96***
H: Injection Molding to AC Assembly	7	0.58*	2.22*
I1: Coils, Press, Finished Goods & Warehouse B to Injection Molding	2	0.3**	1.96***
I2: Injection Molding to Coils, Press, etc.	5	0.6*	1.13*
J1: Coils, Press, etc. to Injection Molding	2	0.3**	1.96***
J2: Injection Molding to Coils, Press, Finished Goods and Warehouse B	5	0.23*	1.26*
K1: Coils, Press, etc. to Injection Molding	5	0.36*	1.83*
K2: Injection Molding to Coils, Press, Finished Goods and Warehouse B	2	0.13**	1.96***
L1: Dehumidifier Assembly to Injection Molding	6	0.22*	1.74*
L2: Injection Molding to dehumidifier assembly	1	0.22**	1.96***

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* Distribution fit using χ^2 test for goodness-of-fit.

** This is the mean value of the measurements taken.

*** A survey of wind speeds in 55 indoor workplaces by Baldwin & Maynard (1998) found that they tend to be lognormally distributed with a GSD of 1.96 m/s. This GSD was used where the number of measurements was too small to fit a distribution.

Table 4-X: Air Velocity Assumptions for TCE and Naphtha Models			
Airflow	**Number of Measurements Taken**	**Geometric Mean of Input Distribution**	**Geometric Standard Deviation of Input Distribution**
Velocity of air passing north from Warehouse B / Finished Goods to Metal Presses	5	0.15*	1.25*
Velocity of air passing south from Metal Presses to Warehouse B / Finished Goods	2	0.22**	1.96***
Velocity of air passing north from Warehouse B / Finished Goods to western virtual compartment containing brazing machines	5	0.15*	1.25*
Velocity of air passing west from virtual compartment containing coil wash, expanding machines and fin presses to eastern virtual compartment containing brazing machines	5	0.17*	1.66*
Velocity of air passing east from virtual compartment containing coil wash, expanding machines and fin presses to eastern virtual compartment containing brazing machines	5	0.17*	1.26*

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* Distribution fit using χ^2 test for goodness-of-fit.

** This is the mean value of the measurements taken.

*** GSD taken from Baldwin & Maynard (1998) survey.

Table 4-XI:
Air Velocity Assumptions Specific to Mineral Spirits Model

(refer to Figure 4-3)

Assumption	**Number of Measurements Taken**	**Velocity (m/s) Distribution**
Velocity of air movement from coils, press, etc. east to fin presses	6	geometric mean: 0.22[*] GSD: 1.28
Velocity of air blowing east from western dehumidifier coil machine	1	geometric mean: 0.29[**] GSD: 1.96[***]
Velocity of air blowing north from western dehumidifier coil machine	1	geometric mean: 0.17[**] GSD: 1.96[***]
Velocity of air blowing south from dehumidifier assembly to east dehumidifier coil machine	1	geometric mean: 0.11[**] GSD: 1.96[***]
Velocity of air blowing west from eastern dehumidifier coil machine	1	geometric mean: 0.11[**] GSD: 1.96[***]
Velocity of air movement from coils, press, etc. east to coil wash	17	Estimated using a regression model: velocity (m/s) = $\beta_0 + \beta_1 x_1$ where $\beta_0 = 0.534$ SE $\beta_0 = 0.041$ $\beta_1 = 0.0032$ SE $\beta_1 = 0$ x_1 = distance in meters from west end of plant

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[*] Lognormal distribution fit using χ^2 test for goodness-of-fit.

[**] This is the value of the measurement.

[***] Lognormal distribution, GSD taken from Baldwin & Maynard (1998) survey.

Estimating TWA Exposures to Each Chemical by Job Title, Department , Year and Season

(Step 3)

In order to estimate TWA exposures for each job title within each department, a second Monte Carlo analysis was run 72 times. For each trial, an amount of time spent in each location was randomly selected for each job title within each department from the ranges reported in step 1 and a concentration for each chemical in each location was randomly selected from the results of step 2. For each occupational title, an estimate of exposure to each chemical was calculated according to the following equation:

$$E_{ij} = \sum_{l=1}^{k} T_{il} C_{jl} \qquad \text{(Equation 3: Exposure Model)}$$

where

E_{ij} is the time-weighted average exposure to chemical j for occupational title i,

k is the number of locations within the plant in which individuals with occupational title i work.

T_{il} is the fraction of time that workers with occupational title i spend in location l.

C_{jl} is the modeled concentration of chemical j in location l.

T_{il} is taken from worker interviews. It is subject to uncertainty in recall. It is subject to variability, due to differences in what a given worker does from one day or one week to the next. It is further subject to variability, due to differences between the activities of different workers with the same job title. C_{jl} takes on a variety of values, due to variability and uncertainty in the inputs. As a result, Monte Carlo simulation was used to estimate E_{ij}. Values for T_{il} and C_{jl} were chosen randomly from the results of step 1 and step 2 respectively.

Rating Occupational Titles by Total Chemical Exposure

(Step 4)

Equation 4 was used to assign an exposure severity score for each occupational title in the facility for each of the 72 trials in step 3. It is as follows:

$$ESS_i = \frac{E_{i,naphtha}}{EL_{naphtha}} + \frac{E_{i,\min eralspirits}}{EL_{\min eralspirits}} + \frac{E_{i,TCE}}{EL_{TCE}} \qquad \text{(Equation 4)}$$

where ESS_i is the exposure severity score for occupational title i. $E_{i,\text{ naphtha}}$ is the TWA exposure level of workers in occupational title i to petroleum naphtha. Similarly $E_{i,\text{ mineral spirits}}$ and $E_{i,\text{ TCE}}$ are the TWA exposures of workers in occupational title i to each of those chemicals respectively. EL_{naphtha}, $EL_{\text{mineral spirits}}$, and EL_{TCE} are exposure limits for each of those chemicals respectively. For EL_{naphtha} and $EL_{\text{mineral spirits}}$, the Recommended Exposure Limits (RELs) of the National Institute for Occupational Safety & Health (NIOSH) were used. For both mineral spirits and petroleum naphtha the NIOSH REL is 350 mg/m^3.

NIOSH has not established a REL for TCE. It simply recommends that, as a probable human carcinogen, TCE should be controlled to the lowest feasible level. For this reason, other numbers must be used to calculate exposure severity scores. Two methods were chosen to do this. One was to use the Threshold Limit Value (TLV©) for TCE, established by the American Conference of Governmental Industrial Hygienists (ACGIH), which is set at 269 mg/m^3 in order to minimize symptoms of headache, fatigue, and irritability (ACGIH, 1991). Plugging the value of the TLV for TCE and of the RELs for petroleum naphtha into Equation 4 yields the following:

$$ESS_{i,TLV} = \frac{E_{i,naphtha}}{350mg/m^3} + \frac{E_{i,\min eralspirits}}{350mg/m^3} + \frac{E_{i,TCE}}{269mg/m^3} \text{ (Equation 4a)}$$

where $ESS_{i,\ TLV}$ is defined as the exposure severity score for occupational title i calculated using the NIOSH RELs for petroleum naphtha and mineral spirits and the ACGIH TLV for TCE. When data are analyzed across job titles, the resulting exposure severity scores is referred to as ESS_{TLV}.

The second method for calculating exposure severity scores was to use the concentration that corresponds to the OSHA significant risk level of 1×10^{-3}. This was done as follows. The EPA cancer potency factor for airborne TCE is 2×10^{-6} $m^3/\mu g$ (Environmental Defense, 2001). This means that the exposure level associated with a risk of 1×10^{-3} is $500\ \mu g/m^3 = 0.5\ mg/m^3$. EPA calculates risk based on the assumption that individuals are exposed 24 hours a day over a 70 year lifetime. For occupational risk, it makes more sense to calculate TWA dose on the basis of a 40 hour work week and a 45 year working lifetime. This means that occupational risk calculations are based on exposure times that are approximately 6.82 times less than the exposure times used by EPA. As a result, the occupational TCE exposure associated with a cancer risk of 1×10^{-3} is $6.82 * 0.5 = 3.41\ mg/m^3$. Plugging this value into

Equation 4, while still using the RELs for petroleum naphtha and mineral spirits yields the following:

$$ESS_{i,CAN} = \frac{E_{i,naphtha}}{350mg/m^3} + \frac{E_{i,\min eralspirits}}{350mg/m^3} + \frac{E_{i,TCE}}{3.41mg/m^3} \quad \text{(Equation 4b)}$$

where $ESS_{i,\,Can}$ is defined as the exposure severity score for occupational title i calculated using the NIOSH RELs for petroleum naphtha and mineral spirits and the cancer potency for TCE. When data are analyzed across job titles, the resulting exposure severity scores is referred to as ESS_{CAN}. Regardless of which way it is calculated, the exposure severity score is unitless. It provides an index for comparing risks before and after pollution prevention actions are implemented. The 'CAN' subscript in Equation 4b refers only to the fact that the cancer potency of TCE is used to calculate the exposure severity score. It is not intended to suggest that exposure to TCE, petroleum naphtha, and mineral spirits puts one at greater risk of cancer than exposure to TCE alone. Petroleum naphtha and mineral spirits are neurotoxicants. They are not carcinogens. The reason for having an exposure severity score that adds an index of TCE exposure severity based on cancer to indices of mineral spirits and naphtha exposure severity, based on neurotoxicity is to express quantitatively the intuitive concept that being exposed to a carcinogen and to a neurotoxicant is worse than being exposed only to a carcinogen or only to a neurotoxicant.

Each job title was assigned an ESS_{TLV} representing the median value of $ESS_{i,\,TLV}$ over 72 trials. Similarly, each job title was assigned an ESS_{CAN} representing the median value of $ESS_{i,CAN}$ over 72 trials. For dates after, 1995 $E_{i,\,TCE} = 0$ because the TCE degreaser was eliminated. As a result, after 1995

$$ESS_{i,CAN} = ESS_{i,TLV} = \frac{E_{i,naphtha}}{350mg/m^3} + \frac{E_{i,\min eralspirits}}{350mg/m^3} \qquad \text{(Equation 4c)}$$

The output of Equation 4c is also referred to as ESS (No TCE).

Determining the Distribution of Exposures Across the Employee Population

In order to estimate the distribution of exposures across a population of workers, it is necessary to know how many workers of each job title were employed in each season in the study period. In the plant studied, a production engineer sends the personnel department a monthly request indicating the number of employees of each job title that will be needed in each department for the following month. These requests were the best available estimates of the number employees who had worked in each job title historically. The production cycle for air conditioners and dehumidifiers requires the greatest number of employees between January and March of year and the least in August and September. For each year of the study period, the plant provided one personnel request for a low staff month and one personnel request for a high staff month. These data were obtained at the level of the individual job title. Exposure severity scores were calculated for each season and year for each job title in the first shift. The analysis was limited to the first shift because it is the shift with the greatest number of employees and all sources of emissions operate during the first shift.

For the purposes of analysis and presentation, job titles were grouped into 'departments' based on the locations in the plant where workers with each job title spent the most time. Many, but not all of the departments correspond to administrative categories used by the plant. In the analysis, within department variability is preserved because the data are analyzed at the job level. Table 4-XII presents the number of first shift employees for each season and year for each department. From the table it can be seen that the largest number of workers worked in AC Assembly / Warehouse A, with dehumidifier assembly generally, but not always second. the dehumidifier assembly line did not operate in the summer of 1997. Injection molding was usually third, but sometimes passed dehumidifier assembly. Employment was always greater in the winter than in the summer.

Table 4-XII:
Number of First Shift Employees per Department by Season and Year

Department	Winter, 1994	Summer, 1994	Winter, 1995	Summer, 1995	Winter, 1996	Summer, 1996	Winter, 1997	Summer, 1997
Aluminum Fin Presses	5	4	5	4	5	6	6	4
Hairpin Tube Bending	4	4	3	2	4	5	5	3
Coil Expanding Machines	27	30	27	20	35	29	29	17
Sheet metal Presses	20	16	24	14	21	18	21	13
Brazing Machines	48	44	44	44	44	44	41	14
Tubing	18	16	16	16	16	16	16	11
Warehouse B	12	9	12	8	12	10	10	4
Dehumidifier Coil Machines	7	7	9	8	10	9	10	0
Dehumidifier Assembly	82	96	89	91	93	92	91	0
Degreaser Vicinity	2	2	2	2	2	2	2	1
AC Assembly / Warehouse A	521	464	585	331	591	477	493	145
Injection Molding / Finished Goods	87	74	104	44	79	72	75	40

ANOVA Modeling

(Step 5)

As indicated above, for each year and season in the study, each job title was assigned an ESS_{TLV} representing the median value of $ESS_{i,TLV}$ over 72 trials. Similarly, for each year and season in the study, each job title was assigned an ESS_{CAN} representing the median value of $ESS_{i, CAN}$ over 72 trials. Analysis of variance (ANOVA) models were constructed to predict $\ln(ESS_{TLV})$ and $\ln(ESS_{CAN})$for each job title. These models were used to examine the impact of the elimination of TCE on worker exposure severity by department controlling for season and production level. Season is important because ventilation and number of employees vary by season. As noted above, two seasons are used in this analysis. Winter represents higher employment and less incoming air than summer. Production took on two levels during the study period. From 1994-1996 production ranged between 1.2 million and 1.3 million units. In 1997, production was approximately 800 thousand units. For the purpose of analysis, production was represented by a binary variable that took on the value 2 for 1994-1996 and 1 for 1997. It should be noted that the cell represented by 'no TCE', summer, and low production, namely summer 1997, is also characterized by the elimination of the dehumidifier coil machines, a small source of mineral spirits. Since no other cell in this analysis reflects the elimination of these machines, it is difficult to separate the impact of the elimination of the dehumidifier coil machine from the effects of season and production level.

The job title is the basic unit of observation for the ANOVA models. Since different job titles have different numbers of employees, a weighted ANOVA was conducted in which the number of employees with a given job title was used as the weight for that job title. In three departments, brazing, dehumidifier coils and tubing, interviews indicated that workers with some job titles remained relatively stationary, but it was unclear exactly where within the department they worked. In some cases, the workers were not necessarily close to each other. The lack of information as to the precise location of workers within these departments was important because the contaminant concentration models divided these departments into two compartments differing in concentration. When a department was divided into two compartments, the compartment with a lower concentration was labeled 'location A.' The other compartment was labeled 'location B.'

For each of the 72 trials of the exposure model, the number of employees in location A with a given job title in a given season and year was randomly selected from a binomial distribution. The number of employees with the same job title and department who worked in location B was determined by subtracting the number of employees in location A from the total number of employees for that job title, season and year. For the purpose of the ANOVA models, a job title for which some of the employees worked in location A and some worked in location B was treated as two job titles. Each job title was weighted in the ANOVA analysis according to the number of employees in its location. In order to test the sensitivity of the ANOVA results to varying assumptions about the location of workers in the three departments for which this was uncertain, the ANOVA models predicting $\ln(ESS_{CAN})$ and $\ln(ESS_{TLV})$ were run with each of three different sets of weights. These weights reflected the 10th, 50th, and 90th percentiles for the number of workers predicted to be in location A for each uncertain job title.

Results

Concentration Models

Tables 4-XIII through 4-XV present the concentration modeling results for each of the three chemicals of concern. The findings of a validation of the model (see Chapter 3) suggest that concentration modeling results are more likely to be underestimates than to be overestimates. It will be observed from Table 4-XV that TCE is modeled for the four seasons during the study period in which it was used. Modeled full-shift TWA concentrations were slightly less in 1995 than in 1994, reflecting slightly lower emissions in 1995. (See Table 4-II.) Modeled full-shift average concentrations for 1994 and 1995 exceed the TLV in the immediate vicinity of the degreaser and in the brazing machine area immediately downwind. Using the EPA cancer potency as described above, the model suggests that the lifetime cancer risk may have exceeded 10^{-3} for workers who spent full shifts in the vicinity of the degreaser, brazing machines, coil wash, coil expanding machines, and aluminum fin presses. The large difference in concentration between the two brazing machine compartments underlines the importance of investigating the sensitivity of the ANOVA model to varying assumptions about the location of workers in the brazing department.

Table 4-XIII:
Modeled Full-Shift TWA TCE Concentrations (mg/m^3) by Season and Year

Location (See Figure 4-1)	**Winter 1994** (Mean S.D.)	**Summer 1994** (Mean S.D.)	**Winter 1995** (Mean S.D.)	**Summer 1995** (Mean S.D.)
Metal Presses	0.010 0.014	0.013 0.024	0.001 0.003	0.01 0.02
Degreaser Vicinity	400.66 9.16	406.06 10.52	386.87 10.36	386.68 8.64
Brazing Machines A	47.28 11.85	46.48 11.19	45.12 10.61	44.94 8.96
Brazing Machines B	418.86 15.58	417.67 16.97	403.14 19.67	403.5 19.8
Coil Wash / Expanding Machines / Fin Presses	16.32 2.41	16.51 1.58	15.83 1.94	15.99 1.57
Warehouse A / AC Assembly	2.52 2.03	2.03 1.7	2.74 2.24	1.89 1.7
Injection Molding / Finished Goods	0.14 0.09	0.14 0.09	0.13 0.09	0.13 0.08
Dehumidifier Assembly / Warehouse B	0.003 0.003	0.004 0.006	0.004 0.006	.003 .004

Table 4-XIV presents the modeled full-shift TWA concentrations of petroleum naphtha. The models suggest that naphtha did not exceed, or even approach the NIOSH REL (350 mg/m^3) at any time during the study period. It can be seen that, as with emissions (Table 4-II), modeled concentrations increase in 1996 after the elimination of TCE. It is likely that this increase is due to the greater volatility of the lubricants for the stamped steel parts that were introduced after the elimination of TCE.

Table 4-XIV:
Modeled Full-Shift TWA Naphtha Concentrations (mg/m^3) by Season and Year

Location (See Figure 4-2)	Winter 1994 (Mean S.D.)	Summer 1994 (Mean S.D.)	Winter 1995 (Mean S.D.)	Summer 1995 (Mean S.D.)	Winter 1996 (Mean S.D.)	Summer 1996 (Mean S.D.)	Winter 1997 (Mean S.D.)	Summer 1997 (Mean S.D.)
Metal Presses	29.94 20.95	31.13 19.29	34.99 26.04	37.83 26.43	63.71 42.71	61.95 40.01	53.69 34.48	56.17 35.45
Degreaser Vicinity	32.49 22.33	33.75 20.57	38.07 27.80	41.05 28.29	69.09 45.57	67.25 42.6	58.36 36.66	60.97 37.72
Brazing Machines / Tube Making A	5.4 2.74	5.36 2.6	6.56 3.65	6.47 3.85	10.92 4.6	11.15 5.2	10.19 5.47	10.15 4.2
Brazing Machines / Tube Making B	50.66 32.02	53.87 32.13	61.11 43.41	65.25 43.51	110.88 71.68	103.36 64.97	93.96 57.11	97.34 58.11
Coil Wash / Expanding Machines / Fin Presses / Hairpin Bending Machines	2.88 1.42	2.81 1.3	3.92 2.96	3.65 2.38	6.06 2.67	6.1 2.95	5.68 2.97	5.49 2.95
Warehouse A / AC Assembly	0.54 0.69	0.30 0.25	0.51 0.47	0.42 0.38	0.72 0.61	0.73 0.82	0.74 0.62	0.57 0.43
Injection Molding / Finished Goods	.09 .12	0.08 0.13	1.94 3.55	0.09 0.17	0.14 0.24	0.18 0.35	0.16 0.23	0.21 0.42
Dehumidifier Assembly / Warehouse B	1.16 2.05	1.04 1.97	1.94 3.55	1.43 2.82	2.26 3.84	2.56 4.34	2.65 4.42	2.31 4.20

Modeled full-shift TWA concentrations of mineral spirits are summarized in Table 4-XV. The modeled concentration of mineral spirits in the proximity of the fin presses far exceeds that in any other part of the plant. This is consistent with the fact that the fin presses are the largest source of mineral spirits emissions, as indicated in Table 4-II. The large reduction in emissions and exposure for 1997 probably reflects the reduced production in that year. Of some note is the decline in concentration in the area of the dehumidifier coils. Although, the concentration was relatively small before the making of separate dehumidifier coils was discontinued, it fell effectively to zero after the discontinuation. This can be considered a minor unintended benefit of the elimination of refrigerant 500, which led to the discontinuation. It is conceivable that the small reduction in exposure in the area of dehumidifier coils could be offset by increases in exposure in the areas of the plant related to the production of air conditioner coils and, after winter 1997, all coils. However, due to the drop in production in 1997, the data do not permit this to be discerned.

Table 4-XV:
Modeled Full-Shift TWA Mineral Spirits Concentrations (mg/m^3) by Season and Year

Location (See Figure 4-3)	**Winter 1994** (Mean S.D.)	**Summer 1994** (Mean S.D.)	**Winter 1995** (Mean S.D.)	**Summer 1995** (Mean S.D.)	**Winter 1996** (Mean S.D.)	**Summer 1996** (Mean S.D.)	**Winter 1997** (Mean S.D.)	**Sum-mer 1997** (Mean S.D.)
Coil Wash	3.78 0.78	3.78 0.89	4.31 0.82	4.37 0.84	4.58 0.9	4.58 1.11	2.57 0.66	1.89 0.69
Coil Expanding Machines	4.06 1.06	4.15 1.28	4.91 1.39	4.98 1.34	5.36 1.77	5.31 1.51	3.26 0.95	2.48 0.85
Aluminum Fin Presses	233.7 9.91	239.7 10.87	283.8 10.19	284.0 11.5	301.5 13.12	300.6 10.74	166.1 7.37	162.6 6.82
Press / Coils / Warehouse B / Finished Goods	0.55 0.10	0.55 0.10	0.62 0.12	0.79 0.13	0.73 0.11	0.79 0.15	0.6 0.1	0.0006 0.0007
Dehumidifier Assembly	0.02 0.006	0.02 0.008	0.03 0.008	0.03 0.01	0.02 0.005	0.01 0.03	0.02 0.006	8.8×10^{-7} 9.8×10^{-7}
AC Assembly / Warehouse A	0.36 0.28	0.27 0.23	0.4 0.29	0.29 0.24	0.36 0.27	0.32 0.23	0.18 0.14	0.14 0.13
Injection Molding/ Finished Goods	0.045 0.026	0.046 0.023	0.05 0.03	0.05 0.03	0.05 0.03	0.06 0.03	0.04 0.02	0.014 0.0097
Dehumidifier Coil Machine (column 23)	2.49 1.34	2.55 1.38	3.37 1.64	3.52 1.76	3.45 1.88	3.34 1.55	3.08 2.01	8.7×10^{-7} 9.7×10^{-7}
Dehumidifier Coil Machine (column 28)	3.56 2.48	3.81 2.73	5.27 3.67	5.99 5.21	5.33 3.94	5.97 5.37	4.15 2.85	8.8×10^{-7} 9.8×10^{-7}
Space between Dehumidifier Coil Machines	6.79 4.46	7.44 5.23	10.21 6.83	11.63 9.93	10.26 7.25	11.44 10.03	8.18 5.62	2.5×10^{-6} 3.9×10^{-6}

Implications of Employee Number Weights for Departments in which Employee Location is Uncertain

As indicated above, interview data left uncertainty as to the locations of employees within the brazing, tubing, and dehumidifier coils departments. Each of these departments was divided into two compartments in the concentration model for at least one of the three contaminants of concern. It can be seen from Table 4-XIII that, within the brazing department, Compartment A has a lower concentration of TCE in each year and season. On Table 4-XIV, it can be seen that brazing / tube making Compartment A, which includes all of brazing compartment A on Table 4-XIII is also the compartment with a lower concentration of petroleum naphtha in each year and season. This result is due to the location of the sources of these chemicals and the direction of airflow. The two compartments do not differ in their concentrations of mineral spirits because, as can be seen in Figure 4-3, they are incorporated into the larger press, coils, warehouse B and finished goods compartment in the mineral spirits model. Figure 4-3 shows that both compartments within the tubing department are also incorporated into this larger compartment in the mineral spirits model. In the TCE model, Figure 4-1 shows that both compartments within the tubing department are incorporated into a larger department that also contains warehouse B and dehumidifier assembly. As a result, for tubing, the only contaminant whose concentration differs between the two compartments is petroleum naphtha.

Finally, as can be seen in Figures 4-1 and 4-2, the dehumidifier coil machine compartments are incorporated into larger compartments containing dehumidifier assembly in both the TCE and naphtha models. The dehumidifier coil compartments differ from each other only in their concentrations of mineral spirits. As can be seen from

Table 4-XV, the dehumidifier coil compartment at column 28 consistently exhibits slightly higher concentrations of mineral spirits than the compartment at column 23.

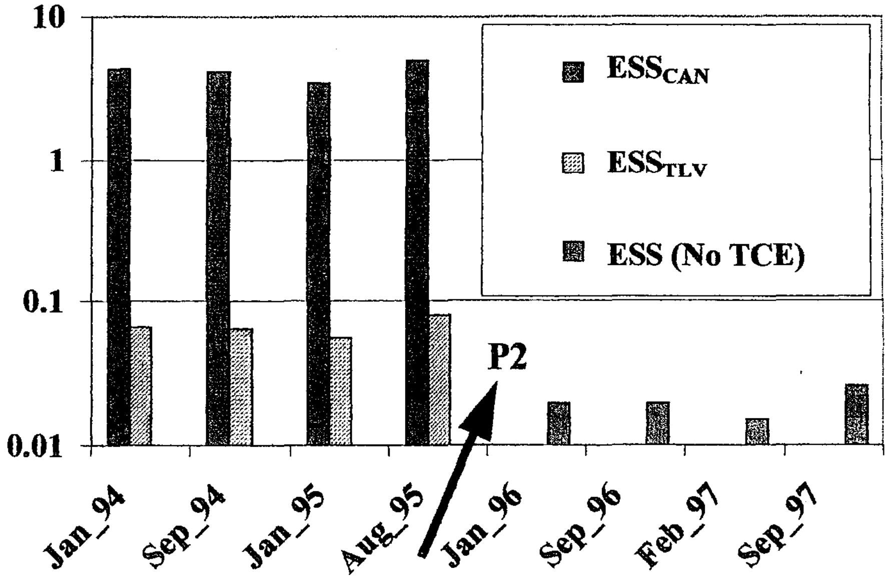
For each of these three departments, the compartment with lower concentrations was defined as location A and the compartment with higher concentrations was defined as location B. Table A-I in the Appendix shows that for all job titles in these departments, the difference between exposure severity scores in location B and those in location A is positive regardless of whether scores are calculated using TCE cancer potency or TCE TLV. This means that the use of employee number weights in an ANOVA model representing the tenth percentile of the distribution of the predicted number of employees in location A will produce a consistent bias toward higher exposure severity scores. Similarly, the use of ninetieth percentile employee number weights for location A will produce a consistent bias toward lower exposure severity scores. As a result, an adequate test of the sensitivity of the results of the ANOVA models to assumptions about employee location may be conducted using 10th, 50th, and 90th percentile employee number weights.

Exposure Severity Scores

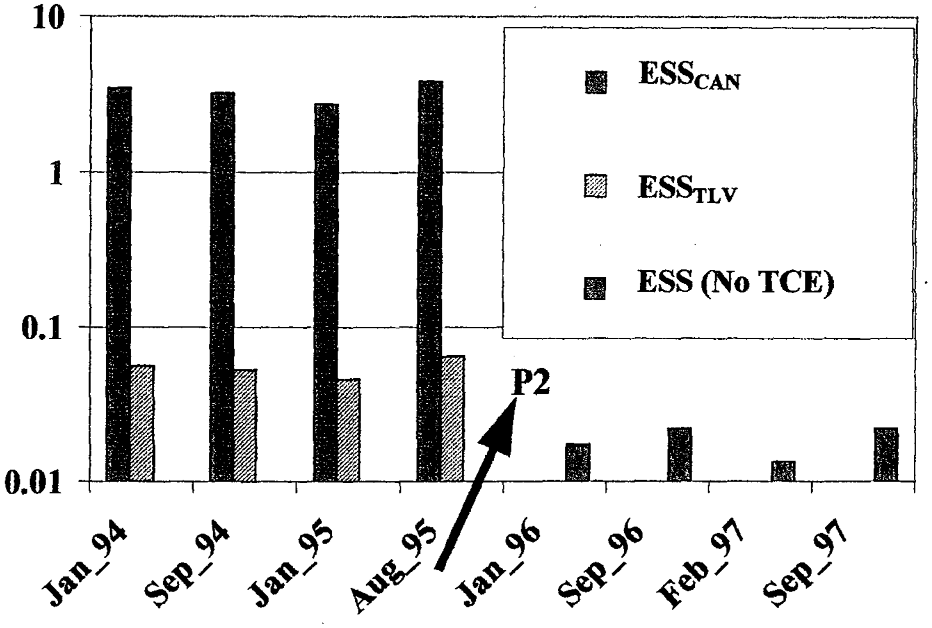
Figure 4-6 shows weighted average exposure severity scores for the entire first shift worker population before and after the elimination of TCE at the end of 1995. Each of the three graphs shows that, when the TLV for TCE was used to calculate exposure severity, scores were consistently higher before the elimination of TCE than they were after its elimination. It must be acknowledged, however, that, when the TLV was used to calculate exposure severity, the average score for the worker population of the plant was quite small, less than 0.1. for all seasons and years. When TCE cancer potency was used to calculate exposure severity, the difference between scores before and after the

Figure 4-6: Weighted Average Exposure Severity Scores before and after TCE Elimination

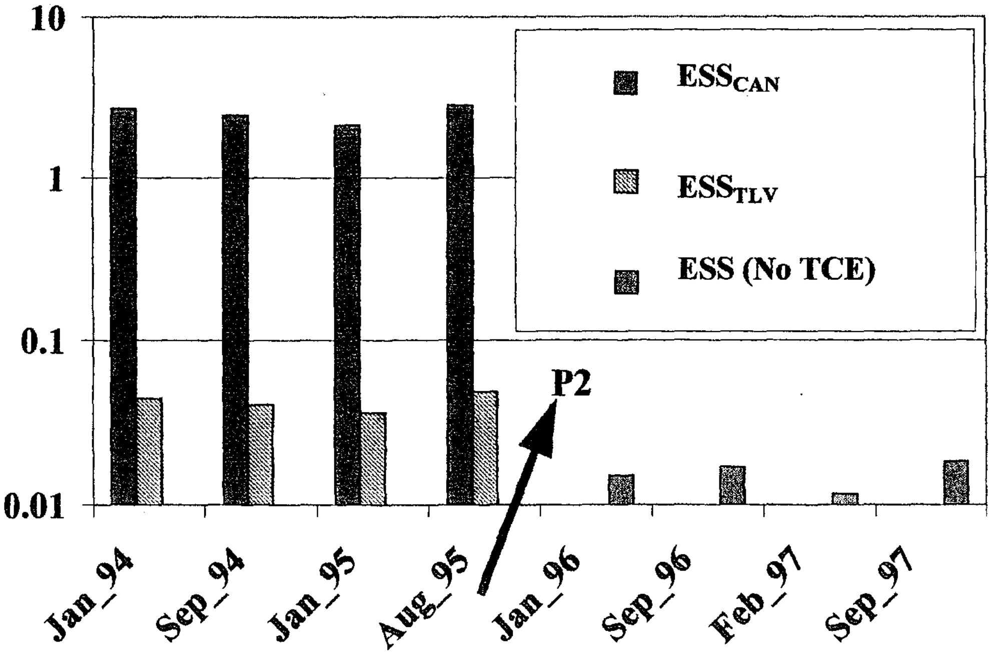
4-6a: 10%ile Employee Number Weights



4-6b: Median Employee Number Weights



4-6c: 90%ile Employee Number Weights



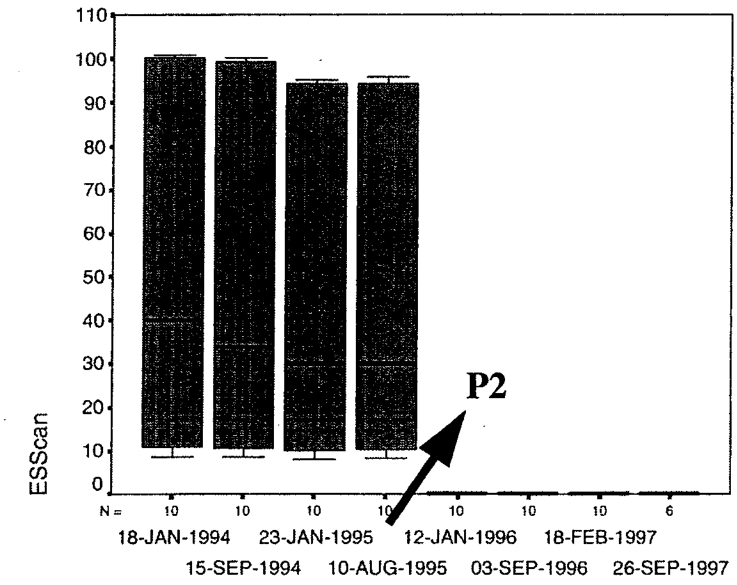
elimination of TCE was much greater. Average scores before the elimination of TCE ranged from 2 to 5, depending on season, year and employee number weight. The behavior of average exposure severity scores is similar for the 10th, 50th and 90th percentile employee number weights, indicating that the differences between these averages before and after the elimination of TCE are not very sensitive to assumptions about the location of employees in departments in which those locations are uncertain.

Figures 4-7a through 4-10 illustrate the change in exposure severity scores for departments that experienced unambiguous reductions in exposure severity after the elimination of TCE. Figure 4-7a shows that, for brazing machine workers, the reductions are quite large when ESS_{CAN} is used. Figure 4-7b indicates that the boxplots before and after the elimination of TCE overlap somewhat, but both the mean and the range before TCE elimination is much higher when ESS_{TLV} is used. Figures 4-8a and 4-8b demonstrate that, for workers in the vicinity of the degreaser, exposure severity was unambiguously lower after the elimination of TCE. It should be noted, however, that this refers only to the degreaser operator and to the input clerk. Although, the job title 'Pit Degreaser' was not removed from the personnel requests immediately after the elimination of TCE, by summer 1997 the input clerk, a job title which had one employee, was the only job in this department. Figures 4-9a, 4-9b and Figure 4-10 show fairly unambiguous reductions in exposure severity for coil expander, air conditioner assembly and warehouse A workers after the elimination of TCE.

Figure 4-7:

Boxplots of Exposure Severity Scores for Brazing Machine Workers

a. Scores Calculated Using TCE Cancer Potency



b. Scores Calculated Using TCE TLV

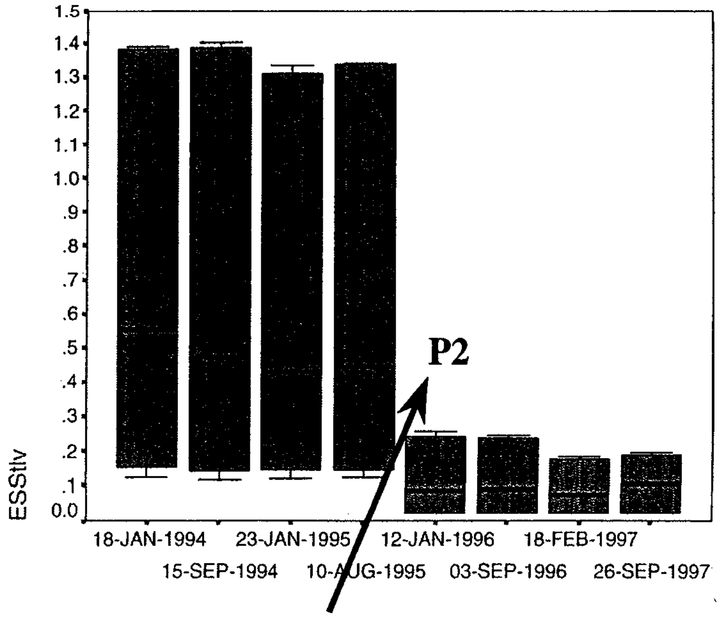
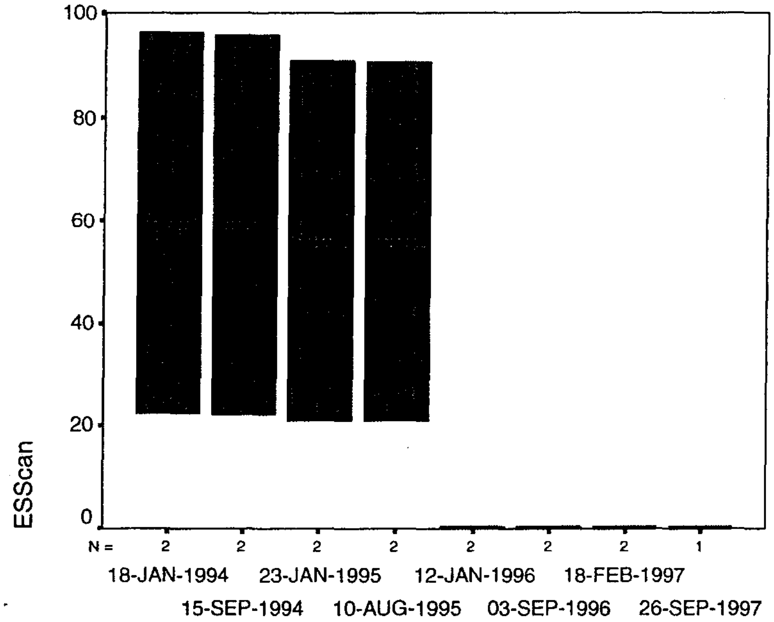


Figure 4-8:
Boxplots of Exposure Severity Scores for Workers in Vicinity of the Degreaser

a. Scores Calculated Using TCE Cancer Potency



b. Scores Calculated Using TCE TLV

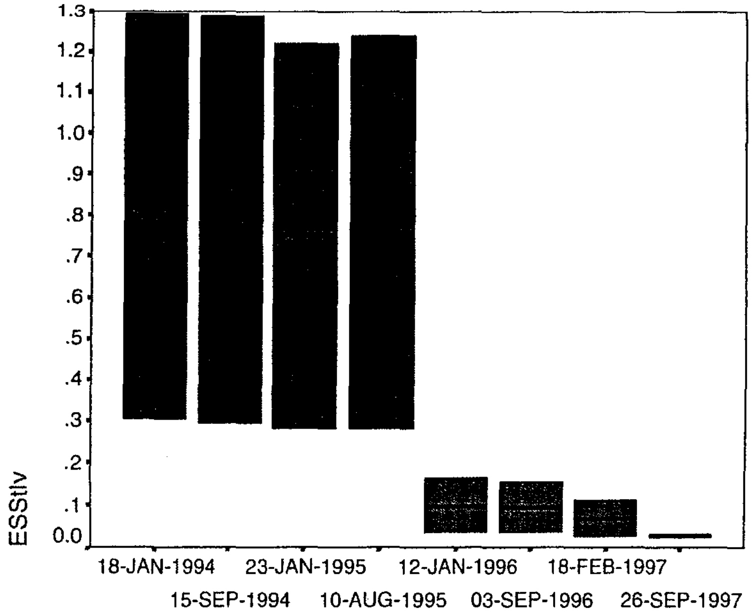
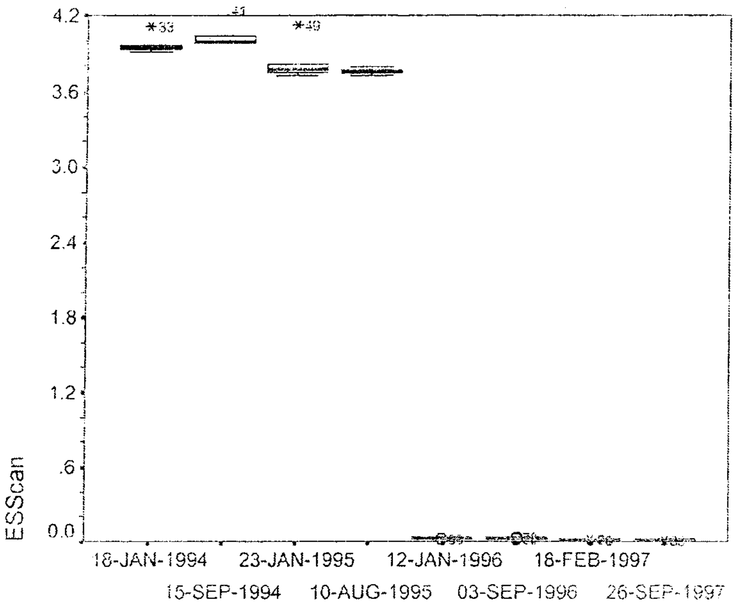


Figure 4-9:
Boxplots of Exposure Severity Scores for Coil Expander Workers

a: Scores Calculated Using TCE Cancer Potency



b: Scores Calculated Using TCE TLV

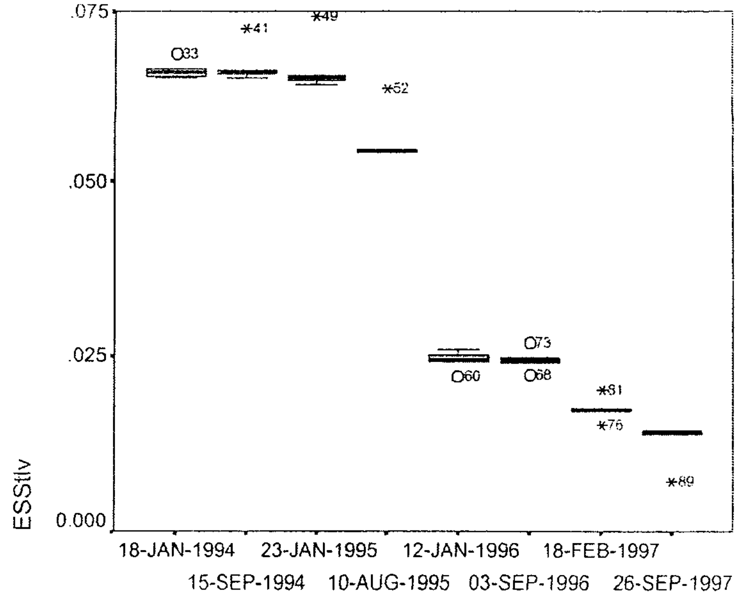
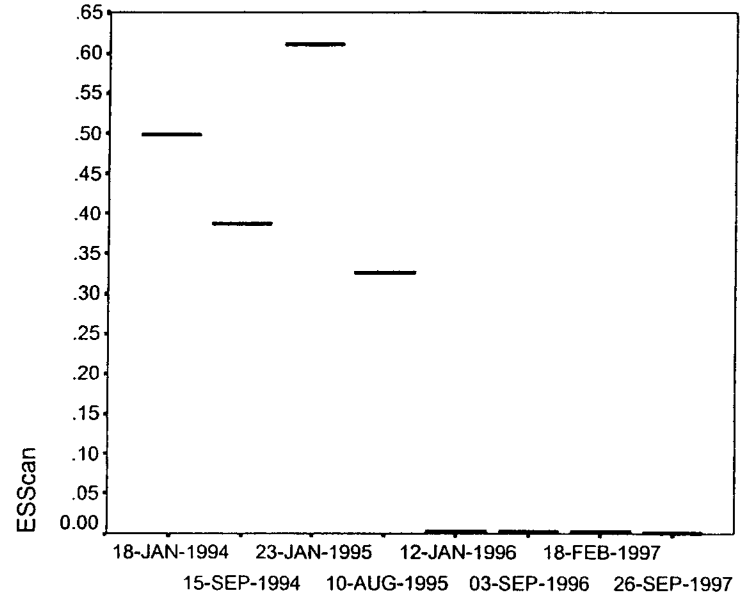
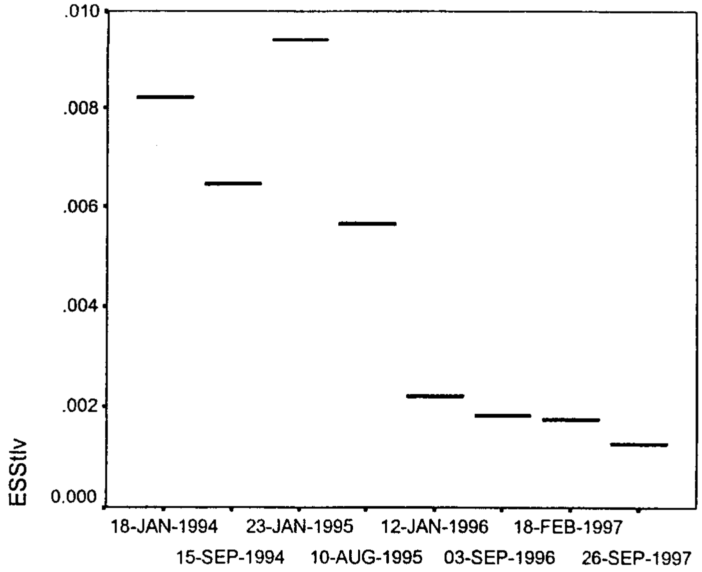


Figure 4-10:
Boxplots of Exposure Severity Scores for Workers in AC Assembly and Warehouse A

a: Scores Calculated Using TCE Cancer Potency

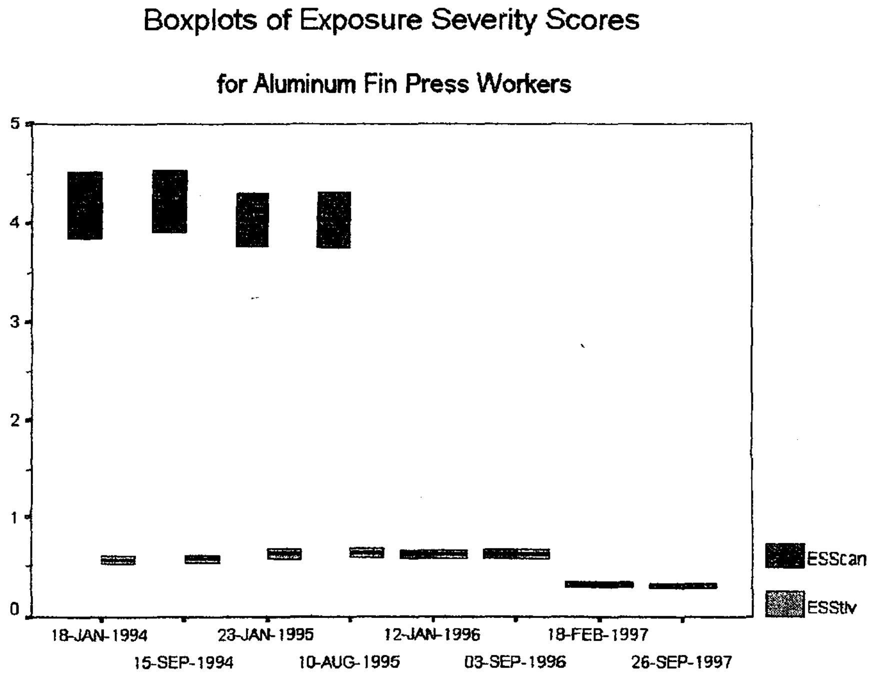


b: Scores Calculated Using TCE TLV



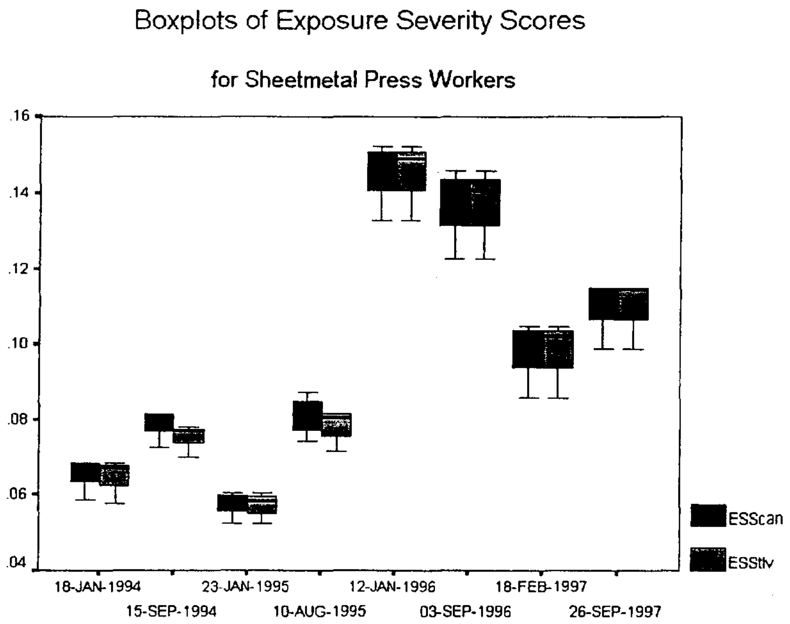
The experience of fin press workers (Figure 4-11) is more ambiguous. When ESS_{CAN} is used, a reduction in exposure severity is seen following the elimination of TCE. However, when ESS_{TLV} is used, exposure severity appears to increase slightly following the elimination of TCE. This can be explained by the increase in mineral spirits concentration in the fin press area in 1996 (Table 4-XV), which, in turn, is driven by increased emissions from the fin presses in that year (Table 4-II). The situation of sheet metal press workers and tubing workers is different from that of the others. As Figures 4-12 and 4-13 indicate, these workers were exposed to so little TCE that, for them ESS_{CAN} was hardly different from ESS_{TLV}. However, their exposure severity scores, though not high, rose after the elimination of TCE. This is due to increased naphtha exposure in these departments after the elimination of TCE (Table 4-XIV), which is driven by increases in naphtha emissions after the elimination of TCE

Figure 4-11:



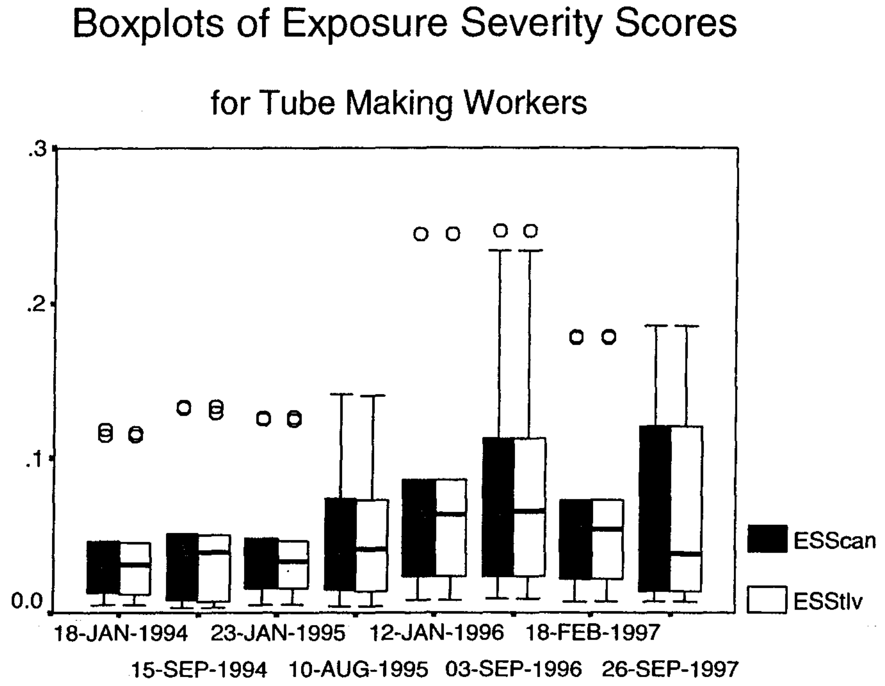
(Table 4-II). It is likely that these increases are due to the use of more volatile lubricants for the sheetmetal presses when the stamped parts were no longer degreased.

Figure 4-12:



Figures are not presented here for workers in hairpin bending, warehouse B, dehumidifier assembly, dehumidifier coils, or injection molding / finished goods because the exposure severity scores for those workers were all less than 0.016 before and after the elimination of TCE.

Figure 4-13:



Analysis of Variance

ANOVA models were used to evaluate the impact of the elimination of TCE on exposure severity, controlling for seasonal variation and production level. In order to satisfy the ANOVA assumptions, the natural logarithms of ESS_{CAN} and ESS_{TLV} were used. Probability-probability (PP) plots (Figures A-1a through A-2b) may be found in the Appendix, which show that $\ln(ESS_{CAN})$ and $\ln(ESS_{TLV})$ satisfy the assumption of normality reasonably well. Regardless of the weight used, the model that best predicted the natural logarithmic transformation of ESS_{TLV} contained department, presence or absence of TCE, season, production level, and terms for interaction between department and TCE presence and between season and production level. For the natural logarithmic transformation of ESS_{CAN}, a similar model is the best fit using 90%ile or median employee number weights. For 10%ile employee number weights, the deviance test for this model compared to a similar model without the interaction term yielded a p value only slightly greater than 0.05. For this reason it was decided to proceed with the analysis using the model with the four main effects terms and two interaction terms described above. Table A-II in the Appendix shows the analysis of deviance results for each model examined.

Table 4-XVI shows parameter estimates for the ANOVA model predicting $\ln(ESS_{CAN})$. The columns show the values estimated for the parameters using 10th, 50th or 90th percentile employee number weights. Due to the presence of interaction terms, the value of a single parameter does not provide complete information about the association between a factor and exposure severity. For example, TCE takes on a strongly negative value (approximately –5 regardless of the weight used) after TCE is eliminated. This means that the elimination of TCE reduced exposure severity scores in general. However, in order measure the association between the elimination of TCE and exposure severity for workers in any particular department, it is necessary to add the parameter for TCE to the parameter for the interaction term DEPARTMENT * TCE.

To illustrate this, let us compare the impact of TCE elimination on aluminum fin press workers to the impact of TCE elimination on sheetmetal press workers. The best estimate of the value of the parameter for [DEPARTMENT = ALUMINUM FIN PRESSES] * [TCE = ELIMINATED] is 2.97 regardless of employee number weight. When this number is added to best estimate of the parameter for [TCE = ELIMINATED], the total is – 2.02. Even after the two parameters are added, it remains the case that exposure severity for aluminum fin press workers fell after the elimination of TCE.

However, the best estimate of the value of the parameter for [DEPARTMENT = SHEETMETAL PRESSES] * [TCE = ELIMINATED] is 5.75, regardless of employee number weight. When this number is added to best estimate of the parameter for [TCE = ELIMINATED], the total is 0.76, meaning that exposure severity for sheetmetal press workers increased after the elimination of TCE.

In general, modeled exposure severity scores fell after the elimination of TCE in those departments for which the TCE-department interaction term is significantly less than 5. The departments in which modeled exposure severity scores fell after the elimination of TCE are brazing machines, degreaser vicinity, aluminum fin presses, coil expanding machines, air conditioner assembly, injection molding, dehumidifier assembly and warehouse B. For sheet metal presses and tubing, the interaction term is significantly greater than 5. This means that, according to the model, these departments experienced increased exposure severity after the elimination of TCE. These model findings are consistent with the boxplots presented above in Figures 4-12 and 4-13. The reasons for the increases in exposure severity scores in these departments after the elimination of TCE are discussed above.

According to Table 4-XVI , the estimate of the impact of TCE elimination on exposure severity is approximately the same regardless of where one assumes the employees were located in those departments in which their locations were uncertain. This can be seen in the fact that the value of the parameter representing TCE elimination is approximately –5 regardless of which employee number weights were used. When the interaction between TCE elimination and department is examined, the greatest difference by employee number weights occurs in the brazing department. Of the three analyses presented, the tenth percentile weights place the greatest number of employees in the location of higher exposure, both before and after the elimination of TCE. When these weights are used, the best estimate of the impact of TCE elimination on $\ln(ESS_{CAN})$ is –0.85. The ninetieth percentile weights place the least number of employees in the location of higher exposure. When these weights are used, the best estimate of the impact of TCE elimination on $\ln(ESS_{CAN})$ is –0.92. The fact that this small difference is greater than that for any other department indicates that imprecision in knowledge as to where some employees were located has little influence on the findings with regard to the impact of the elimination of TCE on exposure severity.

Table 4-XVII shows that the behavior of the predictors for $\ln(ESS_{TLV})$ is similar to their behavior for $\ln(ESS_{CAN})$ with the exception that the aluminum fin presses and warehouse B do not exhibit a significant drop in $\ln(ESS_{TLV})$ after the elimination of TCE. For these two areas, the increase in mineral spirits emissions has a greater influence on exposure severity than the elimination of TCE when TLV is used to calculate exposure severity. As can be seen in Table 4-III, the full-shift average concentration of TCE in the fin press area was approximately 16 mg/m^3 in each season that TCE was present. As indicated above, the TLV for TCE is 269 mg/m^3. When this value is used, the contribution of TCE to exposure severity for a hypothetical worker who spends a full shift in the fin press area is $16/269 \approx 0.06$. When the contribution of TCE to exposure severity falls to zero after the elimination of TCE, the small decline in exposure severity that results is counteracted by an increase in exposure severity resulting from increased exposure to petroleum naphtha and mineral spirits. However, when cancer potency is used to estimate exposure severity, the results are different. As indicated above, the

exposure associated with 10^{-3} cancer risk is 3.41 mg/m^3. When this value is used, the contribution of TCE to exposure severity for the same hypothetical worker is $16/3.41 \approx 4.7$. In this case, when the contribution of TCE to exposure severity falls to zero, the increase in severity, resulting from increased exposure to naphtha and mineral spirits is not high enough to counteract the decline. This difference in the behavior of exposure severity scores operates similarly for warehouse B. According to the models, all other departments fell into one of two cases. In many departments, workers were exposed to concentrations of TCE that were so high that the beneficial impacts of TCE elimination outweighed any increases in exposure to the other two chemicals, even when the TLV was used to calculate severity. In two departments, sheetmetal presses and tubing, exposure to TCE was so low that increases in exposure to petroleum naphtha outweighed the benefits of TCE elimination even when cancer potency was used to calculate severity.

Table 4-XVI:
Parameter Estimates for ANOVA Model
$\ln(ESS_{CAN}) = \beta_0 + \beta_1$*DEPARTMENT
$+ \beta_2$*TCE $+ \beta_3$*DEPARTMENT*TCE $+ \beta_4$*SEASON $+ \beta_5$*PRODUCT $+\beta_6$*SEASON*PRODUCT

Parameter	β (95% C.I.) 10%ile Employee Number Weights	β (95% C.I.) Median Employee Number Weights	β (95% C.I.) 90%ile Employee Number Weights
Intercept (β_0)	-3.36 (-3.51, -3.21)	-3.36 (-3.52, -3.21)	-3.37 (-3.51, -3.22)
[DEPARTMENT = ALUMINUM FIN PRESSES]	4.71 (4.1, 5.32)	4.71 (4.1, 5.32)	4.71 (4.11, 5.31)
[DEPARTMENT = HAIRPIN TUBE BENDING]	-1.5 (-2.21, -0.79)	-1.5 (-2.21, -0.79)	-1.5 (-2.2, -0.8)
[DEPARTMENT = COIL EXPANDING MACHINES]	4.62 (4.33, 4.91)	4.62 (4.33, 4.91)	4.62 (4.33, 4.91)
[DEPARTMENT = SHEETMETAL PRESSES]	0.59 (0.24, 0.94)	0.59 (0.24, 0.94)	0.59 (0.25, 0.94)

Table 4-XVI:
Parameter Estimates for ANOVA Model
$\ln(ESS_{CAN}) = \beta_0 + \beta_1$*DEPARTMENT
$+ \beta_2$*TCE $+ \beta_3$*DEPARTMENT*TCE $+ \beta_4$*SEASON $+ \beta_5$*PRODUCT $+\beta_6$*SEASON*PRODUCT

Parameter	β (95% C.I.) 10%ile Employee Number Weights	β (95% C.I.) Median Employee Number Weights	β (95% C.I.) 90%ile Employee Number Weights
[DEPARTMENT = BRAZING MACHINES]	7.04 (6.8, 7.27)	6.66 (6.42, 6.89)	6.28 (6.05, 6.51)
[DEPARTMENT = TUBING]	-0.03 (-0.37, 0.31)	-0.24 (-0.58, 0.1)	-0.45 (-0.78, -0.12)
[DEPARTMENT = WAREHOUSE B]	-2.73 (-3.15, -2.31)	-2.73 (-3.15, -2.31)	-2.73 (-3.14, -2.32)
[DEPARTMENT = DEHUMIDIFIER COIL MACHINES]	-1.22 (-1.69, -0.74)	-1.36 (-1.83, -0.89)	-1.51 (-1.97, -1.04)
[DEPARTMENT = DEHUMIDIFIER ASSEMBLY]	-3.54 (-3.74, -3.35)	-3.54 (-3.74, -3.35)	-3.54 (-3.73, -3.35)
[DEPARTMENT = DEGREASER VICINITY]	7.07 (6.17, 7.97)	7.07 (6.17, 7.97)	7.07 (6.19, 7.95)
[DEPARTMENT = AC ASSEMBLY]	2.48 (2.33, 2.64)	2.48 (2.33, 2.64)	2.48 (2.33, 2.64)
[DEPARTMENT = INJECTION MOLDING]	0	0	0
[TCE=ELIMINATED]	-4.99 (-5.21, -4.78)	-4.99 (-5.2, -4.77)	-4.99 (-5.2, -4.78)
[TCE=PRESENT]	0	0	0
[SEASON = WINTER]	0.19 (0.12, 0.26)	0.19 (0.12, 0.26)	0.19 (0.12, 0.26)
[SEASON = SUMMER]	0	0	0
[DEPARTMENT = ALUMINUM FIN PRESSES] * [TCE=ELIMINATED]	2.97 (2.13, 3.8)	2.97 (2.13, 3.8)	2.97 (2.15, 3.78)
[DEPARTMENT= ALUMINUM FIN PRESSES] * [TCE=PRESENT]	0	0	0
[DEPARTMENT= HAIRPIN TUBE BENDING] * [TCE=ELIMINATED]	5.57 (4.62, 6.51)	5.57 (4.62, 6.52)	5.57 (4.64, 6.5)
[DEPARTMENT= HAIRPIN TUBE BENDING] * [TCE=PRESENT]	0	0	0
[DEPARTMENT= COIL EXPANDING MACHINES] * [TCE=ELIMINATED]	-0.11 (-0.53, 0.3)	-0.11 (-0.53, 0.3)	-0.11 (-0.52, 0.29)

Table 4-XVI:
Parameter Estimates for ANOVA Model
$\ln(ESS_{CAN}) = \beta_0 + \beta_1$*DEPARTMENT
+ β_2*TCE + β_3*DEPARTMENT*TCE + β_4*SEASON + β_5*PRODUCT + β_6*SEASON*PRODUCT

Parameter	β (95% C.I.) 10%ile Employee Number Weights	β (95% C.I.) Median Employee Number Weights	β (95% C.I.) 90%ile Employee Number Weights
[DEPARTMENT= COIL EXPANDING MACHINES] * [TCE=PRESENT]	0	0	0
[DEPARTMENT= SHEETMETAL PRESSES] * [TCE=ELIMINATED]	5.75 (5.25, 6.25)	5.75 (5.25, 6.25)	5.75 (5.26, 6.24)
[DEPARTMENT= SHEETMETAL PRESSES] * [TCE=PRESENT]	0	0	0
[DEPARTMENT= BRAZING MACHINES] * [TCE=ELIMINATED]	-0.85 (-1.2, -0.5)	-0.89 (-1.24, -0.53)	-0.92 (-1.27, -0.58)
[DEPARTMENT= BRAZING MACHINES] * [TCE=PRESENT]	0	0	0
[DEPARTMENT= TUBING] * [TCE=ELIMINATED]	5.76 (5.27, 6.26)	5.75 (5.25, 6.24)	5.73 (5.24, 6.22)
[DEPARTMENT= TUBING] * [TCE=PRESENT]	0	0	0
[DEPARTMENT= WAREHOUSE B] * [TCE=ELIMINATED]	4.03 (3.42, 4.64)	4.03 (3.42, 4.64)	4.03 (3.43, 4.63)
[DEPARTMENT = WAREHOUSE B] * [TCE=PRESENT]	0	0	0
[DEPARTMENT= DEHUMIDIFIER COIL MACHINES] * [TCE=ELIMINATED]	5.05 (4.36, 5.73)	5.04 (4.35, 5.72)	5.03 (4.36, 5.69)
[DEPARTMENT= DEHUMIDIFIER COIL MACHINES] * [TCE=PRESENT]	0	0	0
[DEPARTMENT= DEHUMIDIFIER ASSEMBLY] * [TCE=ELIMINATED]	0.26 (-0.03, 0.55)	0.26 (-0.03, 0.55)	0.26 (-0.03, 0.54)

Table 4-XVI:
Parameter Estimates for ANOVA Model
$\ln(ESS_{CAN}) = \beta_0 + \beta_1$*DEPARTMENT
$+ \beta_2$*TCE $+ \beta_3$*DEPARTMENT*TCE $+ \beta_4$*SEASON $+ \beta_5$*PRODUCT $+\beta_6$*SEASON*PRODUCT

Parameter	β (95% C.I.) 10%ile Employee Number Weights	β (95% C.I.) Median Employee Number Weights	β (95% C.I.) 90%ile Employee Number Weights
[DEPARTMENT= DEHUMIDIFIER ASSEMBLY] * [TCE=PRESENT]	0	0	0
[DEPARTMENT= DEGREASER VICINITY] * [TCE=ELIMINATED]	-1.49 (-2.8, -0.17)	-1.49 (-2.81, -0.17)	-1.49 (-2.78, -0.2)
[DEPARTMENT= DEGREASER] * [TCE=PRESENT]	0	0	0
[DEPARTMENT= AC ASSEMBLY] * [TCE=ELIMINATED]	-0.41 (-0.63, -0.18)	-0.41 (-0.63, -0.18)	-0.41 (-0.63, -0.19)
[DEPARTMENT= AC ASSEMBLY] * [TCE=PRESENT]	0	0	0
[DEPARTMENT= INJECTION MOLDING] * [TCE=ELIMINATED]	0	0	0
[DEPARTMENT= INJECTION MOLDING] * [TCE=PRESENT]	0	0	0
[PRODUCT = 0.8 MILLION UNITS]	-0.49 (-0.67, -0.32)	-0.51 (-0.69, -0.33)	-0.52 (-0.7, -0.35)
[PRODUCT = 1.2 MILLION UNITS]	0	0	0
[SEASON = WINTER] * [PRODUCT = 0.8 MILLION UNITS]	0.2 (0, 0.39)	0.21 (0.01, 0.41)	0.23 (0.04, 0.42)
[SEASON = WINTER] * [PRODUCT = 1.2 MILLION UNITS]	0	0	0
[SEASON = WINTER] * [PRODUCT = 0.8 MILLION UNITS]	0	0	0
[SEASON = WINTER] * [PRODUCT = 1.2 MILLION UNITS]	0	0	0

Table 4-XVII:
Parameter Estimates for ANOVA Model
$\ln(ESS_{TLV}) = \beta_0 + \beta_1 * DEPARTMENT$
$+ \beta_2 * TCE + \beta_3 * DEPARTMENT * TCE + \beta_4 * SEASON + \beta_5 * PRODUCT + \beta_6 * SEASON * PRODUCT$

Parameter	β (95% C.I.) 10%ile Employee Number Weights	β (95% C.I.) Median Employee Number Weights	β (95% C.I.) 90%ile Employee Number Weights
Intercept	-7.37 (-7.51, -7.22)	-7.37 (-7.51, -7.22)	-7.37 (-7.51, -7.23)
[DEPARTMENT = ALUMINUM FIN PRESSES]	6.8 (6.2, 7.39)	6.8 (6.2, 7.39)	6.8 (6.22, 7.38)
[DEPARTMENT = HAIRPIN TUBE BENDING]	2.44 (1.75, 3.13)	2.44 (1.74, 3.13)	2.44 (1.76, 3.12)
[DEPARTMENT = COIL EXPANDING MACHINES]	4.52 (4.24, 4.81)	4.52 (4.24, 4.81)	4.52 (4.24, 4.8)
[DEPARTMENT = SHEETMETAL PRESSES]	4.58 (4.24, 4.92)	4.58 (4.24, 4.93)	4.58 (4.25, 4.92)
[DEPARTMENT = BRAZING MACHINES]	6.79 (6.56, 7.02)	6.41 (6.18, 6.64)	6.03 (5.81, 6.26)
[DEPARTMENT = TUBING]	3.96 (3.62, 4.29)	3.74 (3.41, 4.08)	3.53 (3.2, 3.85)
[DEPARTMENT = WAREHOUSE B]	0.83 (0.43, 1.24)	0.83 (0.43, 1.24)	0.83 (0.44, 1.23)
[DEPARTMENT = DEHUMIDIFIER COIL MACHINES]	2.72 (2.26, 3.18)	2.55 (2.09, 3.01)	2.38 (1.93, 2.83)
[DEPARTMENT = DEHUMIDIFIER ASSEMBLY]	-3.5 (-3.69, -3.31)	-3.5 (-3.69, -3.31)	-3.5 (-3.69, -3.31)
[DEPARTMENT = DEGREASER]	6.78 (5.9, 7.65)	6.78 (5.9, 7.66)	6.78 (5.92, 7.64)
[DEPARTMENT = AC ASSEMBLY]	2.38 (2.23, 2.53)	2.38 (2.23, 2.53)	2.38 (2.24, 2.53)
[DEPARTMENT = INJECTION MOLDING]	0	0	0
[TCE=ELIMINATED]	-0.98 (-1.19, -0.77)	-0.98 (-1.19, -0.77)	-0.98 (-1.18, -0.77)
[TCE=PRESENT]	0	0	0
[SEASON = WINTER]	0.17 (0.1, 0.24)	0.17 (0.1, 0.25)	0.18 (0.11, 0.25)
[SEASON = SUMMER]	0	0	0
[DEPARTMENT = ALUMINUM FIN PRESSES] * [TCE=ELIMINATED]	0.88 (0.07, 1.69)	0.88 (0.07, 1.7)	0.88 (0.09, 1.68)
[DEPARTMENT= ALUMINUM FIN PRESSES] * [TCE=PRESENT]	0	0	0

Table 4-XVII:
Parameter Estimates for ANOVA Model
$\ln(\text{ESS}_{\text{TLV}}) = \beta_0 + \beta_1\text{*DEPARTMENT}$
$+ \beta_2\text{*TCE} + \beta_3\text{*DEPARTMENT*TCE} + \beta_4\text{*SEASON} + \beta_5\text{*PRODUCT} + \beta_6\text{*SEASON*PRODUCT}$

Parameter	β (95% C.I.) 10%ile Employee Number Weights	β (95% C.I.) Median Employee Number Weights	β (95% C.I.) 90%ile Employee Number Weights
[DEPARTMENT= HAIRPIN TUBE BENDING] * [TCE=ELIMINATED]	1.63 (0.7, 2.55)	1.63 (0.7, 2.55)	1.63 (0.72, 2.53)
[DEPARTMENT= HAIRPIN TUBE BENDING] * [TCE=PRESENT]	0	0	0
[DEPARTMENT= COIL EXPANDING MACHINES] * [TCE=ELIMINATED]	-0.02 (-0.42, 0.39)	-0.02 (-0.42, 0.39)	-0.02 (-0.41, 0.38)
[DEPARTMENT= COIL EXPANDING MACHINES] * [TCE=PRESENT]	0	0	0
[DEPARTMENT= SHEETMETAL PRESSES] * [TCE=ELIMINATED]	1.76 (1.27, 2.24)	1.76 (1.27, 2.24)	1.76 (1.28, 2.23)
[DEPARTMENT= SHEETMETAL PRESSES] * [TCE=PRESENT]	0	0	0
[DEPARTMENT= BRAZING MACHINES] * [TCE=ELIMINATED]	-0.6 (-0.95, -0.26)	-0.64 (-0.99, -0.29)	-0.68 (-1.01, -0.34)
[DEPARTMENT = BRAZING MACHINES] * [TCE=PRESENT]	0	0	0
[DEPARTMENT= TUBING] * [TCE=ELIMINATED]	1.78 (1.29, 2.26)	1.76 (1.28, 2.25)	1.75 (1.28, 2.22)
[DEPARTMENT= TUBING] * [TCE=PRESENT]	0	0	0
[DEPARTMENT= WAREHOUSE B] * [TCE=ELIMINATED]	0.47 (-0.13, 1.06)	0.47 (-0.13, 1.06)	0.47 (-0.12, 1.05)
[DEPARTMENT = WAREHOUSE B] * [TCE=PRESENT]	0	0	0

Table 4-XVII:
Parameter Estimates for ANOVA Model
$\ln(ESS_{TLV}) = \beta_0 + \beta_1$*DEPARTMENT
$+ \beta_2$*TCE $+ \beta_3$*DEPARTMENT*TCE $+ \beta_4$*SEASON $+ \beta_5$*PRODUCT $+\beta_6$*SEASON*PRODUCT

Parameter	β (95% C.I.) 10%ile Employee Number Weights	β (95% C.I.) Median Employee Number Weights	β (95% C.I.) 90%ile Employee Number Weights
[DEPARTMENT= DEHUMIDIFIER COIL MACHINES] * [TCE=ELIMINATED]	1.11 (0.45, 1.78)	1.13 (0.46, 1.8)	1.14 (0.49, 1.79)
[DEPARTMENT= DEHUMIDIFIER COIL MACHINES] * [TCE=PRESENT]	0	0	0
[DEPARTMENT = DEHUMIDIFIER ASSEMBLY] * [TCE=ELIMINATED]	0.22 (-0.07, 0.5)	0.22 (-0.07, 0.5)	0.21 (-0.07, 0.49)
[DEPARTMENT = DEHUMIDIFIER ASSEMBLY] * [TCE=PRESENT]	0	0	0
[DEPARTMENT = DEGREASER] * [TCE=ELIMINATED]	-1.19 (-2.47, 0.09)	-1.19 (-2.48, 0.1)	-1.19 (-2.45, 0.06)
[DEPARTMENT = DEGREASER] * [TCE=PRESENT]	0	0	0
[DEPARTMENT = AC ASSEMBLY] * [TCE=ELIMINATED]	-0.3 (-0.52, -0.08)	-0.3 (-0.53, -0.08)	-0.31 (-0.52, -0.09)
[DEPARTMENT = AC ASSEMBLY] * [TCE=PRESENT]	0	0	0
[DEPARTMENT = INJECTION MOLDING] * [TCE=ELIMINATED]	0	0	0
[DEPARTMENT = INJECTION MOLDING] * [TCE=PRESENT]	0	0	0
[PRODUCT = 0.8 MILLION UNITS]	-0.5 (-0.68, -0.33)	-0.52 (-0.69, -0.34)	-0.53 (-0.7, -0.36)
[PRODUCT = 1.2 MILLION UNITS]	0	0	0
[SEASON = WINTER] * [PRODUCT = 0.8 MILLION UNITS]	0.21 (0.02, 0.41)	0.23 (0.04, 0.42)	0.25 (0.06, 0.44)
[SEASON = WINTER] * [PRODUCT = 1.2 MILLION UNITS]	0	0	0

Table 4-XVII: Parameter Estimates for ANOVA Model $\ln(ESS_{TLV}) = \beta_0 + \beta_1$*DEPARTMENT $+ \beta_2$*TCE $+ \beta_3$*DEPARTMENT*TCE $+ \beta_4$*SEASON $+ \beta_5$*PRODUCT $+\beta_6$*SEASON*PRODUCT			
Parameter	**β (95% C.I.) 10%ile Employee Number Weights**	**β (95% C.I.) Median Employee Number Weights**	**β (95% C.I.) 90%ile Employee Number Weights**
[SEASON = WINTER] * [PRODUCT = 0.8 MILLION UNITS]	0	0	0
[SEASON = WINTER] * [PRODUCT = 1.2 MILLION UNITS]	0	0	0

Figure 4-14a shows the ANOVA model's predictions, under various values of the predictor variables, of the value of ESS_{CAN} for the entire population of first shift workers. It can be seen that the biggest decline in exposure occurs as a result of the elimination of TCE. It can also be seen that exposure severity scores are consistently lower in summer than in winter and that the drop in production in 1997 slightly reduced exposure severity. The predicted values of ESS_{CAN} in Figure 4-14a are somewhat lower than the observed values in Figure 4-6. This may be due to the fact that the data were skewed prior to logarithmic transformation so that the weighted averages presented in Figure 4-6 are based on relatively small number of high values not accounted for in the assumptions of the ANOVA model. Nevertheless, predicted ESS_{CAN} drops by approximately an order of magnitude after the elimination of TCE. Figure 4-14b presents the model's prediction for ESS_{TLV}, showing a decline after the elimination of TCE, but one that is not as great as for ESS_{CAN}. Figures 4-15a through 4-17b illustrate that modeled exposure severity scores fell for workers in the vicinity of the degreaser, brazing machine workers and coil expanding workers after the elimination of TCE regardless of whether ESS_{CAN} or ESS_{TLV} was used. Air conditioner assembly, dehumidifier assembly and injection molding workers exhibited a similar pattern. Workers in warehouse B experienced a decline in exposure severity that was statistically significant when ESS_{CAN} was used, but not when ESS_{TLV} was used. However, even when ESS_{CAN} was used, their upper bound predicted score prior to TCE elimination was 0.004.

Figures 4-18a & b illustrate the fact that fin press workers experienced an independent increase in mineral spirits exposure in 1996. When exposure severity is calculated using TLV, instead of cancer potency, the increased mineral spirits exposure exerts a greater influence on scores than the elimination of TCE. Figures 4-19a & b illustrate the increase in exposure severity experienced by the sheet metal press workers, due to the more volatile lubricant used after the elimination of TCE, as discussed above. Predicted exposure severity scores for tubing workers ranged from 0.02 to 0.1 regardless of whether ESS_{CAN} or ESS_{TLV} was used. However, these workers also experienced a small increase in exposure severity after the elimination of TCE. Hairpin tube bending workers had a similar experience, although their exposure severity scores were in a very low range (0.005 to 0.03).

Figure 4-14a

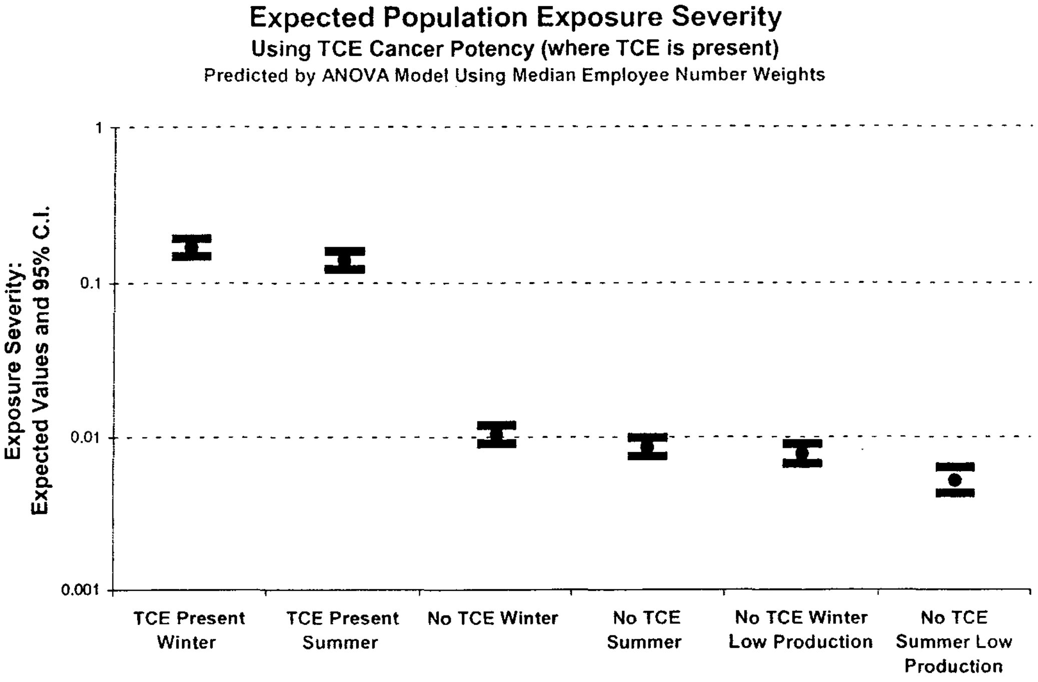


Figure 4-14b

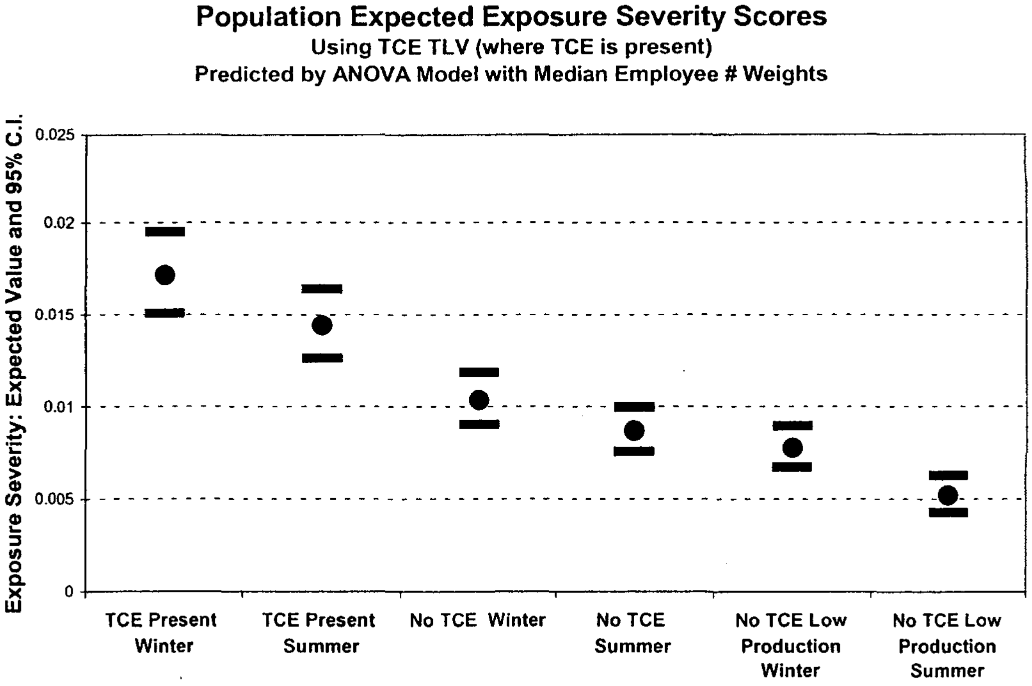


Figure 4-15a

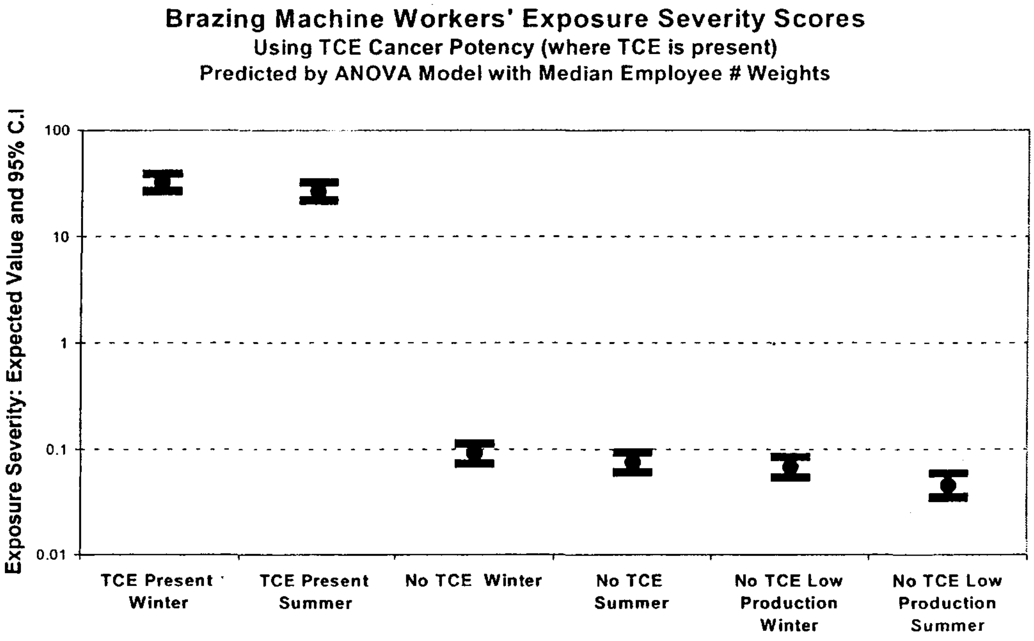


Figure 4-15b

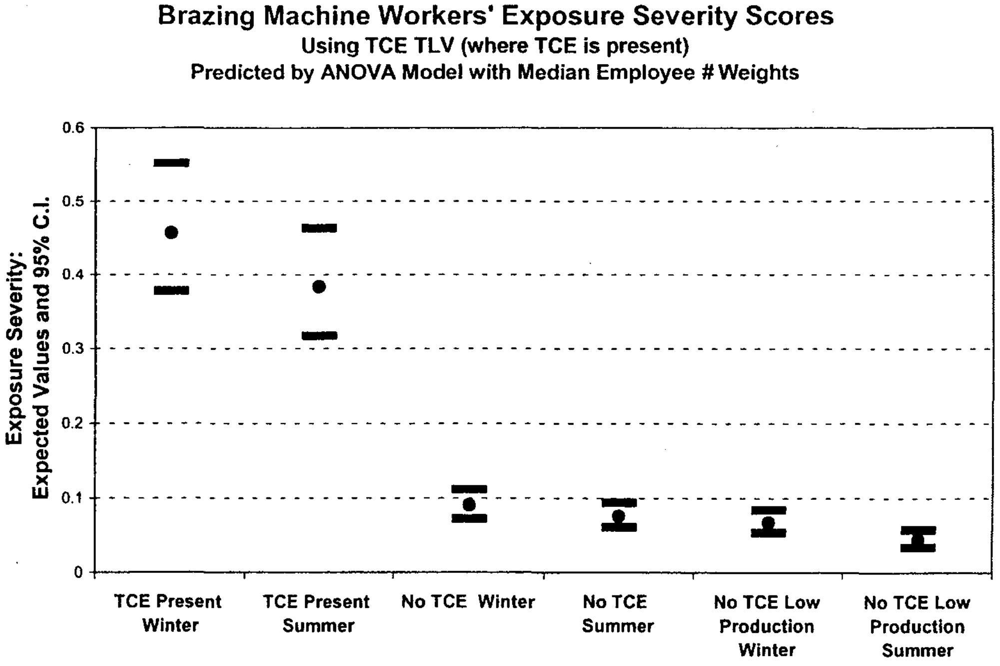


Figure 4-16a

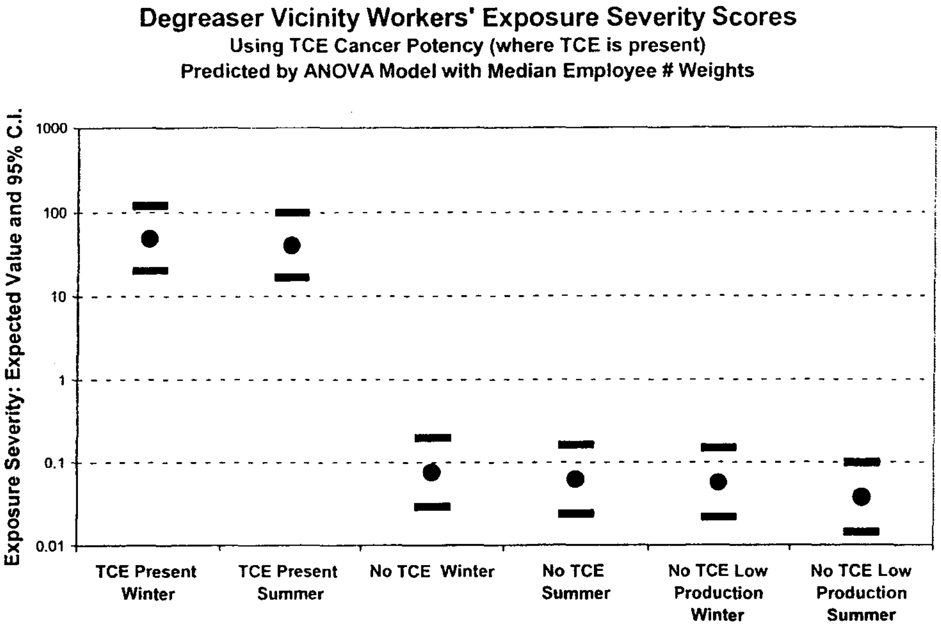


Figure 4-16b

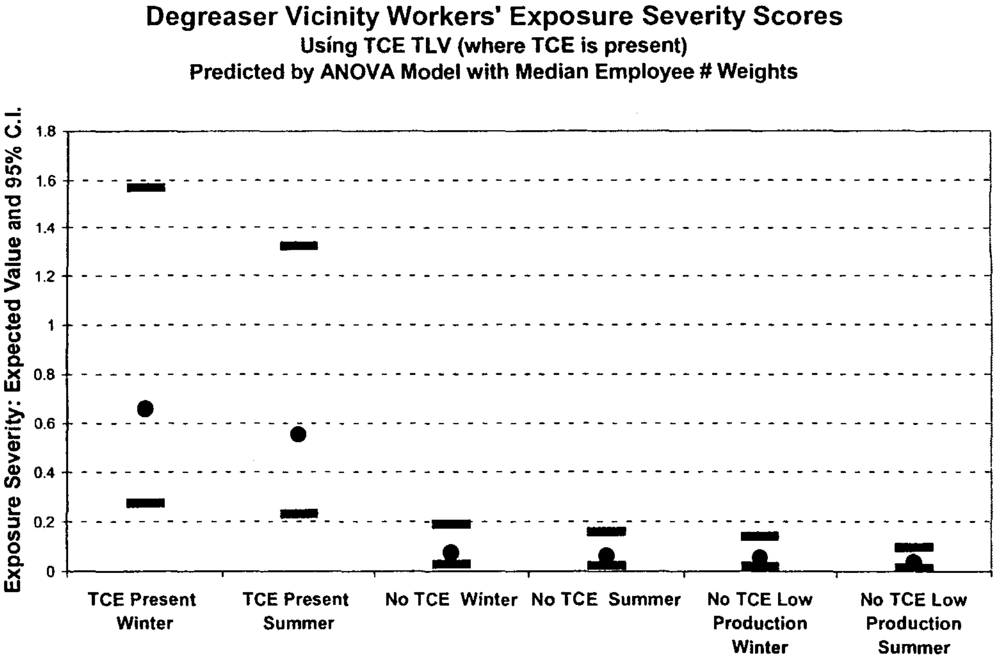


Figure 4-17a

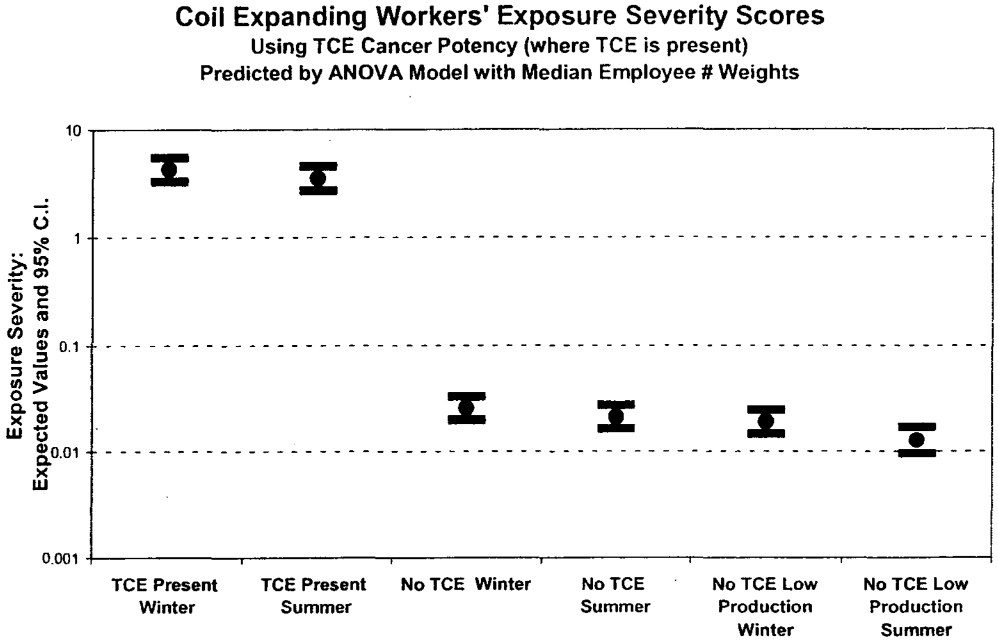


Figure 4-17b

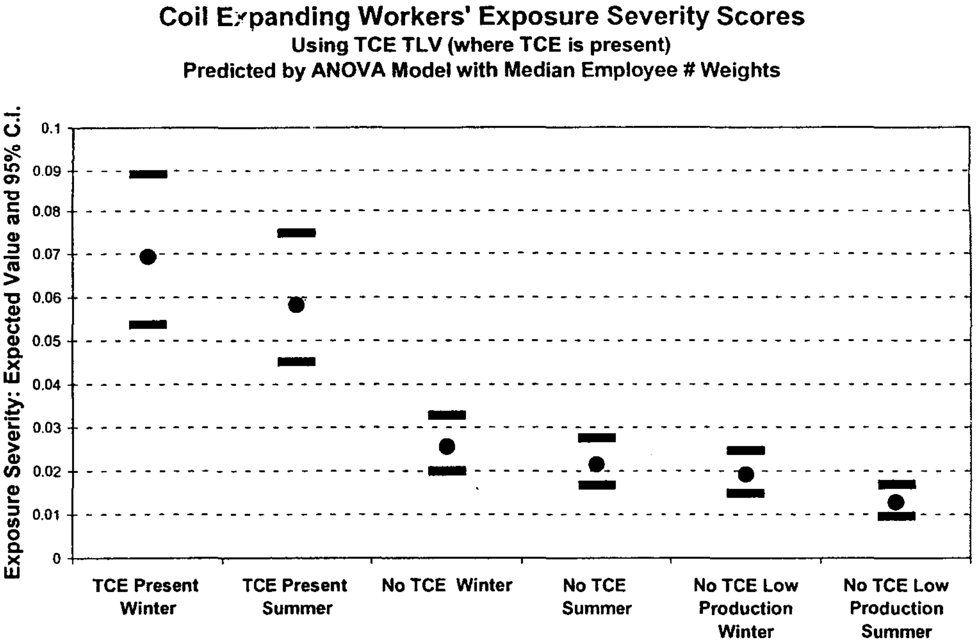


Figure 4-17a

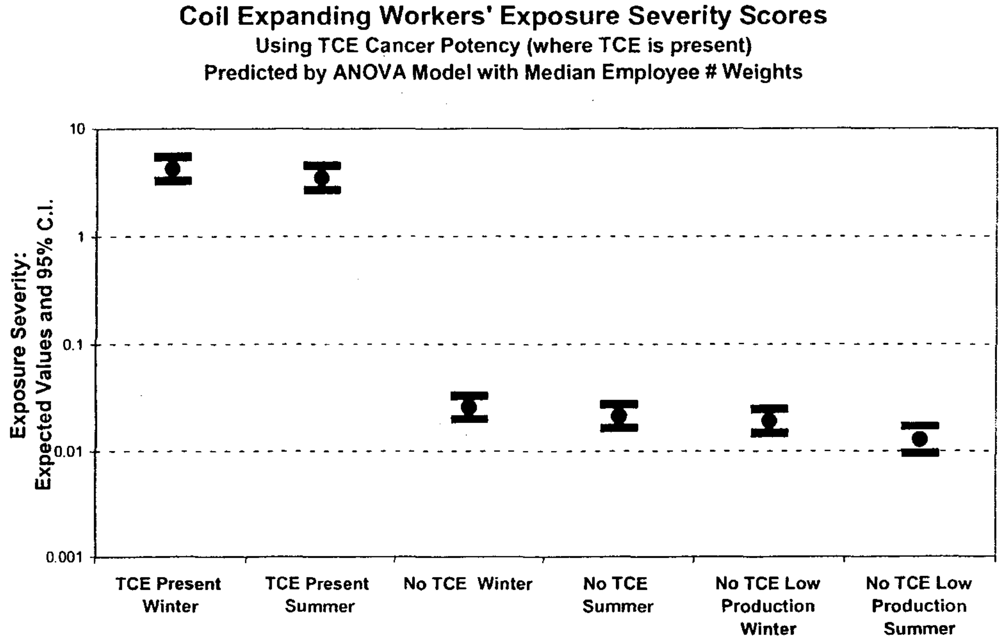


Figure 4-17b

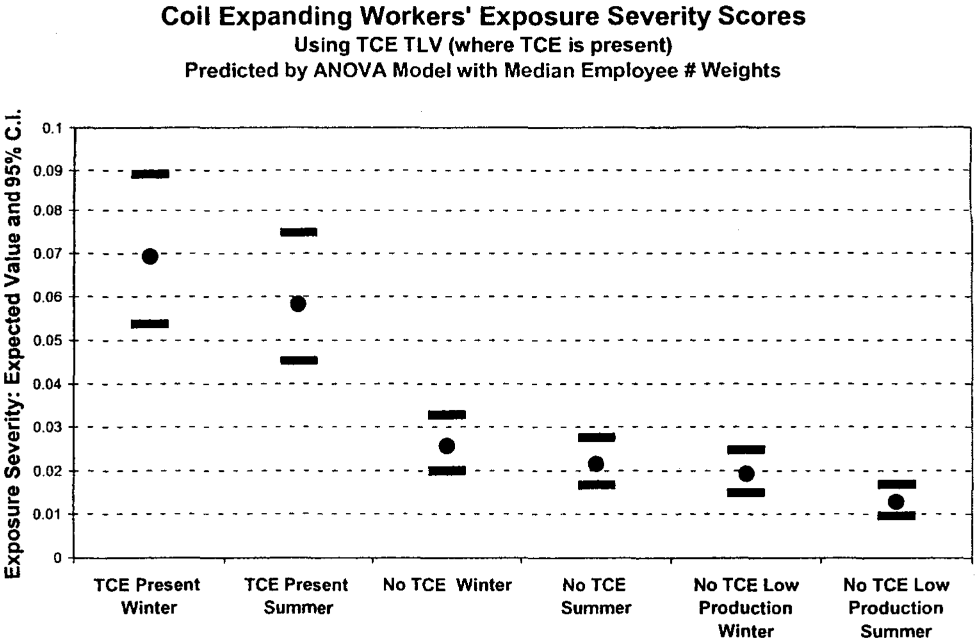


Figure 4-18a

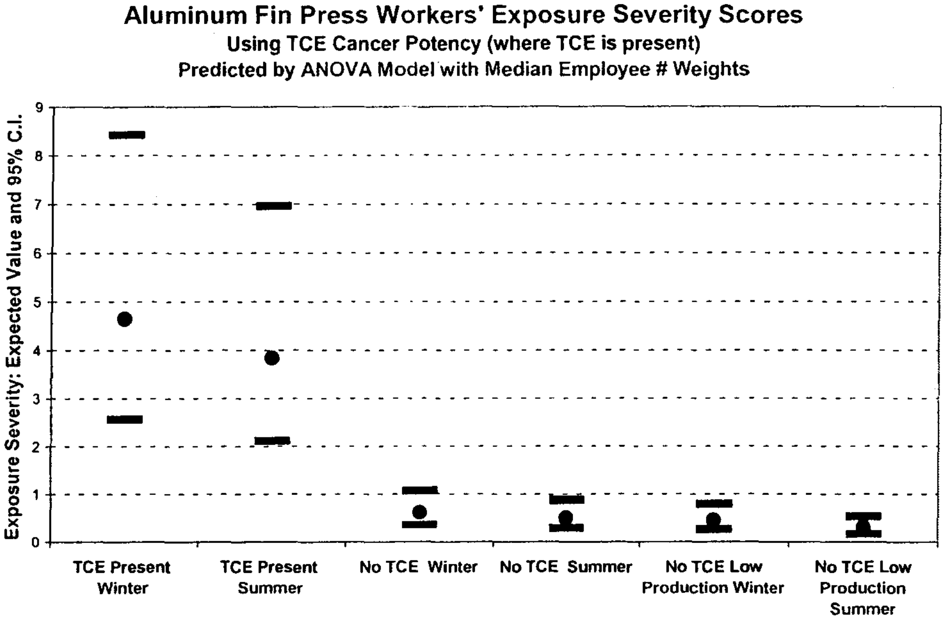


Figure 4-18b

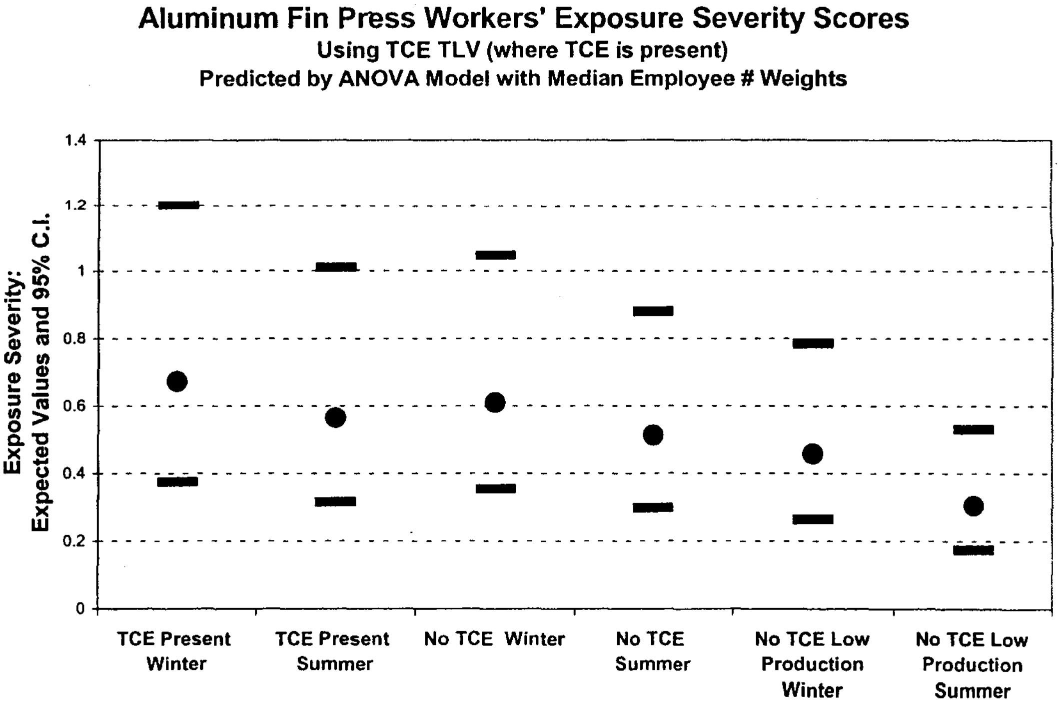


Figure 4-19a

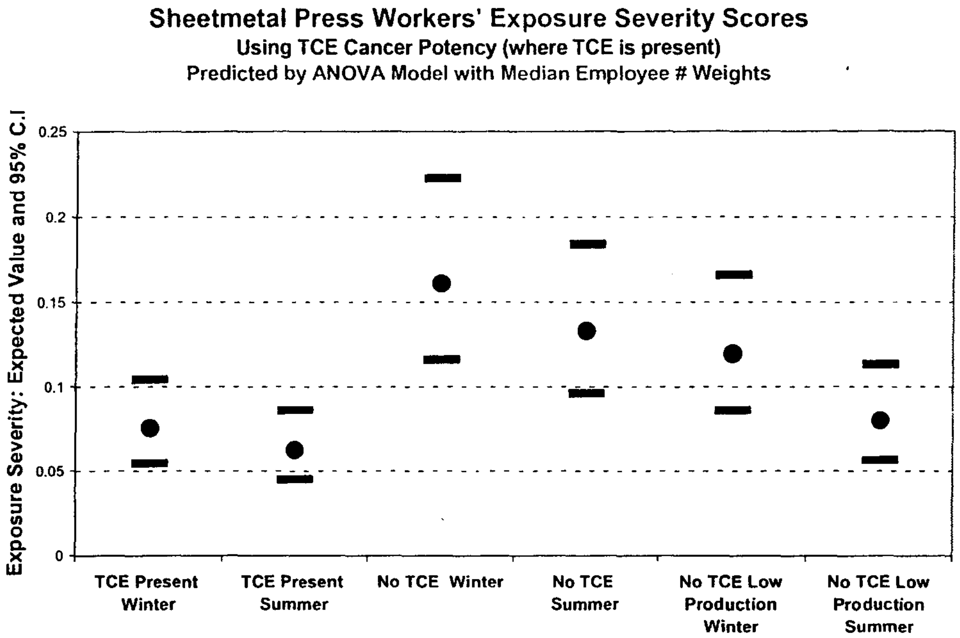
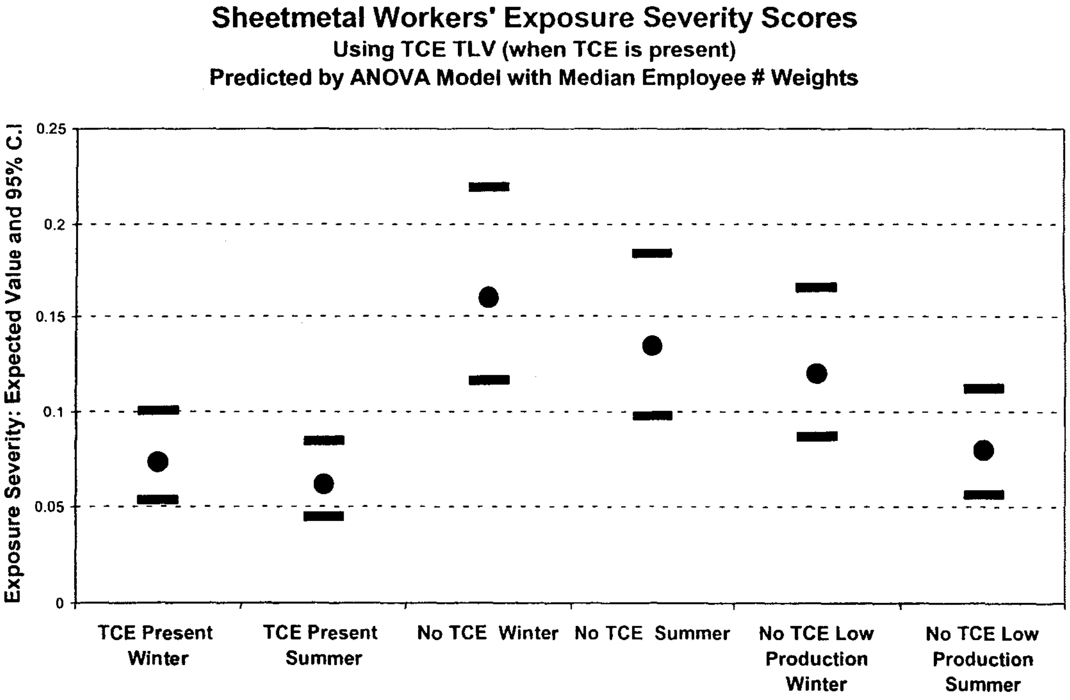


Figure 4-19b



Conclusion and Discussion

This research has shown that the impact of a pollution prevention on occupational exposures can be evaluated quantitatively, even in the absence of baseline exposure data. It provides a method that can be applied to other cases. The major finding is that elimination of a trichloroethylene (TCE) degreaser reduced the severity of occupational exposures in the worker population as a whole. The greatest benefit was experienced by brazing machine workers. The primary intended purpose of this action was to eliminate emissions of TCE to the external environment. While it is not surprising that the workers were better off when they were no longer exposed to TCE, this finding is nevertheless one of the first quantitative demonstrations of the benefits of pollution prevention for occupational health. It is possible that this finding may lead those who promote pollution prevention primarily for its environmental benefits to promote the occupational health benefits of pollution prevention as well. In addition, occupational health professionals, who may have ignored the potential benefits of pollution prevention when those benefits were supported primarily by common sense or anecdotal evidence, may re-examine the opportunities that pollution prevention offers for protecting worker health, now that the benefits have been demonstrated quantitatively.

In two departments, sheet metal presses and tube making, the model estimated small but statistically significant increases in exposure severity scores after the elimination of TCE. These are departments in which, according to the models, exposure to TCE had been small prior to the elimination of the degreaser. However, exposure to naphtha increased after the plant ceased to degrease its metal parts. As discussed above, the likely reason for this increase is the fact that, after degreasing ceased, the plant used lubricants on the sheetmetal press that were more volatile than previously. Whereas previously, degreasing had been used to make sure that metal parts would arrive in assembly areas relatively free of press lubricants, the plant relied on volatilization to achieve this purpose after the elimination of TCE.

Observed increases in exposure severity are small enough that they may not have any health significance, especially since the exposure severity scores after the elimination of TCE were well below one, indicating that exposures were considerably below the REL. However, they provide a quantitative illustration of the fact that implementing pollution prevention in one area can lead to other process changes that increase exposure elsewhere. It is hoped that policy makers and facility pollution prevention planners will take note of the fact that this possibility is no longer merely hypothetical. It has been quantitatively demonstrated to have occurred. Taking note of this fact should lead to increased attention paid to occupational exposures in pollution prevention planning. P2 options whose occupational exposure impacts are beneficial (or at least neutral) should be adopted, while those whose occupational exposure impacts are detrimental should be rejected.

Scientific Report

Chapter 5

Integrated Discussion:

Relationship of Findings to Study Goal, Policy Implications and Avenues for Additional Research

This research was driven by the concern that, despite the proliferation of federal and state legislation promoting pollution prevention (P2) (Burnett, 1998), there has been little research evaluating the impact of pollution prevention on occupational exposures. There is anecdotal evidence that pollution prevention can either reduce (USEPA, 1995) or increase (Mizra *et al.*, 2000) the severity of occupational exposure. Two articles (Ochsner, Michele, 2001; Roelofs, Cora R, Moure-Eraso, Rafael, & Ellenbecker, Michael J., 2000) report questionnaire surveys that found occupational health is not central to the thinking of either government officials or plant managers responsible for pollution prevention. One article (Bartlett, I. W., Dalton, A. J. P., McGuiness, A., & Palmer, H., 1999) found that, under experimental conditions, the substitution of vegetable-based cleaning agents for solvents reduced the severity of worker exposures.

In Chapter 2 it was pointed out that, before the study presented here, there had been no published study that evaluated worker exposures before and after the implementation of a pollution prevention program involving irreversible process changes. One reason for this is a lack of good historical occupational exposure data, a problem noted in Chapter 3. In this study, exposure was modeled, using data from the plant related to emissions, ventilation and compartment volume. In order to model exposure, measurements of air velocity were collected as were data with regard to the amount of time spent by workers at each location where they work.

As indicated in Chapter 1, the overall goal of this study was:

> *To demonstrate the value of considering occupational exposures in the design, implementation, and evaluation of pollution prevention programs.*

In pursuit of the goal, there were two major objectives:

1. *To develop and validate a model that is capable of making use of the data available from the study facility to estimate past airborne concentrations of chemical contaminants*

2. *To apply that model to investigate the impact of pollution prevention on occupational exposures at the study facility.*

Chapter 3 presented the development and validation of the model. Chapter 4 presented the application of the model to investigate the impact of a pollution prevention program on occupational exposures.

Relationship of Findings to Study Goals

The model was validated by using it to predict particulate concentrations in various parts of the plant and comparing those predictions to measurements of particulate matter. The validation found that, for compartments larger than 39,000 m^3, the model predicted the observed concentration reasonably well, with error rates of 60% or less. For compartments greater than 39,000 m^3 that contained particulate sources, the error was no greater than 29.5%. In addition, the model overpredicted particulate concentration in only one compartment greater than 39,000 m^3. In that compartment, the model's prediction was precisely equal to the input value used for particulate matter in the ambient air outside the plant. Ambient outdoor concentrations of contaminants modeled to evaluate the pollution prevention program are negligible. This means that the model's estimated concentration of contaminants of concern for evaluating the P2 program are not likely to be overestimates. Not surprisingly, for reasons presented in Chapter 3, the predictive value of the concentration model was severely limited for compartments less than 5 m^3. However, in the P2 evaluation, the smallest compartment used was more than 300 times that size. While it is an important finding that the model is of limited utility for small compartments, this finding is not surprising and it does little to cast doubt on the findings presented in Chapter 4.

Chapter 4 reported model results indicating that the elimination of a TCE degreaser reduced the average severity of occupational exposures in an air conditioner and dehumidifier manufacturing plant. According to the model results, workers in the brazing department and in the vicinity of the degreaser benefited most. However, the model indicated that metal press and tubing workers experienced a statistically significant increase in exposure severity. According to the model, these workers had been exposed to little TCE before the degreaser was eliminated, but experienced increased exposures to petroleum naphtha after the elimination of TCE. These increased exposures, which are small enough that that are unlikely to have health significance, are probably due to the fact that, after TCE elimination, the plant used metal press lubricants that were more volatile than the ones that had been used previously. This was done to make sure that the parts would reach the assembly line relatively free of lubricant, despite the fact that they were no longer degreased.

The quantitative findings were based on exposure severity scores whose purpose is to make it possible to say that that exposure to one combination of chemicals is better or worse than exposure to another combination. Exposure severity scores are designed to capture the intuitive concept that overall exposure becomes less severe if exposure to one potentially toxic agent is reduced or eliminated while exposure to all other agents remains unchanged. Similarly, exposure becomes more severe if exposure to one potentially toxic agent is increased or exposure to a new potentially toxic agent is introduced while exposure to all other agents remains unchanged. Exposure severity scores are calculated by dividing the TWA exposure for each chemical by the exposure limit for that chemical and aggregating across all the chemicals to which a worker is exposed. Using exposure severity scores made statistical hypothesis testing possible by providing a common metric that could be compared across job titles and across time. This made it possible to report the results indicated above. In this case, the findings were largely due to high concentrations of TCE before the implementation of P2 and zero concentrations after. This was because, whether the TLV or the cancer potency was used, the exposure limit for TCE was considerably lower than for naphtha or mineral spirits. Hence, a given concentration of TCE resulted in a higher exposure severity than a similar concentration of naphtha or mineral spirits. The major disadvantage of exposure severity scores is that they may in some cases assign more weight to an acute non-fatal health effect associated with one agent than to a chronic fatal effect associated with a second agent if the acute effect of the first agent occurs at lower concentration than the chronic effect of the second agent. However, that is not a problem for this case because TCE is associated with a fatal chronic effect, cancer, that the other two agents are not and the acute effects of TCE occur at lower concentrations (ACGIH, 1986; ACGIH, 1991; NIOSH, 1977).

The research has demonstrated quantitatively that a pollution prevention program reduced the severity of occupational exposures. Moreover, it has shown that the impact of a P2 program on occupational exposures can be estimated even when adequate baseline industrial hygiene data are not available. In addition, by showing an increase in exposure severity for two departments, the research illustrated the possibility that P2 can be detrimental to some workers if it leads to process changes that introduce agents into the workplace whose exposure potential or toxicity is greater than those they replace.

The primary finding indicates that workers benefited from the elimination of TCE, even though occupational health was not the primary reason for which TCE was eliminated. A secondary finding was that a subset of workers experienced moderately increased exposure severity, due to a substitution made to accommodate the impact of P2 on the manufacturing process.

These findings suggest that other plants may be able to reduce occupational exposures while implementing P2 programs to reduce environmental releases. In addition, they indicate that modifications designed to accommodate production processes to pollution prevention (e.g. increased volatility of metal press lubricants) can increase the exposure of some workers. Plant personnel who are responsible for designing and implementing pollution prevention would be well-advised to look for both potential occupational exposure reductions and potential new workplace hazards when projects are still in the planning stage. Policy makers should design and implement pollution prevention policies with explicit incentives for incorporating occupational health at the planning stage.

Policy Implications

Given that P2 has the capacity to be either beneficial or detrimental to occupational exposure, it is important to include occupational exposure in the design, planning, implementation and evaluation of pollution prevention programs. Unfortunately, Ochsner and Roelofs *et al.* have documented that this is rarely done. The inattention to occupational exposure in the practice of pollution prevention is part of a larger problem, the more general separation of environmental health from occupational health. The separation of occupational health from environmental health is not unique to pollution prevention. It appears to be so universally taken for granted that there is not much discussion of the separation in the scientific literature with the exception of the work on P2 and occupational health discussed above. The trade literature contains some discussion of the separation, but it tends to be limited to the difficulties of complying with EPA and OSHA regulations addressed to similar exposures or processes (See Heer, 1997, Sapper, 1996, and LaBarr, 1992).

There is, however, a documented example of a problem that resulted from the failure to consider worker exposure in the planning of conventional, end-of-pipe pollution control. (Piltingsrud, H. V., Zimmer, A., & Rourke, A., 1998) reported that Ohio EPA required the installation of an air incinerator at a facility that prints designs on vinyl shower curtains to control volatile organic compound (VOC) discharges to the environs. As a result of the installation of the incinerator, the flow of discharged air was reduced to approximately one-third of previous levels. Reduced air discharge led to solvent vapor concentrations within the workplace atmosphere at levels exceeding NIOSH, OSHA, and ACGIH acceptable concentration levels for worker exposure. Ultimately, NIOSH helped the plant to solve the problem by developing a substitute ink using non-photochemically solvents with lower evaporation rates. This eliminated the need for incineration of the discharged air and reduced exposures to approximately one third of their previous TLV-additive levels. The substitute ink could be considered a form of pollution prevention and it was developed taking into account both environmental and occupational exposures, but the initial approach to the problem was a traditional end-of-pipe approach and illustrates the fact that occupational exposures are considered too infrequently in the practice of environmental health.

Some employers believe that occupational health regulations add costs that yield little return (NFIB, 2001). The research presented here may help such employers to see occupational health protection in a different light. The research provides an example in which both occupational health protection and environmental protection were achieved by completely eliminating a toxic substance from a facility. The elimination of TCE from the study facility removed the need for compliance with regulations governing the management of that substance either for the protection of occupational or environmental health. This section proposes ways in which pollution prevention legislation could incorporate considerations related to occupational exposure. It addresses the federal Pollution Prevention Act and two of the most touted (INFORM, 1995) pieces of state legislation, those of New Jersey and Massachusetts.

Unfortunately, the federal Pollution Prevention Act (101 Public Law 508, § 6601-6610) makes no mention whatsoever of worker health and safety. Although the Act does not assign rulemaking or enforcement authority to any agency, it assigns grantmaking and information collection authority to EPA and not to OSHA. It appears that Congress never considered the possibility that P2 had implications for worker exposure. § 6605 requires the EPA administrator to make matching grants to states for programs to promote the use of source reduction techniques by businesses. In order to maximize the value of state programs funded under this section, EPA could require grant recipients to include an occupational exposure component in programs funded by these matching grants. To insure the funding of grants whose occupational exposure components are likely to be implemented successfully, the agency should invite occupational health professionals from NIOSH, OSHA and the private sector to serve on the committees that review the grant applications. EPA can implement these changes in the P2 grant program without seeking any new authority from Congress. This can occur more quickly and efficiently than assigning a formal role to OSHA or NIOSH in the administration of these grants. The latter option would require an amendment to the federal P2 Act.

§ 6606 requires the EPA administrator to establish a source reduction clearinghouse containing information on management, technical and operational approaches to source reduction. This clearinghouse can be found on the World Wide Web at http://www.epa.gov/opptintr/library/libppic.htm. The clearinghouse contains many documents with technical information about implementing pollution prevention. In order to promote consideration of occupational exposures in the design, implementation, and evaluation of P2 programs EPA could add documents to the clearinghouse discussing how to examine the potential impact on occupational exposures of a pollution prevention plan. To make sure that the documents are of the highest possible quality, the agency could request that OSHA and/or NIOSH produce such a document and review others as candidates for inclusion in the clearinghouse.

§ 6607 mandates that facilities required to report to the Toxic Release Inventory (TRI) under § 313 of the Superfund Amendments and Reauthorization Act of 1986 (SARA) must also report any source reduction and recycling activities that they have undertaken with regard to the chemicals that they are required to report to the TRI. Adding an occupational exposure monitoring requirement to this section would provide several benefits. Knowledge of employee exposure levels could lead to increased worker protection where exposures exceed OSHA action levels or PELs. In other cases, knowledge of exposure levels might lead employers to take voluntary action out of concern for employee health. Required exposure monitoring could increase the amount and quality of exposure data available to occupational epidemiologists, quite possibly leading to increased scientific knowledge of hazards associated with chemical exposure. Finally, such monitoring would make it much easier to evaluate the impact of P2 on occupational exposures. Many details need to be worked out before such a requirement could be implemented. Among these are:

1. Would monitoring be required for all chemicals on the TRI list or a subset?
2. Would the threshold for monitoring be the same as for reporting releases or would new criteria be developed?
3. Could an employer be exempted from monitoring by showing that the likelihood of exposure was low (e.g. a chemical is used only in closed systems)?
4. Would all employees have to be monitored or only those most likely to be exposed?
5. Would the monitoring results be made available only to the company and its employees or would they be reported to the federal government? Would the government be permitted to make the results public?

Unlike the proposals above for implementing § 6605 and § 6606, the Act would have to be amended by Congress before monitoring of occupational exposure could be required. Congress could do this by specifying a subset of chemicals on the TRI list for which occupational exposure monitoring would be required. It could authorize OSHA to add chemicals to the list as the agency might deem appropriate and it could authorize OSHA to resolve many of the other questions above through rulemaking. Although the rest of the Act assigns responsibilities to EPA, it would make more sense to assign these responsibilities to OSHA because OSHA is the federal agency that is primarily responsible for occupational health. There is a precedent for assigning OSHA responsibilities within an act that is primarily directed at EPA. Both the Clean Air Act and its 1990 amendments were aimed primarily at EPA. However, the amendments authorized OSHA to issue a chemical process safety standard designed to protect workers (GAO, 2000). It is quite likely that an amendment and subsequent rulemaking requiring TRI reporters to monitor occupational exposure would be bitterly opposed. The difficulty of the political contest, however, does not make the proposal any less sound as policy.

Unlike the federal Pollution Prevention Act, the New Jersey Pollution Prevention Act gives some recognition to the importance of occupational exposure. In the legislative findings and declarations, the Act states that discharge of hazardous substances "into air and water, onto the land, and into the workplaces and neighborhoods of the State constitutes an unnecessary risk to the environment and to occupational and public health." It further states: "The Legislature therefore determines that it is in the interest of the environment and public and occupational health... to transform the current system of pollution control to a system of pollution prevention." (L.1991,c.235,s.1) The Act defines pollution prevention as "changes in production processes, products or the use of substitute raw materials or products that... reduce or eliminate, without shifting, the risks... to employees, consumers, and the environment and human health." (L.1991,c.235,s.2). Despite the legislature's expressed concern for occupational health, Ochsner (2001) documented that this concern has little impact on the motivations of those responsible for implementing pollution prevention programs at the facility level.

The New Jersey Pollution Prevention Act requires each facility that meets specified criteria to develop a P2 plan, including a source-by-source investigation of pollution prevention opportunities in the facility and a detailed technical and economic analysis of specific P2 options for targeted sources (Anderson and Herb, 1992). Firms are required to submit summaries of their plans to the State. Facilities that submit their complete plans are eligible to participate in the State's facility-wide permit program, in which the plans serve as a basis for writing the permits (Helms et *al.*, 2000). If the New Jersey Legislature wishes to transform its expressed concern about occupational health into action, it could amend the Pollution Prevention Act explicitly to require that the source by source investigation include an evaluation of occupational hazards posed by each source. It could further require that a facility-wide permit not be issued or renewed until it had been reviewed by a qualified occupational health professional to identify previously missed opportunities for elimination of occupational hazards and to determine whether any part of the pollution prevention plan introduced new occupational hazards. The level of scrutiny might vary with the particular plan. Initially, the reviewer might examine the documentation and request written responses on matters that raise potential concerns related to worker exposure. This might be followed by a walk-through evaluation if the reviewer were to conclude that worker exposure concerns could not be satisfied by written responses.

Roelofs *et al.* (2000) perceive the Massachusetts Toxics Use Reduction Act (TURA, Massachusetts Annotated Laws ch.211, 1-23. 1989) as an opportunity for enhanced prevention of occupational injuries and illnesses. The Act refers to occupational exposure no fewer than seven times. Five of these references are in the substantive parts of the Act rather than in the preamble. Under the Act, State government is required to consider discharge of toxic substances into the workplace as well as into the external environment when it considers which categories of industrial facility it considers to be priorities for achieving toxics use reduction. Nevertheless, as previously discussed, occupational exposure is not a priority for those in State government who administer the act. § 10 of the Act requires the submission of an annual report for each toxic substance that a company uses in a quantity greater than 10,000 lbs. or manufactures in a quantity greater than 25,000 lbs. After the first year of reporting, a company is to report the degree (if any) to which it has achieved reductions in toxic by-products and in toxic emissions. This section could be amended to require that companies report the degree (if any) which they achieve reductions in occupational exposures as well. The potential advantages and difficulties associated with such an amendment are similar those discussed above with regard to amending TRI to require reporting occupational exposures.

§ 11 of the Act requires companies that manufacture or use toxic substances in the quantities indicated above to develop toxics use reduction plans. Among other requirements, these plans must include:

- analyses of current and projected toxics use, byproduct generation, and emissions;
- evaluations of types and amounts of toxic substances used, and
- identification of how toxics use reduction is to be achieved.

This section could be amended to require analyses of current and projected occupational exposures to toxic substances and identification of the potential impact on occupational exposure of the method chosen for toxics use reduction. Models similar to the ones presented in this research could be used to estimate the impact of proposed toxics use reduction methods on occupational exposures.

Avenues for Additional Research

It has been observed several times above and extensively discussed in Chapter 2 that there is a shortage of research related to the impact of P2 on occupational exposure. As discussed above, this research is the first to offer a pre-post analysis of the impact on occupational exposures of a P2 program based on irreversible (as opposed to experimental) process changes. As stated in Chapter 1, it is important to develop a base of scientific knowledge as to the impact of pollution prevention on occupational exposure in order to provide decision-makers with a sound basis for action. The research presented here has validated a model, which can be used to estimate historical contaminant concentrations in industrial facilities. In order to continue to build a base of scientific knowledge in this area, it would be a valuable contribution for other researchers to use the model to estimate the impact on occupational exposures of pollution prevention programs in other industrial facilities. The above section discussed proposed amendments to the federal P2 Act and two of the most touted pieces of state P2 legislation. In addition, it discussed proposed changes in the way these legislative acts are carried out. These proposed amendments and changes are aimed at incorporating concerns related occupational exposures into P2. Further research needs to be done to evaluate the impact on occupational exposures of many other state P2 Acts in a manner similar to that of the above evaluation.

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Appendix:

Supplemental Material for Chapter 4

Employee Questionnaire

1. This research will focus on the work you did [dates]. Please think back for a moment about this time of your life. (20 second pause). What was your job title at that time? In what department or part of the plant did you work?

2. Please describe a typical week at that job after you had been doing it for a while and you had experience. Try to include as many of the things you did as you remember. Try to describe the tasks in as much detail as you can. Try to describe where you were in the plant when you did a task.

3. (For each task) How often did you [task]?
   Prompt only if necessary: Once a day or more? (If yes) How many times per day?
   (If no) Once a week or more? (If yes) How many times per week?

4. (For each task) How long did it take you to [task]?
   (Prompt only if necessary) More than an hour or less than an hour?
   (If more) How many hours did [task] take you?
   (If less) How many minutes did [task] take you?

5. (For each task) Please describe as well as you can where you were in the plant when you [task]. What was the nearest machine, production line or other part of the plant? Approximately how many feet or inches were you from it?

6. During the time you worked as a(n) [Title], were there any major changes is the way the work was done?

7. Please describe how the work changed.. (Ask clarifying follow-ups as appropriate). To the nearest month and year that you can remember, when did that change occur?

Table A-I:
Differences between Exposure Severity Scores for Higher and Lower Exposure Locations in Departments for which the Location of Employees is Uncertain

Department & Job	Season & Year	Location A	Location B	Location B ESS_{CAN} minus Location A ESS_{CAN}	Location B ESS_{TLV} minus Location A ESS_{TLV}
Tubing ASSEMBLER	Winter 1994	Between Columns 29 and 32	Between columns 32 and 36	0.102096442	0.102746993
Tubing ASSEMBLER	Summer 1994	Between Columns 29 and 32	Between columns 32 and 36	0.123614734	0.121683471
Tubing ASSEMBLER	Winter 1995	Between Columns 29 and 32	Between columns 32 and 36	0.110238422	0.110140995
Tubing ASSEMBLER	Summer 1995	Between Columns 29 and 32	Between columns 32 and 36	0.120159291	0.120003957
Tubing ASSEMBLER	Winter 1996	Between Columns 29 and 32	Between columns 32 and 36	0.220996208	0.220996208
Tubing ASSEMBLER	Summer 1996	Between Columns 29 and 32	Between columns 32 and 36	0.222447093	0.222447093
Tubing ASSEMBLER	Winter 1997	Between Columns 29 and 32	Between columns 32 and 36	0.155642454	0.155642454
Tubing ASSEMBLER	Summer 1997	Between Columns 29 and 32	Between columns 32 and 36	0.164764482	0.164764482
Dehumidifier Coil ASSEMBLER	Winter 1994	Column 23	Column 28	0.000944682	0.001579757

Table A-I:
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Department & Job	Season & Year	Location A	Location B	Location B ESS_{CAN} minus Location A ESS_{CAN}	Location B ESS_{TLV} minus Location A ESS_{TLV}
Dehumidifier Coil ASSEMBLER	Summer 1994	Column 23	Column 28	0.003165485	0.003352768
Dehumidifier Coil ASSEMBLER	Winter 1995	Column 23	Column 28	0.005949725	0.005442325
Dehumidifier Coil ASSEMBLER	Summer 1995	Column 23	Column 28	0.003974592	0.004156063
Dehumidifier Coil ASSEMBLER	Winter 1996	Column 23	Column 28	0.004776046	0.004776046
Dehumidifier Coil ASSEMBLER	Summer 1996	Column 23	Column 28	0.005661096	0.005661096
Dehumidifier Coil ASSEMBLER	Winter 1997	Column 23	Column 28	0.002287537	0.002287537
Dehumidifier coil setup	Winter 1995	Column 23	Column 28	0.003689172	0.003872063
Dehumidifier coil setup	Summer 1995	Column 23	Column 28	0.002494896	0.004097184
Dehumidifier coil setup	Winter 1996	Column 23	Column 28	0.00412474	0.00412474
Dehumidifier coil setup	Summer 1996	Column 23	Column 28	0.005495063	0.005495063
Dehumidifier Coil setup	Winter 1997	Column 23	Column 28	0.002934473	0.002934473
Dehumidifier Coil MACHINE OPERATOR	Winter 1994	Column 23	Column 28	0.001518358	0.001693707

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Department & Job	Season & Year	Location A	Location B	Location B ESS_{CAN} minus Location A ESS_{CAN}	Location B ESS_{TLV} minus Location A ESS_{TLV}
Dehumidifier Coil MACHINE OPERATOR	Summer 1994	Column 23	Column 28	0.003189917	0.003531509
Dehumidifier Coil MACHINE OPERATOR	Winter 1995	Column 23	Column 28	0.005340331	0.004640675
Dehumidifier Coil MACHINE OPERATOR	Summer 1995	Column 23	Column 28	0.004261288	0.003957969
Dehumidifier Coil MACHINE OPERATOR	Winter 1996	Column 23	Column 28	0.003174215	0.003174215
Dehumidifier Coil MACHINE OPERATOR	Summer 1996	Column 23	Column 28	0.003009326	0.003009326
Dehumidifier COIL MACHINE OPERATOR	Winter 1997	Column 23	Column 28	-0.000188753	-0.000188753
Dehumidifier Coil PACKER-ASSEMBLER	Winter 1995	Column 23	Column 28	0.00331944	0.00388846
Dehumidifier Coil PACKER-ASSEMBLER	Summer 1995	Column 23	Column 28	0.004362452	0.004000396
Dehumidifier Coil PACKER-ASSEMBLER	Winter 1996	Column 23	Column 28	0.003965507	0.003965507
Dehumidifier Coil PACKER-ASSEMBLER	Summer 1996	Column 23	Column 28	0.002714008	0.002714008

Table A-I: Differences between Exposure Severity Scores for Higher and Lower Exposure Locations in Departments for which the Location of Employees is Uncertain

Department & Job	Season & Year	Location A	Location B	Location B ESS_{CAN} minus Location A ESS_{CAN}	Location B ESS_{TLV} minus Location A ESS_{TLV}
Brazing Machines ASSEMBLER	Winter 1994	Between Columns 29 and 32	Between columns 32 and 36	89.80936456	1.22860499
Brazing Machines ASSEMBLER	Summer 1994	Between Columns 29 and 32	Between columns 32 and 36	88.79891588	1.241657078
Brazing Machines ASSEMBLER	Winter 1995	Between Columns 29 and 32	Between columns 32 and 36	84.2559048	1.190204895
Brazing Machines ASSEMBLER	Summer 1995	Between Columns 29 and 32	Between columns 32 and 36	85.22787722	1.18878802
Brazing Machines ASSEMBLER	Winter 1996	Between Columns 29 and 32	Between columns 32 and 36	0.231801481	0.231801481
Brazing Machines ASSEMBLER	Summer 1996	Between Columns 29 and 32	Between columns 32 and 36	0.221052408	0.221052408
Brazing Machines ASSEMBLER	Winter 1997	Between Columns 29 and 32	Between columns 32 and 36	0.155344947	0.155344947
Brazing Machines ASSEMBLER	Summer 1997	Between Columns 29 and 32	Between columns 32 and 36	0.17196529	0.17196529
Brazing Machines BRAZER	Winter 1994	Between Columns 29 and 32	Between columns 32 and 36	89.85894566	1.232322463

Table A-I:
Differences between Exposure Severity Scores for Higher and Lower Exposure Locations in Departments for which the Location of Employees is Uncertain

Department & Job	Season & Year	Location A	Location B	Location B ESS_{CAN} minus Location A ESS_{CAN}	Location B ESS_{TLV} minus Location A ESS_{TLV}
Brazing Machines BRAZER	Summer 1994	Between Columns 29 and 32	Between columns 32 and 36	88.71812762	1.241491555
Brazing Machines BRAZER	Winter 1995	Between Columns 29 and 32	Between columns 32 and 36	85.13065751	1.164941829
Brazing Machines BRAZER	Summer 1995	Between Columns 29 and 32	Between columns 32 and 36	85.37294004	1.190896141
Brazing Machines BRAZER	Winter 1996	Between Columns 29 and 32	Between columns 32 and 36	0.228598907	0.228598907
Brazing Machines BRAZER	Summer 1996	Between Columns 29 and 32	Between columns 32 and 36	0.220130879	0.220130879
Brazing Machines BRAZER	Winter 1997	Between Columns 29 and 32	Between columns 32 and 36	0.152293757	0.152293757
Brazing Machines BRAZER	Summer 1997	Between Columns 29 and 32	Between columns 32 and 36	0.16372478	0.16372478
Brazing Machines PACKER-ASSEMBLER	Winter 1994	Between Columns 29 and 32	Between columns 32 and 36	89.4241419	1.236269085
Brazing Machines PACKER-ASSEMBLER	Summer 1994	Between Columns 29 and 32	Between columns 32 and 36	89.67369605	1.257730768

Table A-I: Differences between Exposure Severity Scores for Higher and Lower Exposure Locations in Departments for which the Location of Employees is Uncertain					
Department & Job	**Season & Year**	**Location A**	**Location B**	**Location B ESS_{CAN} minus Location A ESS_{CAN}**	**Location B ESS_{TLV} minus Location A ESS_{TLV}**
Brazing Machines PACKER-ASSEMBLER	Winter 1995	Between Columns 29 and 32	Between columns 32 and 36	84.84853317	1.167795265
Brazing Machines PACKER-ASSEMBLER	Summer 1995	Between Columns 29 and 32	Between columns 32 and 36	83.95082885	1.19123024
Brazing Machines PACKER-ASSEMBLER	Winter 1996	Between Columns 29 and 32	Between columns 32 and 36	0.215858976	0.215858976
Brazing Machines PACKER-ASSEMBLER	Summer 1996	Between Columns 29 and 32	Between columns 32 and 36	0.213078014	0.213078014
Brazing Machines PACKER-ASSEMBLER	Winter 1997	Between Columns 29 and 32	Between columns 32 and 36	0.157550286	0.157550286
Brazing Machines PACKER-ASSEMBLER	Summer 1997	Between Columns 29 and 32	Between columns 32 and 36	0.166795437	0.166795437
Brazing Machines TESTER	Winter 1994	Between Columns 29 and 32	Between columns 32 and 36	72.89005115	1.005218473
Brazing Machines TESTER	Summer 1994	Between Columns 29 and 32	Between columns 32 and 36	71.35603745	1.030479227
Brazing Machines TESTER	Winter 1995	Between Columns 29 and 32	Between columns 32 and 36	67.6666857	0.963021839

Table A-I:
Differences between Exposure Severity Scores for Higher and Lower Exposure Locations in Departments for which the Location of Employees is Uncertain

Department & Job	Season & Year	Location A	Location B	Location B ESS_{CAN} minus Location A ESS_{CAN}	Location B ESS_{TLV} minus Location A ESS_{TLV}
Brazing Machines TESTER	Summer 1995	Between Columns 29 and 32	Between columns 32 and 36	68.6721275	0.989202349
Brazing Machines TESTER	Winter 1996	Between Columns 29 and 32	Between columns 32 and 36	0.217162409	0.217162409
Brazing Machines TESTER	Summer 1996	Between Columns 29 and 32	Between columns 32 and 36	0.213997091	0.213997091
Brazing Machines TESTER	Winter 1997	Between Columns 29 and 32	Between columns 32 and 36	0.16369181	0.16369181

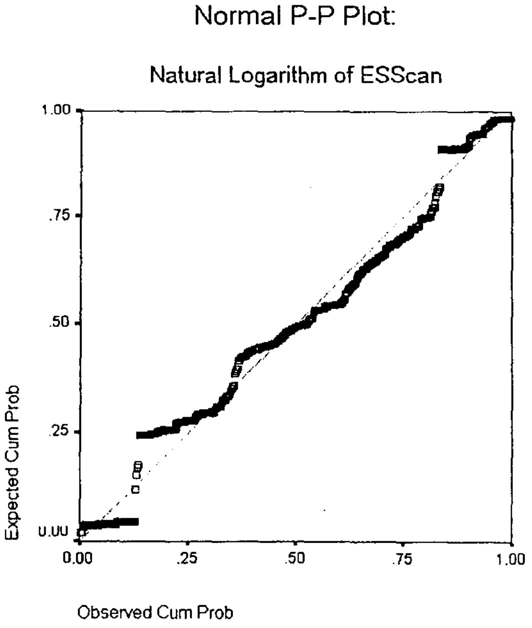

Figure A-1a

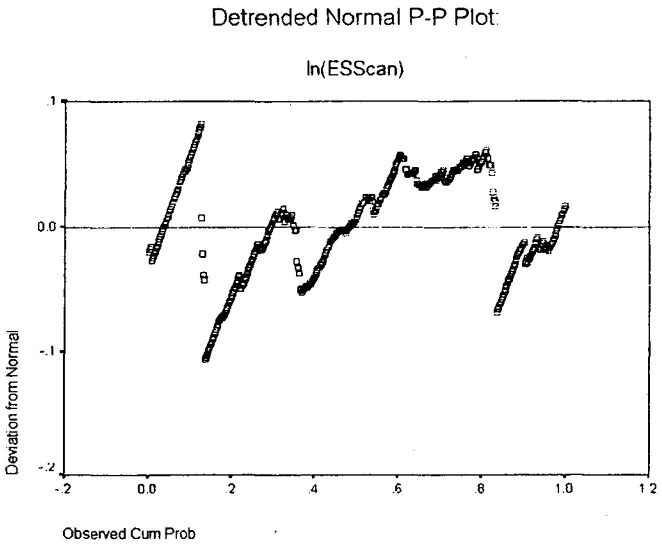

Figure A-1b

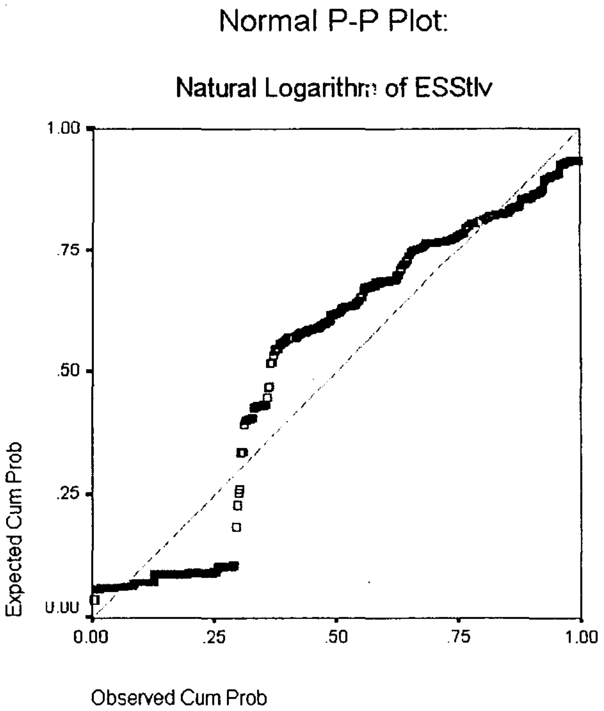

Figure A-2a

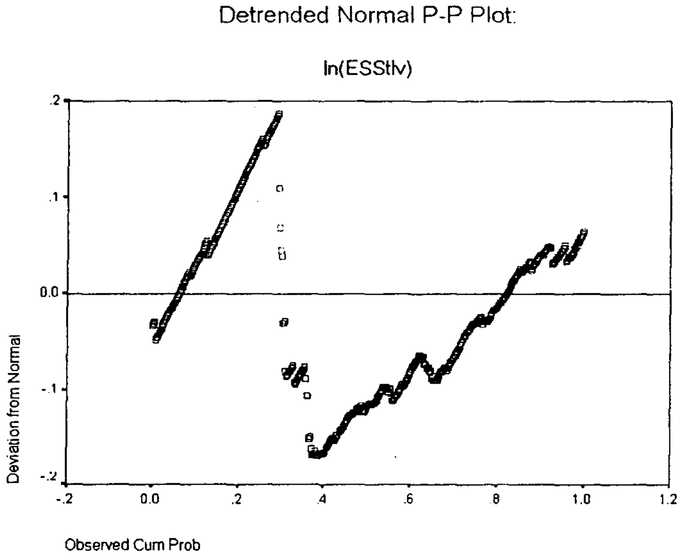

Figure A-2b

Table A-II:
Deviance Analysis of Models to Predict Log-Transformed Exposure Severity Scores Based on TCE TLV and TCE Cancer Potency with Different Employee Number Weights

Dependent	Employee Number Weight	Null Model	Extended Model	F	p
ln(ESS$_{CAN}$)	90%ile	DEPARTMENT TCE	DEPARTMENT TCE DEPARTMENT*TCE	157.45	3.29E-145
ln(ESS$_{CAN}$)	90%ile	DEPARTMENT TCE DEPARTMENT*TCE	DEPARTMENT TCE PRODUCTION LEVEL DEPARTMENT*TCE	33.80	1.17E-08
ln(ESS$_{CAN}$)	90%ile	DEPARTMENT TCE DEPARTMENT*TCE	DEPARTMENT TCE SEASON DEPARTMENT*TCE	27.63	2.29E-07
ln(ESS$_{CAN}$)	90%ile	DEPARTMENT TCE DEPARTMENT*TCE	DEPARTMENT TCE PRODUCTION LEVEL SEASON DEPARTMENT*TCE	39.99	1.10E-16
ln(ESS$_{CAN}$)	90%ile	DEPARTMENT TCE PRODUCTION LEVEL DEPARTMENT*TCE	DEPARTMENT TCE PRODUCTION LEVEL SEASON DEPARTMENT*TCE	42.98	1.56E-10
ln(ESS$_{CAN}$)	90%ile	DEPARTMENT TCE SEASON DEPARTMENT*TCE	DEPARTMENT TCE PRODUCTION LEVEL SEASON DEPARTMENT*TCE	49.32	8.29E-12

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Dependent	Employee Number Weight	Null Model	Extended Model	F	p
$\ln(ESS_{CAN})$	**90%ile**	**DEPARTMENT TCE DEPARTMENT*TCE**	**DEPARTMENT TCE PRODUCTION LEVEL SEASON PRODUCTION LEVEL*SEASON DEPARTMENT*TCE**	**5.39**	**2.07E-02**
$\ln(ESS_{CAN})$	median	DEPARTMENT TCE	DEPARTMENT TCE DEPARTMENT*TCE	153.41	2.72E-147
$\ln(ESS_{CAN})$	median	DEPARTMENT TCE DEPARTMENT*TCE	DEPARTMENT TCE PRODUCTION LEVEL DEPARTMENT*TCE	32.514	2.10E-08
$\ln(ESS_{CAN})$	median	DEPARTMENT TCE DEPARTMENT*TCE	DEPARTMENT TCE SEASON DEPARTMENT*TCE	25.71	5.74E-07
$\ln(ESS_{CAN})$	median	DEPARTMENT TCE DEPARTMENT*TCE	DEPARTMENT TCE PRODUCTION LEVEL SEASON DEPARTMENT*TCE	37.49	8.06E-16
$\ln(ESS_{CAN})$	median	DEPARTMENT TCE PRODUCTION LEVEL DEPARTMENT*TCE	DEPARTMENT TCE PRODUCTION LEVEL SEASON DEPARTMENT*TCE	39.76	6.68E-10
$\ln(ESS_{CAN})$	median	DEPARTMENT TCE SEASON DEPARTMENT*TCE	DEPARTMENT TCE PRODUCTION LEVEL SEASON DEPARTMENT*TCE	46.74	2.56E-11
$\ln(ESS_{CAN})$	**median**	**DEPARTMENT TCE PRODUCTION LEVEL SEASON DEPARTMENT*TCE**	**DEPARTMENT TCE PRODUCTION LEVEL SEASON DEPARTMENT*TCE PRODUCTION LEVEL*SEASON**	**4.41**	**3.64E-02**
$\ln(ESS_{CAN})$	10%ile	DEPARTMENT TCE	DEPARTMENT TCE DEPARTMENT*TCE	153.63	7.65E-144
$\ln(ESS_{CAN})$	10%ile	DEPARTMENT TCE DEPARTMENT*TCE	DEPARTMENT TCE DEPARTMENT*TCE PRODUCTION LEVEL	32.45	2.22E-08
$\ln(ESS_{CAN})$	10%ile	DEPARTMENT TCE DEPARTMENT*TCE	DEPARTMENT TCE SEASON DEPARTMENT*TCE	24.78	9.23E-07
$\ln(ESS_{CAN})$	10%ile	DEPARTMENT TCE DEPARTMENT*TCE	DEPARTMENT TCE PRODUCTION LEVEL SEASON DEPARTMENT*TCE	36.93	1.47E-15

Table A-II:
Deviance Analysis of Models to Predict Log-Transformed Exposure Severity Scores Based on TCE TLV and TCE Cancer Potency with Different Employee Number Weights

Dependent	Employee Number Weight	Null Model	Extended Model	F	p
ln(ESS$_{CAN}$)	10%ile	DEPARTMENT TCE PRODUCTION LEVEL DEPARTMENT*TCE	DEPARTMENT TCE PRODUCTION LEVEL SEASON DEPARTMENT*TCE	38.65	1.17E-09
ln(ESS$_{CAN}$)	10%ile	DEPARTMENT TCE SEASON DEPARTMENT*TCE	DEPARTMENT TCE PRODUCTION LEVEL SEASON DEPARTMENT*TCE	46.57	2.91E-11
ln(ESS$_{CAN}$)	**10%ile**	**DEPARTMENT TCE PRODUCTION LEVEL SEASON DEPARTMENT*TCE**	**DEPARTMENT TCE PRODUCTION LEVEL SEASON DEPARTMENT*TCE PRODUCTION LEVEL*SEASON**	**3.74**	**5.39E-02**
ln(ESS$_{TLV}$)	90%ile	DEPARTMENT TCE	DEPARTMENT TCE DEPARTMENT*TCE	18.0	1.14E-29
ln(ESS$_{TLV}$)	90%ile	DEPARTMENT TCE DEPARTMENT*TCE	DEPARTMENT TCE DEPARTMENT*TCE PRODUCTION LEVEL	35.74	4.66E-09
ln(ESS$_{TLV}$)	90%ile	DEPARTMENT TCE DEPARTMENT*TCE	DEPARTMENT TCE SEASON DEPARTMENT*TCE	24.74	9.44E-07
ln(ESS$_{TLV}$)	90%ile	DEPARTMENT TCE DEPARTMENT*TCE	DEPARTMENT TCE SEASON PRODUCTION LEVEL DEPARTMENT*TCE	29.22	1.22E-12
ln(ESS$_{TLV}$)	90%ile	DEPARTMENT TCE SEASON DEPARTMENT*TCE	DEPARTMENT TCE SEASON PRODUCTION LEVEL DEPARTMENT*TCE	30.91	4.70E-08
ln(ESS$_{TLV}$)	90%ile	DEPARTMENT TCE DEPARTMENT*TCE PRODUCTION LEVEL	DEPARTMENT TCE SEASON PRODUCTION LEVEL DEPARTMENT*TCE	19.56	1.23E-05
ln(ESS$_{TLV}$)	**90%ile**	**DEPARTMENT TCE SEASON PRODUCTION LEVEL DEPARTMENT*TCE**	**DEPARTMENT TCE PRODUCTION LEVEL SEASON DEPARTMENT*TCE PRODUCTION LEVEL*SEASON**	**26.72**	**3.57E-07**
ln(ESS$_{TLV}$)	median	DEPARTMENT TCE	DEPARTMENT TCE DEPARTMENT*TCE	17.36	6.38E-29
ln(ESS$_{TLV}$)	median	DEPARTMENT TCE DEPARTMENT*TCE	DEPARTMENT TCE PRODUCTION LEVEL DEPARTMENT*TCE	34.26	9.12E-09

Table A-II:
Deviance Analysis of Models to Predict Log-Transformed Exposure Severity Scores Based on TCE TLV and TCE Cancer Potency with Different Employee Number Weights

Dependent	Employee Number Weight	Null Model	Extended Model	F	p
$\ln(ESS_{TLV})$	median	DEPARTMENT TCE DEPARTMENT*TCE	DEPARTMENT TCE SEASON DEPARTMENT*TCE	22.78	2.44E-06
$\ln(ESS_{TLV})$	median	DEPARTMENT TCE DEPARTMENT*TCE	DEPARTMENT TCE SEASON PRODUCTION LEVEL DEPARTMENT*TCE	36.52	1.85E-15
$\ln(ESS_{TLV})$	median	DEPARTMENT TCE PRODUCTION LEVEL DEPARTMENT*TCE	DEPARTMENT TCE SEASON PRODUCTION LEVEL DEPARTMENT*TCE	36.21	3.60E-09
$\ln(ESS_{TLV})$	median	DEPARTMENT TCE SEASON DEPARTMENT*TCE	DEPARTMENT TCE SEASON PRODUCTION LEVEL DEPARTMENT*TCE	47.97	1.44E-11
$\ln(ESS_{TLV})$	**median**	**DEPARTMENT TCE SEASON PRODUCTION LEVEL DEPARTMENT*TCE**	**DEPARTMENT TCE PRODUCTION LEVEL SEASON DEPARTMENT*TCE PRODUCTION LEVEL*SEASON**	**5.39**	**2.06E-02**
$\ln(ESS_{TLV})$	10%ile	DEPARTMENT TCE	DEPARTMENT TCE DEPARTMENT*TCE	17.35	3.74E-05
$\ln(ESS_{TLV})$	10%ile	DEPARTMENT TCE DEPARTMENT*TCE	DEPARTMENT TCE DEPARTMENT*TCE PRODUCTION LEVEL	34.36	8.92E-09
$\ln(ESS_{TLV})$	10%ile	DEPARTMENT TCE DEPARTMENT*TCE	DEPARTMENT TCE SEASON DEPARTMENT*TCE	21.89	3.84E-06
$\ln(ESS_{TLV})$	10%ile	DEPARTMENT TCE DEPARTMENT*TCE	DEPARTMENT TCE SEASON PRODUCTION LEVEL DEPARTMENT*TCE	36.09	3.02E-15
$\ln(ESS_{TLV})$	10%ile	DEPARTMENT TCE SEASON DEPARTMENT*TCE	DEPARTMENT TCE SEASON PRODUCTION LEVEL DEPARTMENT*TCE	47.97	1.53E-11
$\ln(ESS_{TLV})$	10%ile	DEPARTMENT TCE DEPARTMENT*TCE PRODUCTION LEVEL	DEPARTMENT TCE SEASON PRODUCTION LEVEL DEPARTMENT*TCE	35.17	6.09E-09
$\ln(ESS_{TLV})$	**10%ile**	**DEPARTMENT TCE SEASON PRODUCTION LEVEL DEPARTMENT*TCE**	**DEPARTMENT TCE SEASON PRODUCTION LEVEL SEASON*PRODUCTION LEVEL DEPARTMENT*TCE**	**4.67**	**3.12E-02**

Anticipated Future Publications

Publication 1: Chapter 3 will be edited and submitted to a relevant journal. Relevant literature review material from Chapter 2 will be included as well.

Publication 2: Chapter 4 will be edited and submitted to a relevant journal. Discussion of policy implications from Chapter 5 and relevant literature review material from Chapter 2 will be included as well.