RETROSPECTIVE EXPOSURE ASSESSMENT IN INDUSTRIAL SETTINGS

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Principal Investigator: Gurumurthy Ramachandran, Ph. D., CIH

Research carried out at: Division of Environmental and Occupational Health, School of Public Health, University of Minnesota, Box 807, Mayo, 420 Delaware Street S.E., Minneapolis, MN 55455

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I. ABSTRACT OF THE REPORT

A variety of health effects are caused by chronic, cumulative exposure over time to pollutants. In these cases, to establish dose-response relationships for epidemiological and risk assessment purposes, it is vital to determine the exposures of individuals or cohorts as functions of time. Most existing occupational exposure databases, however, do not contain continuous records of historical exposures to airborne contaminants. These gaps in the historical record may be filled by using the knowledge-base that experts and professionals in the field possess.

In this project, we present a new framework, based on Bayesian probabilistic reasoning, for obtaining estimates of exposure histories for airborne particulates from limited historical measurements, using subjective expert judgment. The framework has great potential applications in instances where there is sparse information or missing data on past exposures. Traditional methods, using only sparsely available historical measurements, result in estimates with large uncertainties. Limited information on estimates of airborne concentrations and worker exposures to airborne nickel aerosol are used to estimate the uncertainty in historical air monitoring data. This uncertainty arises from environmental variabilities, systematic biases as well as uncertainty due to various measurement criteria used over a period of several decades. Retrospective exposure reconstruction based solely on such historical measurements leads to estimates with such large error bars as to be not useful for developing quantitative dose-response relationships for epidemiology. This is demonstrated in the first part of the project.

However, estimation of the variance in historical measurements enables the calculation of a likelihood function which is then used to obtain posterior probability distributions for exposures. Additional information, in the form of expert judgments informed by knowledge of historical plant conditions, is brought to bear on this process. The experts are provided with an information packet that contains historical process information, process throughput levels for each year, the dimensions of the workplace, ventilation records, and task descriptions for each job category. Based on this information, the experts provide subjective prior probability distributions for input parameters to a general ventilation model that predicts building concentrations. These priors can be synthesized with the historical measurements using the Bayes formalism. The prior distributions of exposures are updated using the average measured exposures (historical measurements) and their associated variances to obtain the posterior probability distributions for building concentrations as well as concentrations at specific locations in the building. Expert input was also obtained from a plant industrial hygienist, in the form of probability distributions, regarding the amounts of time spent by each job category in different locations in the building. Monte-Carlo sampling, from the posterior probability distributions of concentrations in different micro-environments and the probability distributions of time spent by each job category in those micro-environments, was used to obtain worker exposures using a time-weighted averaging model. Results of this analysis are compared with those obtained using a more traditional methodology for retrospective exposure assessment.

II. SIGNIFICANT FINDINGS

1. It was shown that using only the sparsely available historical measurements results in estimates with large associated uncertainties.

2. However, additional information can be brought to bear on this process: (a) estimates of uncertainty in the historical data set, including systematic biases, and (b) expert judgments informed by knowledge of historical plant production rates, emission factors, ventilation rates, and worker activity patterns. This information can be synthesized with the historical measurements using the Bayes formalism.

3. A new framework for retrospective exposure assessment has been articulated using Bayesian probabilistic methods for synthesizing expert judgment, historical information about workplace conditions, and incomplete or sparse measurements, in order to determine exposure as a function of time and place.

4. The methodology has been applied to obtain the concentration history of nickel aerosol in a smelter, and the exposure history of different job codes.

5. A comparison of the concentration history obtained using only the historical measurements with that obtained using Bayesian methods shows that while the median levels obtained using the two methods are comparable, the uncertainties are greatly reduced for the Bayesian method. The same is true for the exposure history as well.

6. The approach used here emphasizes the need for detailed information about the industrial operations, materials, tasks, and other environmental variables obtained from company archives and site visits. Without such information, quantitative exposure assessment with manageable uncertainties would be impossible.

III. USEFULNESS OF FINDINGS

There are many documented cases (*e.g.*, asbestos, tobacco smoke, and radon daughters) of a causal relationship between the health risk for disease and long term exposure to airborne environmental particulate contaminants. Strictly speaking, the health hazard in such instances is related to the temporal history of an individual's exposure, the kinetics of deposition and clearance of the inhaled material, and some measure of the 'harmfulness' or potency of the contaminant. All of these are time-dependent quantities, and the integrated dose at time t since the start of the exposure may be expressed in a general form as

$$\text{Dose} = \int_0^T f\{E(t), R(t), G(t)\}dt \qquad (1)$$

Here, $E(t)$ is the exposure history derived from measurements of aerosol concentration, $R(t)$ is a function describing the retention of inhaled particles in the lung tissue that is well-documented in lung deposition models which are derived from toxicological data, and $G(t)$ describes the time-dependent potency of the contaminant to cause harm to the tissue. Most exposure-based epidemiology assumes that cumulative exposure, *i.e.*, $\int_0^T E(t)dt$, is a good measure of dose. It is important to realize that this is an approximation that is only valid when $R(t)$ and $G(t)$ are unity. Unlike simpler models that calculate dose as the cumulative exposure where each exposure is equally weighted, this model gives greater weight to the effect of earlier exposures through the parameter $G(t)$. Thus it is reasonable to expect that the deposited particles which stay a long time in the lung from earlier exposures have a greater impact on the health outcome than particles deposited more recently. In this manner, exposure histories can in principle, be used in conjunction with pharmacokinetic and pharmacodynamic models to obtain better estimates of biologically-relevant doses to organs or tissues.

The above model underscores the importance of having exposure data expressed as a function of time. While long-term prospective epidemiological studies can be very useful in determining the relationship between exposure and disease, this is not a luxury that can often be afforded by industries and standards-setting bodies, which have to act on information available currently. Therefore, to establish robust quantitative dose-response relationships for epidemiological purposes, it is vital to reconstruct past exposures of individuals or populations as functions of time over the periods of interest.

However, there is a paucity of historic exposure data for occupational air contaminants, with exceptions such as the coal mining industry. In most cases, cumulative exposure surrogates (*e.g.*, using duration of employment in an industry as a surrogate for cumulative exposure) or semi-quantitative estimates (*e.g.*, describing exposures nominally as "high", "moderate" or "low") have been used. These surrogates do not allow for the quantitative evaluation of health risks.

The process of reconstructing exposure over long periods is fraught with a number of uncertainties and subjective biases: measurement criteria, instruments and analysis methods that change over time and changes in workplace practices, industrial processes, and plant-specific ventilation patterns that may modify exposures. Measurements of personal exposures to airborne particulates are, at best, temporally sporadic, and for the period prior to 1970's, not even available. Due to these uncertainties and constraints, it is important to develop a systematic framework to estimate historical levels of exposure over a time span that has epidemiological significance and analyze various assumptions that are built into these estimates.

In this project, I present and validate a scheme, which requires additional inputs in order to estimate exposures as a function of time from relatively sparse discrete measurements. These additional inputs take the form of expert judgments from professionals with relevant experience and insights. A formal Bayesian probabilistic

framework is presented for synthesizing expert judgment, historical information about workplace conditions, and incomplete measurements to determine exposure as a function of time and place. This takes the form of an exposure matrix by time and task-group, where exposures will be represented as probability distributions. Such an exposure matrix can then be used directly in epidemiological studies. This approach has the advantage of explicitly accounting for the relevant uncertainties and yields a probability distribution of the exposure history. That is, for each point in time in a given workplace, the exposure will be represented as a probability distribution. By way of illustration, the framework will be used for determining exposures to nickel aerosols for different task-groups of workers in a nickel smelting plant.

Such an approach necessarily draws on findings from a wide variety of fields: engineering knowledge of the factors affecting the generation and dispersion of combustion aerosols, ventilation theory, studies of aerosol sampler performance characteristics, uncertainty analysis, psychology of expert judgment elicitation and decision making.

IV. SCIENTIFIC REPORT

A. BACKGROUND

While a number of retrospective studies have classified workers by surrogate measures of exposure such as length of employment, type of job or type of industry, this results in a relationship between job history and exposure that is dichotomous (exposed or unexposed) or ordinal (high, medium or low). Classifications of this type may overlap resulting in misclassification and false negatives (Seixas and Checkoway, 1995). This may be adequate for studies that focus on large, acute risks of disease where associations are not hidden by misclassification and quantitative exposure assessment is not critical. Retrospective epidemiological studies for diseases with long latency periods require the reconstruction of exposures over several decades to establish robust quantitative dose-response relationships.

However such exposure reconstruction is limited by the paucity of historic exposure data; in most instances measurements are either unavailable or only sporadically available. At the same time measurement criteria, instruments and analysis methods change over a time-scale of decades along with changes in workplace practices, industrial processes, and plant-specific ventilation patterns that modify exposures. This leads to the use of estimation techniques such as employee interviews, work histories, mathematical and statistical modeling and extrapolation from a few existing exposure values to all exposures (e.g., Verma et al., 1989; Plato et al., 1997; Hornung et al., 1994; Lewis et al., 1997; Hallock et al., 1994). While it is implicitly recognized that these techniques are subjective, there has been no systematic evaluation of the uncertainties in exposure estimates that such methods yield. Additionally, there has been no effort to systematically use all these pieces of information in a logically consistent manner.

Quantitative retrospective exposure assessment for occupational epidemiology comprises estimating the exposure levels for different worker categories as a function of time over the time period of interest. However, historic occupational exposure measurements are often only sporadically available, and subject to a number of uncertainties and biases.

There are enormous uncertainties in estimates of exposures assessed retrospectively using only such measurements, emphasizing the long-recognized need for additional information that can refine these estimates. A number of researchers have proposed using deterministic modeling with subjectively determined, non-random adjustments to project historical exposures from more recent measurements (Esmen, 1979; Schneider et al. 1991). More recently, Cherrie and Schneider (1999) have described using structured subjective assessments for reconstructing exposures.

B. SPECIFIC AIMS

This research develops a Bayesian framework for obtaining estimates of exposure histories for airborne particulates from limited historical measurements, using subjective expert judgment. The expert judgments are based on knowledge of historical plant conditions and work practices, and deterministic models describing aerosol generation, ventilation, and worker activity patterns. Knowledge of sampler performance, relationships between different types of instruments, uncertainties in measurements, and systematic biases are incorporated into the process. The end product is a probability distribution of the exposure of task groups of workers at each past interval, in the form of an exposure matrix.

If the exposure is represented by e, and the measured data are represented by m, then the updated probability distribution for e is given by:

$$P_{post}(e/m) = \frac{P_0(e)\ P_L(m/e)}{P(m)} \qquad (2)$$

where $P_0(e)$ is the probability distribution of e prior to making the measurement, $P_L(m/e)$ is the likelihood that given the true value e, the measurement m is observed, $P(m)$ is the probability that the measurement m is observed, and $P_{post}(e/m)$ is the updated probability (or the posterior) that the exposure is e given that the measurement m is observed.

In this study, this framework is used to estimate personal exposures to nickel aerosol in a nickel smelter in the following manner:

(1) All the available historical measurements are normalized to a common metric that is relevant to the known health effects of airborne nickel.

(2) The total variability in exposures for the worker population is estimated, and used to calculate the likelihood function, $P_L(m/e)$.

(3) Expert judgment in conjunction with physical models is obtained in the form of probability distributions, and this constitutes the "prior", $P_0(e)$.

(4) The prior distribution is updated using the average measured exposure and its associated variance to obtain the posterior probability distribution, $P_{post}(e/m)$.

The remainder of the report is divided into two parts. The first part deals with assessment of the uncertainty in historical measurements, and demonstrating the limitations of traditional methods of retrospective exposure assessment. The second part describes how expert inputs to deterministic models in conjunction with the historical measurements can be used to obtain better estimates of past exposures.

C. QUANTIFYING VARIABILITY IN HISTORICAL MEASUREMENTS

1. METHODS

a) Collection and Organization of Data

The nickel smelter consists of 26 distinct workgroups/areas (Table 1). For each workgroup/area, there is a set of measurements for the years 1956 to 1979. Within one year, there were one or more measurements and a workgroup area had anywhere from one to nine workstations where sampling was conducted (some years do not have any monitoring data available). Measurements were provided by the company in the form of lists. These lists were organized according to building, year and workstation (*e.g.*, Figure 1). In these lists, measurements are assigned to a year and a workstation (there is also summary data available that is not assigned to a specific workstation). To ensure workstations were assigned to the correct workgroup/area, expert input was obtained from a veteran employee familiar with the layout and work activities of the nickel smelter.

Over the period 1956-1979, measurements were collected using three methods that yielded different metrics of the airborne concentration of nickel: instantaneous particle number concentrations, mass concentrations from area samples, and mass concentrations from personal samples. Table 1 also lists the years for which each type of measurement was obtained in a particular workplace. The following sub-sections describe these measurement methods in greater detail, followed by a description of the procedures used in converting these into the inhalable metric.

Konimeter Measurements

Particles are measured by jet impaction onto a glass slide coated with adhesive. 5 cm^3 of air is impacted onto a 5 mm diameter spot of the adhesive slide. The sample is instantaneous (with a sampling duration of approximately one-third of a second) and collected from the worker's breathing zone. Collected samples are counted under an optical microscope or an automatic particle scanner and expressed in number of particles per cubic centimeter (ppcc). Measurements were taken from 1956 to 1975 throughout the plant. The measurements are specific to a particular location in a workplace (known as a work station). Each reported measurement is an average of three konimeter readings. Since the konimeter takes instantaneous samples, data tend to be very noisy. However the measurements are fairly representative of the dustiness of the operations (operations known for dustiness tended to have higher konimeter measurements).

Hi Volume Measurements

These integrated mass concentration measurements were made using a Hurricane air sampler (Model #16002, Gelman Instrument Company) with a sampling flow rate of up

to 125 cfm and a sampling time of roughly three hours. Pleated paper filters (TFA type "S" with a diameter of 4 inches) were used in the sampler filter holder to sample dust. The filter were dried, cooled and weighed in aluminum foil wrap before and after sampling. The measurements (expressed as mg/m^3) were taken from 1970 through 1977. Samples either measured total dust or nickel.

Personal 37-mm filter measurements

Personal 37-mm filter samplers are worn by workers on their bodies and measure integrated mass concentrations over a full shift. While they purportedly measure 'total' concentration, in fact their aspiration efficiency is lesser than the inhalable IOM sampler (Mark and Vincent, 1986) for larger particle sizes. Therefore these measurements also need to be converted to inhalable concentrations using conversion factors. Measurements are taken at a rate of 2 liters/min and are expressed in mg/m^3. Data from these measurements are available from 1976 to 1979.

b) Conversion of Various Types of Data to a Common Health-Related Metric

All raw, original measurements from the historical data set must be converted to the personal inhalable metric that is relevant to human health. Since the raw, original measurements were made using a variety of instruments described earlier that measured different metrics, several conversions need to be made to obtain inhalable fractions from the raw, original data. Table 1 shows that for most workgroups, there are a number of years when at least two measurement methods were concurrently used. Thus one simplistic approach might be to perform linear regressions between each of the different sets of measurements to obtain conversion factors. This approach can lead to some very unreasonable conclusions. This is because even though two measurement methods might have been used in the same span of years, they were typically not used to measure the same aerosol simultaneously by locating them side-by-side. Therefore a better approach is to obtain the conversion factors from side-by-side measurements using the various instruments. The procedures for each conversion process are described below. Table 2 contains the actual conversion factors used for each building and each type of measurement.

Conversion of Konimeter Data to a Personal Inhalable Values

The process of converting konimeter measurements involved two steps. The first step was to convert the particle counts to a respirable mass concentration value. Respirable mass concentration values were then converted to a personal inhalable mass concentration value. If *K-R* represents a conversion factor from konimeter counts to respirable mass cocnnetration, and *R-Inh* represents a conversion factor from respirable to inhalable mass concentration, then (*K-R* x *R-Inh*) represents the conversion factor from konimeter counts to inhalable mass concentration.

Conversion factors to obtain respirable values from konimeter dust counts were obtained from side by side comparisons of konimeter measurements and real-time, 1-minute average respirable aerosol concentrations measured by a GCA instrument. The GCA respirable dust monitor has been described by Marple and Rubow (1978). Personnel at the Ontario nickel smelter conducted these side-by-side comparisons in 1976-77. Average counts of three dust spots taken by konimeter measurements (expressed in ppcc) were compared to readings of the G.C.A. (expressed in mg/m^3). Side-by-side measurements were conducted at three different times in twelve separate locations. Figure 2 shows the data from these side-by-side comparisons. A linear regression fit to the data yielded a slope of 0.0021 which was used as a conversion factor from konimeter count to respirable mass concentration. Since the data had significant scatter, we decided to fit two more regression lines whose slopes would cover the range of plausible conversion factors. The three conversion factors were 0.00059, 0.0021, and 0.0063 ($mg\ m^{-3}$/ppcc).

Conversion factors for respirable dust to personal inhalable dust were obtained from particle size distributions of the inhalable fraction of dust in the nickel smelter. These size distributions were obtained using an 8-stage personal cascade impactor (with an entry stage and an after-filter) that sampled the inhalable mass fraction, the Personal Inhalable Dust Spectrometer (PIDS) described by Gibson et al. (1987). The PIDS was used by Tsai (1995) to sample worker exposures in three different locations (Matte Processing, Matte Crushing and Converter Aisle) of the Nickel smelter. These impactor measurements were then inverted to obtain bimodal lognormal particle size distributions using an algorithm described by Ramachandran et al. (1996). From these distributions the respirable subfraction masses were determined. The respirable mass was then divided by the inhalable mass to get a ratio of respirable to inhalable. The ratio of respirable to inhalable mass concentration was 0.1 (Converter Aisle), and 0.09 and 0.14 (Matte Processing and Matte Crushing). For areas where no actual measurements of the conversion factor were available, a default value of 0.1 as used. The respirable values were divided by the conversion factor to obtain inhalable values. The assumption in using size distributions measured in 1995 to obtain conversion factors for earlier decades is that while there may have been changes in concentration levels over the years, the size distribution should not have changed since the processes have not changed dramatically. Thus each value of konimeter particle count led to three inhalable values.

Conversion of Hi Volume Total Dust Measurements and 37-mm Filter Measurements to Personal Inhalable Mass Concentrations

The process of converting Hi Volume measurements to personal inhalable values also included two steps. Hi Volume measurements were first converted to a 'total', personal 37-mm value. Personal 37-mm values were then converted to personal inhalable values. Personnel at the nickel smelter conducted side-by-side comparisons of Hi Volume measurements and personal-37mm measurements in 1976. Comparisons were conducted in two locations in the smelter complex. Conversion factors were obtained from these comparisons by dividing personal 37-mm values by Hi Volume values. Two conversion factor values were obtained, 0.1 and 0.4, which were used for all plant areas. Conversion

factors were multiplied by the Hi Volume data to obtain a personal 37-mm 'total' dust concentration.

Side-by-side comparisons of measurements made with personal 37-mm filter samplers and inhalable IOM samplers were conducted in a study at the nickel smelter (Tsai *et al.*, 1995). Comparisons were done for six different worker groups in the smelter. Table 3 presents conversion factors obtained from side-by-side comparisons. Conversion factors from the six different processes sampled in Tsai's paper were appropriately matched to each workgroup in Table 1. Nickel aerosol conversion values in Tsai *et al.* (1995) were used for nickel measurements. If no conversion factors in Tsai et al. matched a particular workgroup, the conversion factor for 'whole process' was used. Thus there was one conversion factor for each workarea.

c) Assessing Uncertainty in Historical Measurements

Within historical monitoring data sets, errors and uncertainties must be accounted for so those using the data appreciate its strengths and weaknesses (Mulhausen, 1997). Uncertainties in airborne measurement of contaminants arise from a variety of sources. Analytical variability consists of normally distributed random collection and analytical error, and is typically small. A much larger source of uncertainty is lognormally distributed environmental variability, which includes between-worker and between-shift variability for personal exposures, spatial and temporal variability for area measurements. A third source of uncertainty in this study arises from the multiple conversion factors used to convert historical measurements made with different instruments to a common metric. For instance, each raw konimeter measurement (itself an average of three samples) is converted into three inhalable values, each Hi Vol measurement is converted into two inhalable values etc. This procedure was followed for each year for each work station in each building. The variability in these converted values then reflect the three types of uncertainties listed above.

A fourth source of uncertainty - systematic bias in the measurement strategy and seasonal variability – is also very important, although rarely dealt with. Objectives for monitoring vary with circumstance. Monitoring may be used to evaluate employee exposure, assist in the design/evaluation of control measures or document compliance with government regulations. Biases result from selections that go into the monitoring process, *e.g.,* selecting high-risk tasks or high exposure periods for monitoring, resulting in only workers who are highly exposed being monitored, or selecting the same time of day for each sampling period resulting in high correlation of day to day measurements. Each situation utilizes a different monitoring strategy producing unique biases; the type of air sampling instrument used, whether area or personal samples were obtained, on whom and where and when the monitoring was done, and how many samples were taken. These biases are hard to evaluate and therefore typically ignored while calculating uncertainty around exposure estimates. Shlyakhter (1994) quantified unsuspected uncertainties by analyzing trends in several historical data sets (e.g., measurements of excess uranium in soil, elementary particle data, nuclear moments, and neutron

scattering). He examined data sets with a long time record to get a temporal evolution of errors. The data sets were converted to a standard format with a probability distribution. Each measurement in the historical data set with its associated reported uncertainty ($A_{old} \pm \Delta_{old}$) was paired with a more recent (assumed true) measurement with its reported uncertainty ($A_{new} \pm \Delta_{new}$). The normalized standard deviation was then found as:

$$X = \frac{[(A_{new} \pm \Delta_{new}) - (A_{old} \pm \Delta old)]}{\Delta_{old}} \qquad (3)$$

The value of X was equal to how far the estimated standard error was away from the currently accepted value. He found that empirical probability distributions of the normalized deviations of the measured quantities from the true values do not follow the usually implied normal (or lognormal) distribution. Figure 3, based on Shlyakhter (1994) shows the cumulative probability of errors (in terms of $|x|$ standard deviations) for different values of an exponential parameter u. Shlyakhter's work suggests a wider distribution such as that in Figure 3 describes the data better than a normal or lognormal distribution. Long tails in the distribution of deviations from true values are grossly under-estimated by the normal distribution. For example, in a normal distribution the 95% confidence interval contains data within 1.96 standard deviations from the mean. To include the longer tails and a 95% confidence interval, the standard deviation must be doubled to 3.8. However, to account for unsuspected errors, we need to use the exponential distribution with $u = 1$. This implies that the number of standard deviations for 95% confidence intervals is 3.8 (the point where the $u = 1$ curve intersects the 0.05 percentile in the cumulative distribution). Thus, the uncertainty is almost doubled when systematic errors are accounted for.

The distribution of errors for the various environmental data sets analyzed by Shlyakhter were similar, suggesting that a pattern of overconfidence may exist in a wide variety of environmental measurements. Shlyakhter's findings are thus assumed to be applicable to the data set analyzed in this project. We therefore calculated the 95% confidence intervals for the converted measurements for each year, and then multiplied this confidence interval by a factor of 3.8/1.96 to account for systematic bias. This wider confidence interval now accounts for analytical variability, environmental variability and systematic biases. Thus for each year, we can estimate the mean inhalable concentration and the uncertainty associated with this estimate. These data are used to construct a likelihood function for the actual historical measurements. Since exposures are usually distributed log-normally, we assume that the likelihood function is given by

$$P_L(m/e) = \frac{\exp\left(\frac{-1}{2(\ln \sigma_m)^2}(\ln m - \ln e)^2\right)}{\sqrt{2\pi}\, e\, \ln \sigma_m} \qquad (4)$$

where $P_L(m/e)$ is the probability that a measured exposure, m, is observed when the true exposure is e. Here m is the mean inhalable concentration for a particular year, and σm is the standard deviation of the measurements for that year.

d) Development of a Questionnaire for Time Activity Patterns of Workers

A professional industrial hygienist employed at the nickel smelter for more than 15 years was asked to estimate the range of time (in hours) each worker category (job code) spent at a given workstation. A spreadsheet consisting of worker categories, standard tasks that each worker category performed and workstations each worker category spent time at was developed along with the questionnaire. A typical questionnaire-spreadsheet filled out by the expert industrial hygienist is shown in Table 4. The ranges are uniform or flat probability distributions, i.e., all values in a range, say 4-5 hours, are equi-probable. The job categories were divided into two broad classes – *operations* and *maintenance*. *Maintenance* workers such as laborers, electrical crew and carpenters work in more than one building, so they were placed in a separate category from workers who mainly worked in one workgroup area. Time activity patterns for maintenance workers were not obtained since these were very variable. The time activity patterns for *operations* workers evolved over time. Earlier in the plant's history each job code worked in only one specific area (corresponding to a workstation), but over time the workforce was decreased and job categories were combined, resulting in workers becoming more mobile and working in many areas within a building. This process was gradual and expert advice from the industrial hygienist allowed us to determine when it happened for each job category. Another potential confounder was that the same nominal worker category (job code) existed in several different workgroups and tasks performed by a worker category in one workgroup was not be the same as in another workgroup. For example, the worker category Binman exists in the following buildings: Flash Furnace, Roasters and Reverbs, Converter Flux Bins, Sand Bins, Coal Plant, Crushing Plant and Reverts Handling. In each section, the tasks of the Binman were different.

2. RESULTS AND DISCUSSION

a) Spatial and Total Variability in Measurements

Table 5 lists the mean inhalable concentrations and the variability at each station in the converter aisle area of the smelter complex by year. In the table, the italicized numbers refer to the 95% confidence intervals (with zero as the lower limit), and the numbers in bold refer to the number of measurements. While the konimeter measurements were made at five well-defined locations (stations) in the converter aisle, the locations of the Hi-Vol, personal 37-mm measurements, and "workroom" measurements (which were a combination of Hi-Vol and personal 37-mm filter samples) are unknown. In Table 5, the Hi-Vol measurements for each year between 1972 and 1975 have the same value, and the "workroom" and personal measurements between 1976 and 1979 have the same value for each year. This is because the data set provided by the company collected all the measurements of each type made during those years into one group. We therefore assumed that the mean and standard deviation for each type of measurement are the same

for each of those years. Another thing that should be kept in mind is that the variability is calculated using the converted measurements, so that each konimeter measurement translates into six converted inhalable measurements, and each Hi-Vol measurement translates into two converted inhalable measurements. Within a workgroup area, variability exists both spatially and temporally (within-year). Variability exists within a year at a particular workstation. This variability was determined by obtaining the standard deviation of all inhalable dust data within one year at one station then correcting for systematic bias. In addition, we calculated the total variability across all workstations for each year. The last column lists the average inhalable concentration for the entire workplace and the total (spatial and within-year) variability. This was obtained by using all inhalable data across the entire building to obtain the 95% confidence interval and multiplying it by 3.8/1.96 to account for systematic bias, and bounding the lower limit of the 95% confidence interval to zero. Figure 4 is a plot of the average inhalable concentration for the entire workgroup area for every year. The error bars represent the total variability and are equal to the 95% confidence intervals for the converted measurements. While the estimated average inhalable concentrations for the years 1960-1979 are all less than 10 mg/m^3, the upper 95% confidence limits were as much as 3-5 times higher than the averages.

b) Retrospective exposure assessment using concentration measurements and time activity patterns

For each job category, using information about time spent in different micro-environments or workstations (estimates obtained from the expert industrial hygienist), and the concentrations of inhalable aerosol in those micro-environments (obtained after converting historical data to the inhalable basis) we can estimate exposures as a time weighted average:

$$E_i = \frac{\sum_{j=1}^{N} C_j t_{ij}}{\sum_{j=1}^{N} t_{ij}} \qquad (5)$$

The subscript j refers to the j^{th} micro-environment and the subscript i refers to the ith job category. For illustration, we estimated the exposure history for job category 827, the "skimmer converter". In Table 6, workstations 49 and 57 are both similar skimmer platforms in different locations; likewise workstations 60 and 56 are similar puncher platforms in different locations. Exposures at these similar workstations are usually similar according to the plant industrial hygienist and therefore for the years where there

is no data for workstation 49 or 60, we used data from workstations 57 and 56 respectively.

Monte Carlo simulation allows for a characterization of the range of exposures and their likelihood of occurrence, instead of obtaining a single point estimate of exposure. This is preferable because both the concentration and time spent in each micro-environment are described in terms of probability distributions. In Monte Carlo simulation, the probability distribution of each input variable (in this case, C_j and t_{ij} for each year of interest) is sampled randomly a large number of times (100,000). For each sample, the exposure is calculated using Equation (5), and thus the entire distribution of exposures is obtained. The inhalable concentrations were assumed to be lognormal distributions whose mean and standard deviations were known from Table 5. The time spent in each micro-environment (workstation) was assumed to be a uniform distribution between the limits estimated by the industrial hygienist. Results are displayed in Table 6 and Figure 5. As can be seen, exposure histories obtained from limited historical measurements have a lot of variability resulting in wide probability distributions.

3. CONCLUSIONS

Historical measurement data typically have large uncertainties associated with them. These uncertainties arise from environmental variabilities, systematic biases as well as uncertainties due to various measurement criteria used over a period of several decades. Retrospective exposure reconstruction based solely on such historical measurements leads to estimates with such large error bars as to be not useful for developing quantitative dose-response relationships for epidemiology. However, a framework based on Bayesian probabilistic reasoning can be applied to reduce the uncertainty around the estimates. Expert judgment, based on historical plant information in conjunction with physical models, in the form of probability distributions can be combined with sparse historical measurements. This requires the calculation of a likelihood function for the historical measurements, using an assumed variance in the measurements. In this paper, this uncertainty has been evaluated for a specific workplace in a nickel smelter for every year during the period 1956-1979. The next paper will use this information to construct the likelihood functions that will be used along with the expert judgments to reconstruct exposures to nickel aerosol.

D. SYNTHESIZING EXPERT INPUTS WITH HISTORICAL MEASUREMENTS

1. BAYESIAN METHODOLOGY

A Bayesian view of a measurement is that the process serves to refine previous knowledge of physical parameters by narrowing their probability distributions. This process of refining previous knowledge of the parameters is also called *updating*. If the physical quantity of interest (*e.g.*, the concentration of inhalable nickel aerosol in a particular workplace) is represented by e, and the measurement process furnishes a number represented by M, then the Bayesian expression for the updated probability distribution of e is

$$P_{post}(e/M) = \frac{P_0(e)\ P_L(M/e)}{P(M)} \qquad (6)$$

where $P_0(e)$ is the probability distribution of e prior to making the measurement, $P_L(M/e)$ is the likelihood that given the true value e, the measurement m is observed, $P(M)$ is the probability that the measurement M is observed, and $P_{post}(e/M)$ is the updated probability (or the posterior) that the exposure is e given that the measurement M is observed.

The Bayes formulation is combined with Monte Carlo simulations to provide the updated probability distribution of the exposure given assumptions on the probability distribution of e prior to measurement (obtained from expert judgment elicitation), and the actual historical measurement M with its corresponding expected error. The updated probability density $P_{post}(e/M)$ is used to determine the best estimate for e.

Monte Carlo simulation is a powerful technique used for modeling in the presence of uncertainty. A deterministic model, which shall be described later, is used to predict the concentration of inhalable nickel aerosol in the workplace as well as personal exposures to it. Estimates of input parameters to this model and the uncertainties in these estimates are provided by experts in the form of a joint probability distribution. The model is evaluated for each sample (*i.e.*, each set of input parameters), resulting in a simulated probability distribution for the model output (*i.e.*, the concentration of nickel aerosol). This distribution characterizes the uncertainty in model output, given the assumed uncertainty in the input parameters, and the model structure. A "real world" observation of the measurement is used to update the model output from the Monte Carlo run using Bayes' rule. This synthesis is called the Bayesian Monte Carlo method, and has used by Patwardhan and Small (1992) in predictions of sea level rise due to global climate change, and Kandlikar (1994) to reconcile uncertainties in the global methane cycle. Subsequently, Ramachandran and Kandlikar (1996) used this methodology to obtain estimates of aerosol size distribution parameters from aerosol spectrometer data.

The algorithm proceeds as follows (Kandlikar, 1994):

A. The concentration model is used to predict the measurements, based on the input parameters. Prior joint probability distributions are defined to describe the uncertainty in the values of the input parameters.

B. A Monte Carlo or a stratified sampling scheme such as Latin Hypercube sampling is used to sample from this distribution.

C. The model is run with each set of sampled input size distribution parameters to calculate a prior distribution of model output (*i.e.,* the concentration).

D. The likelihood function for model output is evaluated using the error structure of the historical measurements (presented earlier).

E. The model output and observed measurement are reconciled using Bayes' rule to yield posteriors for model output.

The selection of priors for the input parameters is subjective and based on the prior expertise and knowledge of plant historical conditions. In some cases, these subjective distributions are uniform over a large region of the parameter space, and are therefore called "non-informative" priors. The likelihood function is empirically determined by the error structure of the measurement process.

The procedure is mathematically formulated as below. Consider a model with a vector of input parameters, $\vec{f} = [x_1, x_2, .. x_n]$, whose output is e. The input parameters are uncertain (or unknown). The input uncertainty is represented by a joint probability distribution function. We randomly sample from this distribution, generating a probability mass function corresponding to the original distribution. Let j ($j = 1$ to m) be the index for sample runs of the model, and k ($k = 1$ to n) be the index for model inputs. For any model run j, a probability mass function $P_j(x_k)$ is associated with each input model variable x_k. Similarly, a probability mass function $P(e_j)$ is associated with each output e_j. With a random or stratified sampling scheme such as Latin Hypercube, each sample contributes equally to the prior probability mass function. Therefore, with a sample size of m, the distribution for the model output is approximated by a discrete probability mass function with a probability mass of $1/m$ for each sample.

The likelihood function for the measurement M, given a model output e_j is evaluated. If the error (ε) on M is log-normally distributed (a justifiable assumption for occupational exposures) with a geometric standard deviation σ_M, then the likelihood function is given by

$$L(M/e_j) = \frac{\exp\left(\frac{-1}{2(\ln\sigma_M)^2}(\ln(M)-\ln(e_j))^2\right)}{\sqrt{2\pi}\, e_j \ln(\sigma_M)} \qquad (7)$$

The posterior mass function for the sample model output e_j is determined by Bayes' rule as

$$P(e_j/M) = \frac{P(e_j)L(M/e_j)}{\sum_{j=1}^{m} P(e_j)L(M/e_j)} \quad (8)$$

Since the prior probability mass $P(e_j)$ for each sample run is $1/m$, Equation (8) reduces to

$$P(e_j/M) = \frac{L(M/e_j)}{\sum_{j=1}^{m} L(M/e_j)} \quad (9)$$

In the Bayes-Monte Carlo approach, m sets of values for the input parameters are sampled and m values for the model output e_j are obtained. For each set, the distance (M - e_j) between the model output and the true value of the measurement is evaluated. These distances are assigned weights such that the smaller the distance the greater its weight. Additionally, since the measurements contain errors, the assigned weights have to reflect the magnitude of this error relative to the distance (M - e_j). The above procedure is described by the likelihood function given in Equation (7). Since this weighting procedure is done for ensembles of values over the prior ranges of the exposures, statistical estimates for historical exposures can be determined.

2. METHODOLOGY FOR OBTAINING EXPERT PRIORS

As described in the previous section, expert inputs to a physical model are used to obtain a prior probability distribution of past exposure. Rather than ask the experts to estimate exposure in a single step, they are instead asked to provide estimates of "exposure modifiers". These modifiers depend on factors such as changes in the process, changes in ventilation patterns, and changes in workplace practices. These modifying factors are explicitly included in a physical model that predicts airborne concentrations in a workplace as well as personal exposures for various job categories in that workplace. Even subjective assessments of past exposures rest on a particular rationale and set of assumptions. It is better, therefore, to disaggregate the problem using a deterministic model, allowing expert judgment on its individual aspects (Morgan and Henrion, 1990). The experts use a conceptualization of the exposure process that comprises (a) an aerosol generation mechanism whose strength depends on the process throughput and an emission factor for the process, (b) a ventilation process that disperses the aerosol in the work area and is described by the flow rate of air and the mixing efficiency in the room, and (c) the fraction of time that the worker spends in each area within the workplace. A physical model that incorporates these elements is used to predict exposures. The experts are provided with an information packet that contains historical process information, process throughput levels for each year, the dimensions of the workplace, ventilation records, and task descriptions for each job category. Based on this information alone, the experts are asked to provide subjective probability distributions for each input parameter for the exposure model that is described in the next section. It is important to note that the

experts were not provided information on the actual historical concentration measurements.

The interviews of the experts were conducted by telephone and email. The elicitation protocol included several elements - a description of the goals of the project, a review of the available information on plant processes, a discussion of how the experts were selected, a brief summary of the literature on scientific judgment and expert assessment, and finally the interview questions themselves. The experts are reminded, throughout the interview, of the findings from expert elicitation research literature that experts tend to be "overconfident", i.e., they tend to underestimate uncertainty. Therefore, the interviewer challenges each judgment provided by the expert, requiring the expert to provide a rationale for the judgment.

a) ***The Exposure Model***

The general ventilation or box model was used to predict workplace air concentration under steady state conditions,

$$C_{equil} = \frac{G}{(V_s A + K Q_{vent} + R)} \tag{10}$$

where G is the aerosol mass generation rate, A is the horizontal cross-sectional area of the workarea (*i.e.*, floor area), V_s is the settling velocity of the aerosol particles, Q_{vent} is the volumetric flow rate of air through the workplace, K is the dimensionless ventilation mixing efficiency, and R is the removal rate by other mechanisms. The K value selected, ranges from 1 to 10 (ACGIH, 1998). The generation rate G (mass of aerosol/time) is the product of the production rate of Bessemer matte PR (tons/year) and the emission factor EF (kg of aerosol/ton of matte produced).

Time weighted average worker exposures for a particular job code were obtained using

$$E_i = \frac{\sum_{j=1}^{N} C_j t_{ij}}{\sum_{j=1}^{N} t_{ij}} \tag{11}$$

where E_i is the time-weighted integrated exposure for worker i over a time interval, C_j is the aerosol concentration in the j^{th} task microenvironment, and t_{ij} is the time spent by the i^{th} worker in the j^{th} task microenvironment.

The model uses a number of parameters that are determined or inferred from historical records with some degree of uncertainty. These uncertainties arise due to scientific uncertainties about how much each exposure modifier changes exposure, and characterization of this uncertainty must rely on subjective expert judgment. Based on the information about the plant conditions and processes, the experts provide estimates for all

the variables in Eq. (10) and Eq. (11). While these estimates are in the form of probability distributions, the experts were free to choose the form of the probability distribution. Thus if the expert chose a uniform distribution, they would have to provide the upper and lower limits of the probability distribution, whereas if they chose a normal distribution, they would have to provide the mean and the standard deviation.

b) *Historical Plant Information Provided to the Experts*

While actual historical exposure measurements might be sparsely available, other types of information about the workplace are sometimes available that are helpful in reconstructing exposures. The plant industrial hygienist for the nickel smelter provided access to a wide variety of internal company documents and records, that were then summarized and synthesized to create a more manageable information packet that was provided to the experts.

The information packet contained the following pieces of information:

i. *Outline of nickel smelting operations.* This described the various physical and chemical transformations that the ore underwent in the smelter in general, and the converter aisle in particular. Bessemer converting, the operation that occurs in the converter aisle that was the focus of this study, is a process whose purpose is to oxidize iron and sulfur in the ore, eliminating all the iron sulfide. Nickel, copper, precious metals, and most or all of the sulfur that was combined with them remain in the matte. This is the finished or "Bessemer" matte, the key intermediate in producing refined nickel products.

ii. *Process flow sheets and layout of the converter area of the smelter.* These were summarized from more detailed process diagrams and engineering drawings of the workplace. Figures 6 and 7 show the general layout of the converter aisle building with the converters (numbered from 1 to 19) and the principal ventilators identified. The gray numbered rectangles in Figure 6 show the locations where historical measurements were made.

iii. *Ventilation Data.* Large quantities of dust, fume and sulfur dioxide gas are produced in the converting process. The dust is recovered in the Cottrell electrostatic precipitators and returned to the process. A large proportion of the gas is discharged to the atmosphere through a stack that is 500 feet in height, or is vented through large roof ventilators in the buildings. The hot processes are responsible for strong convection currents that create effective natural ventilation in these areas.

The converter aisle building of the smelting plant consists of 19 converters (see Figure 6). The problem of dust collection and venting of the gases in this area is enormous as a result of the ladling in and out of the converters of the molten material, and the blowing process in the converters for oxidation purposes. Ventilation in the converter building is provided mainly by natural draft. Between 1956 and 1960, seven roof ventilators were installed to exhaust 3,500,000 cfm from the converter building. Figure 7 shows a view of the converter building showing the ventilators. An additional cross flue and Cottrell plant were installed to treat converter gas. In 1960, a very large

new draw-off flue was added to the venting installations of this plant. Air is drawn through the lower sections of the building walls discharging through roof ventilators, at an estimated volume of 5,500,000 cfm for the years 1960-1963. An additional 2,000,000 cfm of air is drawn through the converter hoods and flue openings, and then flows with the converter gas to the converter Cottrell plant and to a stack that is 500 feet tall. For the years 1971-1979, see Figure 8 which gives flow rates, temperature and pressure for the nickel converter cross flue, the mid flue, and the copper converter cross flue.

iv. *Particulate Emissions.* In 1979, plant personnel conducted a series of experiments to determine the quantity of particulate emissions from the nickel converters. A measuring system was built and tested on a ventilator atop a converter. The gas was collected via a 12-probe grid and analyzed continuously by filtration for particulates. The dust was collected on a Staplex type S paper filter. Average dust loadings were obtained every 1-3 hours. Typically 1-5 grams of dust were recovered, weighed and analyzed. Emissions from a ventilator located above and across the aisle from two adjacent nickel converters were monitored and correlated with the activities of the two converters. Since the two converters were sharing the ventilator, continuous visual estimates of the fractions of total emissions entering the ventilator coming from various sources, including each of the two converters under study, had to be made alongside the actual ventilator monitoring work. These visual estimates were subjective and introduced a source of error. The filter was changed every 1-3 hours and weighed to determine the quantity of the particulate matter. 1050 data sets were analyzed and the error quantified. The overall maximum error limits in the calculation of fugitive emissions were ±90%, with the most probable value being about ±60%. The rate of PM emissions varied between 0.006 kg/min and 0.045 kg/min with an average of 0.019 kg/min. The average particulate concentration was 3 mg/m^3 with variations from 1 to 11 mg/m^3. The average rate of particulate fugitive emissions was 0.19 kg/ton of Bessemer matte. This measurement, albeit just at one point in time, and with significant errors, provided a useful anchor point for the experts.

v. *Particle Size Distributions.* These were obtained using a Personal Inhalable Dust Spectrometer – a personal 8-stage cascade impactor with an inhalable entry and an after-filter during the early 1990s (Tsai, 1995). Based on these measurements, the size distribution was approximated as bimodal lognormal distribution. The size distribution can be described using five parameters: the fraction of the total masses in each of the two modes, α_1 and α_2, the mass median aerodynamic diameters of the two modes - $MMAD_1$ and $MMAD_2$, and the geometric standard deviations of the two modes - GSD_1 and GSD_2. For the converter aisle, the values of the parameters were: $\alpha_1 = 0.12$, $\alpha_2 = 0.88$; $MMAD_1 = 1.63$ μm, $MMAD_2 = 30$ μm; $GSD_1 = 1.31$, $GSD_2 = 2.25$.

vi. *Production Levels of Bessemer Matte*: Bessemer matte is the output of the nickel converter operation, and these data were obtained from company records. For each year between 1959 and 1979, data were available for the average number of converters in operation during that year and the production of matte per converter month. Using these two pieces of information, the annual production of Bessemer matte was estimated. For the years when such data was unavailable, the tonnage of primary matte entering the Casting and Cooling building, downstream of the converter operations, was taken to be

the amount of Bessemer matte produced. There was usually a 10-15% discrepancy in estimating Bessemer matte production using these two methods. Table 7 gives the annual amount of Bessemer matte cast using these two estimation methods.

c) *Expert Selection*

Inputs to models were elicited from three experts. Two experts provided probability distributions for the input parameters to the model given in Eq. (10), which predicted concentrations to airborne nickel. These two experts were selected on the strength of their contribution to the occupational hygiene literature, status in the scientific community (signified by membership on editorial committees of key journals and scientific committees), their familiarity with workplace environments, and not the least, their willingness to do the task *gratis*. The third expert was an in-plant industrial hygienist with many years of employment at the smelter, and a thorough knowledge of the various activities at the smelter. This expert provide probability distributions for the time spent by each job category at various locations within the smelter complex, used in Eq. (11). While it would have been preferable to obtain expert inputs from many more experts to provide for a balance in institutional perspectives, this was not feasible for monetary reasons. However, the selection criteria assured that the individuals chosen had *substantive expertise*, referring to the knowledge the expert has about the quantity of interest. *Calibration* is a measure of the accuracy of the expert judgment. Some studies have shown that professional industrial hygienists are well calibrated for assessing exposures (Hawkins and Evans, 1989). However the additional precaution of using anchoring information was used. Under this heuristic, for instance, a starting value a parameter was provided to the experts in their information packet, which can then be adjusted by them to reflect their uncertainty about the parameter estimate. For instance, in estimating the aerosol generation rate parameter, G, the experts use information from an experiment done in the late 1970's to evaluate the emission factor (described in a previous section), and annual Bessemer matte production data, as anchoring information.

3. RESULTS AND DISCUSSION

a) *Expert Prior Elicitation*

Table 8 describes the judgments of the two experts regarding the values of the input parameters for the models. Expert 1 chose normal distributions to describe all parameter estimates, while Expert 2 used uniform distributions. For the production rates of Bessemer matte, *PR*, both experts were fairly confident of the values provided by the company, as evidenced by the small values of uncertainty around the mean values.

Expert 1 assumed the total flows measured in 1960-63 applied from 1958 until 1971. He apportioned this 7,500,000 cfm (212,795 m^3/min) between the nickel and copper converter areas, using the fraction of the converter aisle lengths used for nickel and copper converters (See Figures 6 and 7 for building dimensions). This yielded a flow

of Q_{vent} = 95,706 m^3/min for the nickel converter area. For the years 1971-1979, he used the roof ventilation of 5,500,000 cfm plus the Cottrell flow rates (corrected for temperature) to give a new total of 7,082,400 cfm (200,946 m^3/min), which was apportioned as before to yield a flow of Q_{vent} = 90,377 m^3/min for the nickel converter area. The flows were assigned an RSD of 0.30 for both time periods, reflecting the expert's degree of uncertainty in these estimates. Expert 2 estimated that 2/3 of the space in the converter aisle was occupied by nickel converters and 1/3 contained copper converters, and divided the flow rates through these two regions of the building in the same ratio. The flow rates for the years 1958-1960 were Q_{vent} = 50,000-100,000 m^3/min, and for the years 1961-1970 were Q_{vent} = 100,000-200,000 m^3/min. However, for the years 1971-1979, the ventilation rates through these two areas were assumed to be the same: Q_{vent} = 120,000-200,000 m^3/min.

For the emission factors, *EF*, Expert 1 used the mean value of 0.19 kg/ton, obtained from the in-plant experiment described in a previous section, but assumed a relative standard deviation (RSD) of 0.30 for the period 1970-1979, with the RSD increasing to 0.40 for an earlier period 1958-1969. Expert 2 used the experimentally determined value for 1977-1979 with a range of 0.15-0.23. For the period 1971-1976, he slightly increased the uncertainty bounds around this value to 0.13-0.25. For the previous two time periods, he used the ratio of the flow rate in 1979 (when the experimentally derived value was obtained) to the flow rates in the previous time periods to scale up the emission factor proportionally, yielding values of 0.21 and 0.41 respectively. He simultaneously, increased the uncertainty bounds around these estimates.

Expert 1 provided a value of 5 for the dimensionless mixing factor, *K*, with a RSD of 0.05. While Expert 2 used a value of $K = 4$, he was ambivalent about the use of this parameter in the model. He did not want to provide uncertainty bounds for this parameter, reasoning that *K* is itself a protective, uncertainty factor that is used during design of ventilation systems.

Expert 1 used the bimodal particle size distribution (psd) information (described in a previous section) to calculate a aerosol mass-weighted settling velocity. The psd was divided into 20 size intervals, and the settling velocity was calculated for the midpoint for each particle size range. These velocities were then weighted by the fractional mass of particles in each size range, and their average was obtained. This settling velocity was multiplied by the floor area (198 m x 27.45 m) to yield the settling term, V_sA, in Eq. (10). The RSD of this term was given a value of 0.10. Expert 2 did not use the psd information, and ignored the settling velocity term in the model. Both experts also ignored other removal mechanisms, represented by *R* in Eq. (10).

It is important to point out that the experts were provided a choice of two models for predicting building concentrations - the general ventilation model described earlier, and a two-compartment model that predicts near-field and far-field concentrations. Both experts decided that the general ventilation model was the appropriate one to use in this context, given the level of uncertainties in the information provided to them. Both assigned probability weights of zero to the two-compartment model, and unity to the

general ventilation model which reflected the confidence of the experts in each model. In this manner, model uncertainty was accounted for.

There is an extensive literature on obtaining consensus among the experts (Winkler, 1986; Cooke, 1991; Clement and Winkler, 1999), ranging from mathematical functional aggregation techniques to behavioral methods. Each method has its advantages and disadvantages. In this study, it was decided to not seek consensus among the experts. This made explicit the differences in scientific judgments of the two experts.

b) *Monte-Carlo Simulations to Obtain Expert Priors*

A commercially available software (Decisioneering,1996) was used to obtain 100,000 independent samples consisting of sets of values for each of the input parameters, for each year. The samples were obtained by Monte-Carlo sampling from the probability density functions provided by the two experts for the input parameters. The model in Eq. (10) was run for each of these 100,000 sets of input values to obtain a simulated probability distribution of values for aerosol concentration in the building. This distribution characterizes the uncertainty in the aerosol concentrations in the building for each year, given the assumed uncertainty in the input parameters, and the model structure. As an example, Figure 9 shows the input parameter distributions and the output aerosol concentration probability distribution for one year (1965), using input from Expert 2.

Figure 10 shows the median nickel aerosol concentrations in the building for each year as obtained from subjective model inputs from both experts. The error bars represent the range between the 2.5 and 97.5 percentiles of the 100,000 Monte Carlo simulation outputs. For the years 1958-1960, the estimates of Expert 2 were higher than those of Expert 1 by a factor of 10. However, for the period 1961-1979, while the estimates of Expert 2 were systematically higher by a factor of 2-3, they were not statistically different from the estimates of Expert 1. The reasons are not hard to discern. For 1958-1960, Expert 2 had an emission factor that was more than twice that of Expert 1. At the same time, Expert 2 did not include the particle settling term in Eq. (10) while Expert 1 provided a value for the term that was as significant as the flow rate term. For 1961-1979, the emission factor estimates of the two experts became more similar, but the flow rates estimated by Expert 2 became much higher than Expert 1. These two factors led to the concentration estimates of the two experts becoming more closely aligned, even though the differences regarding the settling term remained.

c) *Concentration History for Converter Building: Updating Expert Priors with Historical Measurements*

An estimate of the mean inhalable concentration for each year and the associated uncertainty was obtained in Table 5. These data are used to construct a likelihood function for the actual historical measurements. Since exposures are usually distributed log-normally, we assume that the likelihood function is given by Eq. (7), where M is the mean inhalable concentration for a particular year, and σ_M is the geometric standard deviation of the measurements for that year. The next step in the Bayes method is to

update the expert prior probability distributions for each year, using this lognormal likelihood function, to produce the posterior probability distributions. Figure 11 shows the results of the Bayes updating for both the experts. A comparison with Figure 10 shows that the posteriors are not very different from the priors, even though for most years the intervals within which 95% of the values lie are slightly narrower. This is seen more clearly in Figure 12, which shows the cumulative probability distributions for the prior (according to Expert 2), the posterior, and the historical measurements for 1976. The historical measurement, which has a median value of 1.0 mg/m^3 with a GSD of 2.85, covers a wide range. The interval within which 95% of the values lie ranges from 0.1 mg/m^3 to 10.3 mg/m^3. The prior distribution has a median of 3.59 mg/m^3, with the 2.5^{th} percentile and 97.5^{th} percentile values being 2.19 mg/m^3 and 5.84 mg/m^3 respectively. The prior has a much narrower distribution than the distribution of actual measurements, with the result that the measurements do not have any significant effect during the updating. The posteriors are, therefore, very similar to the priors. This finding does not change even when systematic errors in the historical measurements are ignored (with the effect of, roughly, halving the 95% confidence intervals for the measurements).

It is interesting to compare the concentration history in the converter building obtained using only the historical measurements with that obtained using Bayesian updating of expert judgment. Figure 13 shows that while the median levels obtained using the two methods are comparable, the error bars are greatly reduced for the Bayesian method. For all the years with the exception of 1960, the ranges for the Bayes updated concentrations were between 1-7 mg/m^3. For most of the years, the historical measurements ranged between 0.01-35 mg/m^3.

d) *Exposure History for a Specific Job Code*

Using information about time spent by a particular job category in different microenvironments or workstations and the concentrations of inhalable aerosol in those microenvironments, one can obtain the exposure history for that job category (Eq. (6)). In this section, we will obtain the exposure history of job code 827, the "skimmer converter" as an example. The historical measurements in each microenvironment and their associated uncertainties are given in Table 6. The expert priors (for the entire building) along with these microenvironment measurements were used to obtain posterior probability distributions for concentrations in these microenvironments. Workstations 49 and 57 are both similar skimmer platforms in different locations; likewise workstations 60 and 56 are similar puncher platforms in different locations. Exposures at these similar workstations are usually similar according to the plant industrial hygienist and therefore probability distributions for time spent in these micro-environments. Using these samples in Eq. (11), the exposures for this job category were estimated for each year from 1960-1976. For the years 1977-1979, there were no microenvironment specific measurements, and so the exposures were assumed equal to the building concentrations. Figure 14 shows a comparison of the Bayes posterior exposure distributions according to the two experts with the exposures obtained using conventional methods. The Bayes posterior distributions are much narrower than, and lie within, the distributions obtained using historical measurements alone.

4. CONCLUSIONS

Validation of retrospective exposure assessments, *i.e.*, ensuring that the results are close to the "true" values, always poses a significant problem. One method that has been proposed is to use the technique to predict current exposures for which, presumably, complete information is available. The limitation of this method is that most exposure assessment methods (including expert judgment) are better at predicting recent exposures than at predicting exposures that occurred several decades ago. Thus success of any method in predicting current exposures should not be taken as a validation of its prediction of past exposures. Cherrie and Schneider (1999) used the correlation between estimated and measured values as a measure of validity, although they recognized the obvious limitation that the measured values are sparse and contain substantial error. In this study, the correlations between the median values of the expert priors (and posteriors) and the measurements are $R^2_{adj} = 0.6$ and 0.5 for the two experts respectively. All the expert posterior values fell within the confidence limits placed around the measurements, although this was because the measurements had very wide error bars. Another flawed measure of validation is that except for the very earliest years (1956-1960), the two expert priors (and posteriors) are remarkably similar ($R^2_{adj} = 0.9$ for the median values of the priors and posteriors). This agreement between the experts, while reassuring, may also be due to their similar backgrounds (academic occupational hygienists with expertise in aerosol science).

Given the lack of objective measures of validity, the only reasonable alternative is to invoke the rationality of the methodology. The use of a deterministic, physical model provides a rational framework for predicting exposures. While the inputs to these models are subjective probability distributions, they are anchored in actual historical plant information. Thus, an argument could be made that if one accepts that the physical model chosen is appropriate and the choices for input parameters are reasonable, then one logically has to also accept the results of the rational procedure described in this paper.

This paper presents the practical application of a Bayesian framework to retrospective exposure assessment in a nickel smelter. It was shown that using only the sparsely available historical measurements results in estimates with large associated uncertainties. However, additional information can be brought to bear on this process: (a) estimates of uncertainty in the historical data set, including systematic biases, and (b) expert judgments informed by knowledge of historical plant production rates, emission factors, ventilation rates, and worker activity patterns. This information can be synthesized with the historical measurements using the Bayes formalism.

The approach used here emphasizes the need for detailed information about the industrial operations, materials, tasks, and other environmental variables obtained from company archives and site visits. Without such information, quantitative exposure assessment with manageable uncertainties would be impossible.

V. REFERENCES

1. ACGIH (1998). Industrial Ventilation manual of Recommended Practice. 23rd Edition. ACGIH, Cincinnati.
2. Cherrie, J.W. and Schneider, T. (1999). Validation of a new method for structured subjective assessment of past concentrations. *Ann. Occup. Hyg.*, 43:235-245.
3. Clemen, R.T., and Winkler, R.L. (1999). *Risk Anal.*, 19:187-203.
4. Cooke, R.M. (1991). Experts in Uncertainty: Opinion and Subjective Probability in Science. Oxford University Press, Oxford.
5. Decisioneering, Inc. (1996). Crystal Ball [Computer Software].
6. Doll, R. (1990). Report of the International Committee on Nickel Carcinogenesis in Man. *Scandinavian Journal of Work, Environment and Health*, 16 (special issue): 1-82.
7. Esmen, N. (1979). Retrospective industrial hygiene surveys. *American Industrial Hygiene Association Journal*, 40:58-65.
8. Gibson, H., Vincent, J.H. and Mark, D. (1987). A personal inspirable dust spectrometer for applications in occupational hygiene research. *Ann. Occ. Hyg.* 31: 463-479.)
9. Hallock, M.F., Smith, T.J., Woskie, S.R., and Hammond, S.K. (1994). Estimation of historical exposures to machning fluids in the automotive industry. *American Journal of Industrial Medicine*, 26:621-634.
10. Hawkins, N.C., and Evans, J.S. (1989). Subjective estimation of toluene exposures: A calibration study of industrial hygienists. *Applied Ind Hyg J.*, 4:61-68.
11. Hornung, R.W., Greife, A.L., Stayner, L.T., Steenland, N.K., Herrick, R.F., Eliott, L.J., Ringenburg, V.L., and Morawetz, J. (1994). Statistical model for prediction of retrospective exposure to ethylene oxide in an occupational mortality study. *American Journal of Industrial Medicine*, 25:825-836.
12. Kandlikar, M. (1994). Reconciling uncertainties in integrated science and policy models: applications to global climate change. Ph. D. thesis, Carnegie-Mellon University.
13. Lewis, S.J., Bell, G.M., Cordingley, N., Pearlman, E.D., and Rushton, L. (1997). Retrospective estimation of exposure to benzene in a leukaemia case-control study of petroleum marketing and distribution workers in the United Kingdom. *Occupational and Environmental Medicine*, 54:167-175.
14. Mark, D., and Vincent, J.H. (1986). A new personal sampler for airborne total dust in workplaces. *Annals of Occupational Hygiene*, 30:89-102.
15. Marple, V.A., and Rubow, K.L. (1978). An evaluation of the GCA respirable dust monitor 101-1. *American Industrial Hygiene Association Journal.* 39(1):17-25.

16. Morgan, M.G., and Henrion, M. (1990). *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*. Cambridge University Press, Cambridge, England.

17. Mulhausen, J. (1998). *A Strategy for Exposure Assessment*. AIHA Press. American Industrial Hygiene Association and the Exposure Assessment Strategies Committee.

18. Patwardhan, A., and Small, M.J. (1992). Bayesian methods for model uncertainty analysis with application to future sea level rise. *Risk Anal.*, 12:513-523.

19. Plato, N., Gustavson, P., Krantz, S. (1997). Assessment of past exposures to man-made vitreous fibers in the Swedish prefabricated house industry. *American Journal of Industrial Medicine*, 32:349-354.

20. Ramachandran, G., Johnson, E.W., and Vincent, J.H. (1996). Inversion Techniques for Personal Cascade Impactor Data", *Journal of Aerosol Science*, 27(7):1083-1097.

21. Ramachandran, G., and Vincent, J.H. (1999). A Bayesian approach to retrospective exposure assessment. *Applied Occupational and Environmental Hygiene*. 14(8):547-557.

22. Ramachandran, G., and Vincent, J.H. (1999). A Bayesian approach to retrospective exposure assessment. *Applied Occupational and Environmental Hygiene*. 14(8):547-557.

23. Schneider, T., Jørgensen, O., and Lauersen, B.(1991). Evaluation of exposure information. *Applied Occupational and Environmental Hygiene*, 6:475-481.

24. Shlyakhter, A. (1994). An improved framework for uncertainty analysis: Accounting for unsuspected errors. *Risk Analysis*, 14(4):441-447.

25. Seixas, N.S., and Checkoway, H. (1995). Exposure assessment in industry specific retrospective occupational epidemiology studies. *Occupational & Environmental Medicine*. 52(10):625-633.

26. Tsai, P.J. (1995). Health-related aerosol exposures of nickel industry workers. Ph.D. dissertation, University of Minnesota.

27. Tsai, P.J., Vincent, J.H., Wahl, G., Maldonado, G. (1995). Occupational exposures to inhalable and total aerosol in the primary nickel production industry. *Occupational and Environmental Medicine*, 52:793-799.

28. Verma, D.K., Sebestyen, A., Julian, J.A., Muir, D.C.F., Scmidt, H., Bernolz, C.D., Shannon, H.S. (1989). Silica exposures and silicosis among Ontario hardrock miners: II Exposure estimates. *American Journal of Industrial Medicine*, 16:13-28.

29. Winkler, R.L. (1986). Expert resolution. *Management Sci*, 32:298-306.

VI. PRESENT AND FUTURE EXPECTED PUBLICATIONS ARISING FROM THE RESEARCH

1. Ramachandran, G., and Vincent, J.H. (1999). A Bayesian approach to retrospective exposure assessment. *Applied Occupational and Environmental Hygiene*. 14(8):547-557.

2. Ramachandran, G., and Forte, K. (2000). Retrospective exposure assessment using Bayesian methods: Quantifying variability in historical measurements. Submitted to *Ann. Occup. Hyg.*

3. Ramachandran, G. (2000). Retrospective exposure assessment using Bayesian methods: Synthesizing expert inputs with historical measurements. Submitted to *Ann. Occup. Hyg.*

VII. TABLE CAPTIONS

Table 1. Table of worker groups, activities performed in each, types of monitoring data available and years monitoring was done.

Table 2. Conversion factors used for each type of measurement in each workgroup/area.

Table 3. Conversion factors for personal 37-mm to inhalable dust (Tsai et. al., 1995).

Table 4. Typical time activity pattern diary for a job code filled out by a professional industrial hygienist. The estimated ranges of times spent on different tasks represent uniform probability distributions.

Table 5. Average inhalable concentrations (converted) and their variability including systematic biases (*italics*) and number of measurements (**bold**) by year and location (station) in the workplace. The locations of the Hi-Vol, workroom and personal 37-mm measurements are unknown. The last column contains overall average inhalable concentrations and their total variabilities.

Table 6. Exposure history for job category 827 (Skimmer Converter) in the converer aisle.

Table 7. Production rates of Bessemer matte in the converter aisle

Table 8. Expert inputs for parameters to general ventilation model.

VIII. FIGURE CAPTIONS

Figure 1. Example of organized data for the converter building. On the Y-axis, the konimeter measurements are in units of particles per cubic centimeters (ppcc) while the Hi-Vol and personal 37-mm measurements are in units of mg/m3.
Figure 2. Side-by-side measurements of konimeter counts and 1-minute respirable mass concentrations. The slopes of the three regression lines represent the range of conversion factors to convert konimeter counts to respirable mass concentrations.
Figure 3. Cumulative probability of errors (in terms of number of standard deviations) for a normal distribution and for most physical environmental data (Shlyakhter, 1994).
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Figure 9. Distributions of input and output parameters for Monte Carlo sampling to determine expert priors. Input parameter distributions include production rate (tons/year), flow rate (m3/min), and emission factor (kg/ton of matte), and the output parameter is the aerosol concentration (mg/m3).

Figure 10. Outputs of Monte-Carlo simulations using expert inputs to a predictive model for inhalable nickel concentration. 100,000 sample runs were performed to obtain the distribution of model outputs for each year, using the set of input parameters provided by each expert. These are the expert prior probability distributions. The error bars represent the range between the 2.5^{th} and the 97.5^{th} percentiles of the outputs.

Figure 11. Posterior probability distributions for the building air concentration of inhalable nickel. The error bars represent the range between the 2.5^{th} and the 97.5^{th} percentiles.

Figure 12. Cumulative probability distributions for the prior (Expert 2), the posterior, and the historical measurements for 1976.

Figure 13. Comparison of posterior probability distributions (for both experts) with historical measurements. The error bars represent the range between the 2.5^{th} and the 97.5^{th} percentiles.

Figure 14. Comparison of posterior probability distribution of exposure history of job code 827 (skimmer converter) for inhalable nickel aerosol with conventional exposure history.

Table 1. Table of worker groups, activities performed in each, types of monitoring data available and years monitoring was done.

Group	Workplace Activity	Measurement type & Years Measurements were taken		
		Koni-meter	Hi Volume	37-mm
1	Converter Building General	1960-75		1976-79
2	Nickel converter operations to produce Bessemer matte from reverb furnace matte and other materials	1956-75	1972-79	1976-79
3	Copper converter operations to produce blister copper from copper reverb furnace matte		1975-79	1976-79
4	Sand floor-maintain flow of flux, reverts, and scrap to converters	1956-75	1972-79	
5	Separation of high grade copper sulfide from slurry for reversion to smelting	1964-75	1956-59, 1972-79	1976-79
6	Transfer of molten Bessemer matte to moulds for slow cooling	1956-75		1976-79
6A	matte casting Building General		1972-75	1976-79
7	Breaking and crushing of slow cooled Bessemer matte ingots and transfer to matte processing	1956-75	1964-77	1976-79
8	Flash Furnace Receiving copper concentrate	1973	1973-79	1976-79
9	Flash Furnace Top floor Dry Bin Storage	1956-75	1972-77	1976-79
10	Flash Furnace Drying and Feeding of copper concentrate	1956-75	1972-76	1976-79
11	Tapping copper matte and skimming slag from flash furnace	1956-75	1972-75	
12	Flash Furnace Building General		1966-76	1976-79
13	Receiving and distributing nickel concentrate and flux to roasters	1956-75	1964-79	
14	Roasting of nickel concentrate and flux mixture and feeding to nickel reverb furnaces	1956-75	1964-79	1976-79
15	Skimming slag and tapping high grade nickel matte from nickel reverbs	1960	1966, 73, 74 & 1976-79	1976-79
16	Roasters and reverbs Building General	1956-75	1964-66, 1972-75	1976-79
17	Blast furnace-feed receiving and charging	1956-75	1964-66, 1972-75	
18	Blast Furnaces-matte tapping, slag skimming and general	1956-75	1964-79	
19	Electric furnace smelting of copper sulfides; matte processing metallics with acid converter operation.	1956-75	1964-76	1976-79
20	Receive and distribute flux, reverts and scrap to converter feed bins		1972-76	1976-79
21	Receive and distribute Levack Conc. and/or ore for downstream processing.			1976-79
22	Receive and distribute sand, coal, reverts and/or other fluxes and materials to downstream processing.	1956-75		
23	Pulverize, dry, and distribute coal to all reverbatory furnaces	1956-75		
24	Crush and distribute mine ore to mill processing	1956-75	1964-71	
25	Electrostatically process smelter off-gases to remove bulk of particulates using cottrells		1967-70	
26	Crush and distribute converter floor scrap for recycle to converters		1975-79, 1972-75	1976-79

Table 2. Conversion factors used for each type of measurement in each workgroup/area.

Group	Konimeter to Respirable	Respirable to Inhalable	Hi Volume to Personal-37mm	Personal-37mm to Inhalable
1	.0063, .00059, .0021	.1	.1029, .42735	1.97
2	.0063, .00059, .0021	.1	.1029, .42735	1.97
3	.0063, .00059, .0021	.1	.1029, .42735	1.97
4	.0063, .00059, .0021	.1	.1029, .42735	1.97
5	.0063, .00059, .0021	.1	.1029, .42735	1.97
6	.0063, .00059, .0021	.09, .14	.1029, .42735	1.97
6a	.0063, .00059, .0021	.1	.1029, .42735	1.97
7	.0063, .00059, .0021	.09, .14	.1029, .42735	2.11
8	.0063, .00059, .0021	.1	.1029, .42735	1.97
9	.0063, .00059, .0021	.1	.1029, .42735	1.89
10	.0063, .00059, .0021	.1	.1029, .42735	1.89
11	.0063, .00059, .0021	.1	.1029, .42735	1.89
12	.0063, .00059, .0021	.1	.1029, .42735	1.89
13	.0063, .00059, .0021	.1	.1029, .42735	1.84
14	.0063, .00059, .0021	.1	.1029, .42735	1.84
15	.0063, .00059, .0021	.1	.1029, .42735	1.84
16	.0063, .00059, .0021	.1	.1029, .42735	1.84
17	.0063, .00059, .0021	.1	.1029, .42735	1.89
18	.0063, .00059, .0021	.1	.1029, .42735	1.97
19	.0063, .00059, .0021	.1	.1029, .42735	1.97
20	.0063, .00059, .0021	.1	.1029, .42735	1.97
21	.0063, .00059, .0021	.1	.1029, .42735	1.97
22	.0063, .00059, .0021	.1	.1029, .42735	
23	.0063, .00059, .0021	.1	.1029, .42735	
24	.0063, .00059, .0021	.1	.1029, .42735	1.97
25	.0063, .00059, .0021	.1	.1029, .42735	2.22
26	.0063, .00059, .0021	.09, .14	.1029, .42735	1.97

Table 3. Conversion factors for personal 37-mm to inhalable dust (Tsai et. al., 1995).

Workgroup/Area	Inhalable/ 37-mm for dust	Number of samples	Inhalable/ 37-mm for nickel aerosol	Number of samples
Cottrell air Cleaner	2.22	4	1.94	4
Fluidised Bed Roaster	1.84	6	1.76	5
Furnace Area	1.89	9	1.57	8
Matte Crushing	1.87	6	1.59	5
Matte Processing	2.11	12	1.58	11
Whole Process	1.97	39	1.65	35

Table 4. Typical time activity pattern diary for a job code filled out by a professional industrial hygienist. The estimated ranges of times spent on different tasks represent uniform probability distributions.

Job Code	Tasks	Typical Daily Hours Spent at Each Station in Converter Aisle							
		CONVERTERS 1-13 Conventional			STRETCH CONVERTERS #3, 5 AFTER 1978			#6,8,9 1993	
		# 1 Flux Platform	# 60 Puncher Platform	# 49 Skimmer Platform	# 55 Flux Platform	# 56 Puncher Platform	# 57 Skimmer Platform	# 77 Skimmer Platform	# 75 Flux Platform
827 (Skimmer Converter) 1952-present	Operates electric controls to raise or lower hoods, to turn converter to charge furnace matte, to skim slag, cast bessemer matte or blister copper to position for blowing.			4-5			4-5	4-5	
	Manually operates air valves to control tuyere air, maintains temperature to produce bessemer matte or blister copper.		1-2			1-2			
	Takes spoon and bar samples and punch bar colour tests.			0.5-1			0.5-1	0.5-1	
	Operates conveyor to add flux, revert scrap or concentrates to conveyor through flux gun, manually bars and hammers accretions from flux gun or directs cleaning.	2-3			2-3				2-3

Table 5. Average inhalable concentrations (converted) and their variability including systematic biases (*italics*) and number of measurements (**bold**) by year and location (station) in the workplace. The locations of the Hi-Vol, workroom and personal 37-mm measurements are unknown. The last column contains overall average inhalable concentrations and their total variabilities.

Year	Konimeter Inhalable dust Station 60 (mg/m3)	Konimeter Inhalable dust Station 49 (mg/m3)	Konimeter Inhalable dust Station 56 (mg/m3)	Konimeter Inhalable dust Station 57 (mg/m3)	Konimeter Inhalable dust Station 1 (mg/m3)	Hi Vol Inhalable Total Dust mg/m3	Workroom Inhalable Total Dust (mg/m3)	Personal Inhalable (mg/m3)	Inhalable dust Entire Workplace (mg/m3)
1960			5.0 *(0,23.9)* **(1)**	2.5 *(0,11.8)* **(1)**					3.8 *(0,18.1)*
1961	2.7 *(0,11.9)* **(2)**			4.1 *(0,18)* **(2)**					3.4 *(0,15)*
1962	5.3 *(0,27.2)* **(2)**	5.5 (0,27.8) (2)							5.4 *(0,26.5)*
1963			2.9 *(0,12.9)* **(2)**	2.5 *(0,12.1)* **(2)**					2.8 *(0,12.4)*
1964			6.0 *(0,27)* **(2)**	3.2 *(0,14.8)* **(2)**					4.7 *(0,21.9)*
1965	2.2 *(0,10.4)* **(1)**		2.4 *(0,11.4)* **(1)**	3.8 *(0,16.4)* **(2)**					3.0 *(0,13.4)*
1966	3.3 *(0,15.5)* **(1)**	4.6 *(0,21.6)* **(1)**							3.9 *(0,17.5)*
1967			4.3 *(0,20.7)* **(2)**	13.4 *(0,77.4)* **(2)**					8.9 *(0, 57)*
1968	5.8 *(0,25.1)* **(2)**	6.6 *(0,33.4)* **(2)**							6.2 *(0,28.5)*
1969	6.5 *(0,31)* **(1)**	7.9 *(0,37.7)* **(1)**							7.2 *(0,31.8)*
1970	6.9 *(0,32)* **(2)**	6.8 *(0,31.5)* **(2)**							6.9 *(0,30.7)*
1971	6.9 *(0,31.7)* **(2)**	7.7 *(0,33.6)* **(2)**							7.3 *(0,31.6)*
1972	5.8 *(0,25.5)* **(2)**	6.6 *(0,29.6)* **(2)**				0.9 *(0,3.8)* **(5)**			5.5 *(0,25.8)*
1973	6.6 *(0,28.9)* **(2)**	6.1 *(0,27.4)* **(2)**				0.9 *(0,3.8)* **(5)**			5.5 *(0,26.1)*
1974	4.6 *(0,20.1)* **(2)**	3.9 *(0,17.3)* **(2)**				0.9 *(0,3.8)* **(5)**			3.8 *(0,17.4)*
1975	1.5 *(0,7.1)* **(2)**	1.5 *(0,7.1)* **(1)**	5.7 *(0,26.9)* **(1)**	10.8 *(0,51.4)* **(1)**	0.9 *(0,3.7)* **(5)**	0.9 *(0,3.8)* **(5)**			2.9 *(0,21.9)*
1976					0.7 *(0,3.3)* **(8)**	0.6 *(0,2.6)* **(16)**	1.7 *(0,10.3)* **(118)**	5.2 *(0,9.5)* **(50)**	1.0 *(0, 5.6)*
1977						0.6 *(0,2.6)* **(16)**	1.7 *(0,10.3)* **(118)**	5.2 *(0,9.5)* **(50)**	1.96 *(0,9.8)*
1978						0.6 *(0,2.6)* **(16)**	1.7 *(0,10.3)* **(118)**	5.2 *(0,9.5)* **(50)**	1.96 *(0,9.8)*
1979						0.6 *(0,2.6)* **(16)**	1.7 *(0,10.3)* **(118)**	5.2 *(0,9.5)* **(50)**	1.96 *(0,9.8)*

Table 6. Exposure history for job category 827 (Skimmer Converter) in the converer aisle.

Year	Time range job class 827 spent at each station in workgroup/area 2 (hours).					Concentration range of inhalable dust at each station in workgroup/area 2 (mg/m3).					Exposure of job class 827 during each year (mg/m3).
	Station #49	Station #60	Station #1	Station #56	Station #57	Station #49	Station #60	Station #1	Station #56	Station #57	
1960									5.0 *(0,23.9)*	2.5 *(0,11.8)*	3.1 (0,7.1)
1961							2.7 *(0,11.9)*			4.1 *(0,18)*	3.8 (0,9.1)
1962						5.5 (0,27.8)	5.3 *(0,27.2)*				5.5 (0,13.8)
1963									2.9 *(0,12.9)*	2.5 *(0,12.1)*	2.6 (0.2,6.2)
1964									6.0 *(0,27)*	3.2 *(0,14.8)*	3.8 (0.3,8.8)
1965							2.2 *(0,10.4)*		2.4 *(0,11.4)*	3.8 *(0,16.4)*	3.4 (0.3,8.2)
1966						4.6 *(0,21.6)*	3.3 *(0,15.5)*				4.3 (0.3,10.6)
1967									4.3 *(0,20.7)*	13.4 *(0,77.4)*	11.3 (0,33)
1968	4.5-6	1-2	2-3			6.6 *(0,33.4)*	5.8 *(0,25.1)*				6.4 (0.4,16.1)
1969						7.9 *(0,37.7)*	6.5 *(0,31)*				7.6 (0.4,18.8)
1970						6.8 *(0,31.5)*	6.9 *(0,32)*				6.8 (0.5,16.4)
1971						7.7 *(0,33.6)*	6.9 *(0,31.7)*				7.5 (0.7,17.6)
1972						6.6 *(0,29.6)*	5.8 *(0,25.5)*				6.4 (0.6,15.3)
1973						6.1 *(0,27.4)*	6.6 *(0,28.9)*				6.2 (0.5,14.2)
1974						3.9 *(0,17.3)*	4.6 *(0,20.1)*				4.1 (0.4,9.3)
1975						1.5 *(0,7.1)*	1.5 *(0,7.1)*	0.9 *(0,3.7)*	5.7 *(0,26.9)*	10.8 *(0,51.4)*	1.4 (0.2,2.9)
1976								0.7 *(0,3.3)*			0.7 (0,1.9)
1977											
1978				1-2	4.5-6						
1979											

Table 7. Production rates of Bessemer matte in the converter aisle

Year	Bessemer Matte Cast (Dry Tons)
1958	265,905
1959	332,806
1960	358,755
1961	384,408
1962	293,357
1963	269,916
1964	337,896
1965	330,808
1966	296,163
1967	371,340
1968	340,128
1969	221,135
1970	357,667
1971	334,631
1972	421,180
1973	418,161
1974	448,338
1975	456,549
1976	422,670
1977	170,872
1978	185,774
1979	145,749

Table 8. Expert inputs for parameters to general ventilation model.

Parameter/Year	Expert 1 Input			Parameter/Year	Expert 2 Input		
	Distribution	Mean Value	Relative Standard Deviation		Distribution	Mean Value	Lower and Upper Bound of Distribution
Bessemer Matte Production for each year (dry tons/year)	Normal	From Table 1	0.05	Bessemer Matte Production for each year (dry tons/year)	Uniform	From Table 1	± 5 % of mean
Flow Rate (m^3/min) 1958-1963	Normal	95,706	0.30	Flow Rate (m^3/min) 1958-1960	Uniform	75,000	50,000 - 100,000
Flow Rate (m^3/min) 1964-1979	Normal	90,377	0.30	Flow Rate (m^3/min) 1961-1970	Uniform	140,000	100,000 - 200,000
Emission Factor (kg/ton) 1958-1969	Normal	0.19	0.40	Flow Rate (m^3/min) 1971-1976	Uniform	156,221	100,000 - 200,000
Emission Factor (kg/ton) 1970-1979	Normal	0.19	0.30	Flow Rate (m^3/min) 1976-1979	Uniform	156,221	120,000 - 220,000
Mass Weighted Average Settling Velocity for Aerosol x Floor Area (m^3/s) 1958-1969	Normal	67,838	0.40	Emission Factor (kg/ton) 1958-1960	Uniform	0.41	0.20 - 0.60
				Emission Factor (kg/ton) 1961-1970	Uniform	0.21	0.10 - 0.30
Mass Weighted Average Settling Velocity for Aerosol x Floor Area (m^3/s) 1958-1969	Normal	67,838	0.40	Emission Factor (kg/ton) 1971-1976	Uniform	0.19	0.13 - 0.25
				Emission Factor (kg/ton) 1977-1979	Uniform	0.19	0.15 - 0.23
Mixing Factor, K (dimensionless)	Normal	5	0.05	Mixing Factor, K (dimensionless)	None	4.0	None

Figure 1. Example of organized data for the converter building. On the Y-axis, the konimeter measurements are in units of particles per cubic centimeters (ppcc) while the Hi-Vol and personal 37-mm measurements are in units of mg/m3.

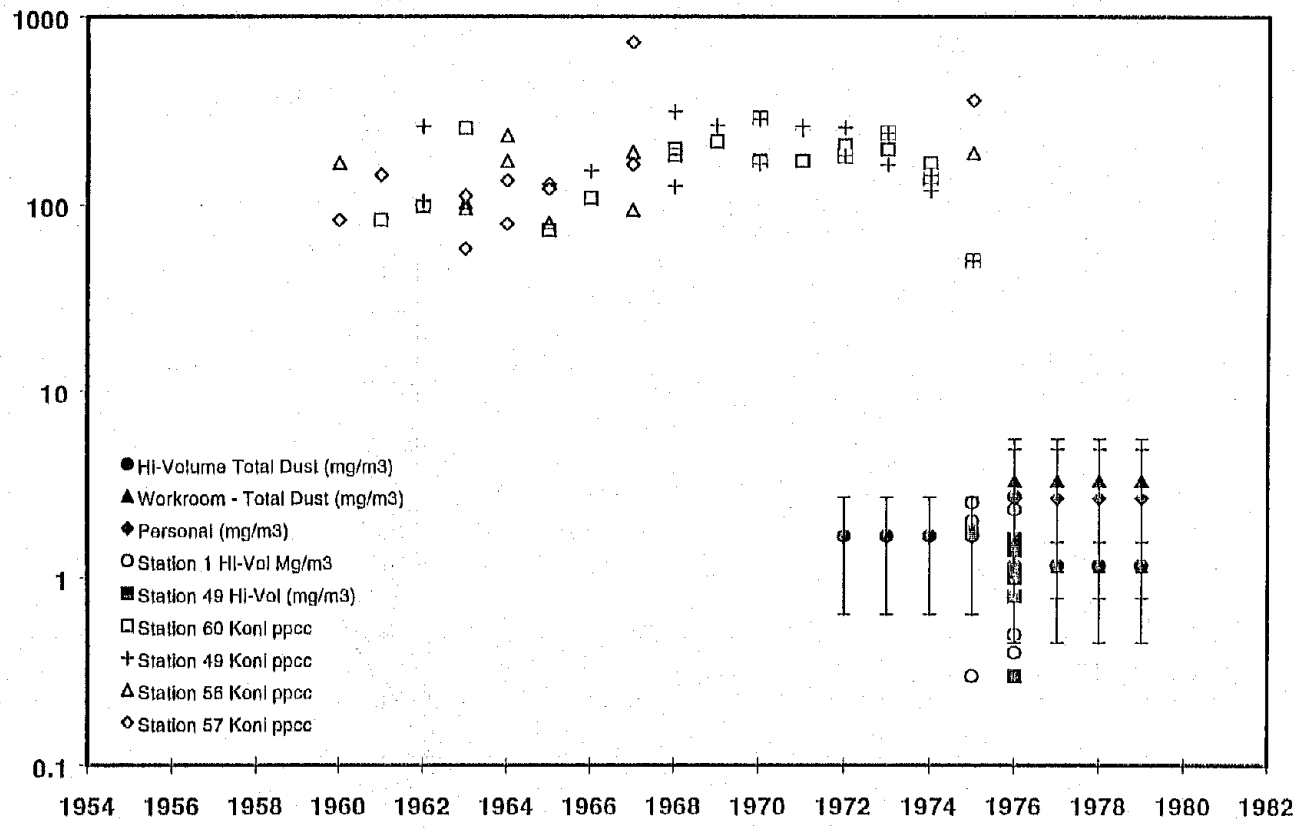

Figure 2. Side-by-side measurements of konimeter counts and 1-minute respirable mass concentrations. The slopes of the three regression lines represent the range of conversion factors to convert konimeter counts to respirable mass concentrations.

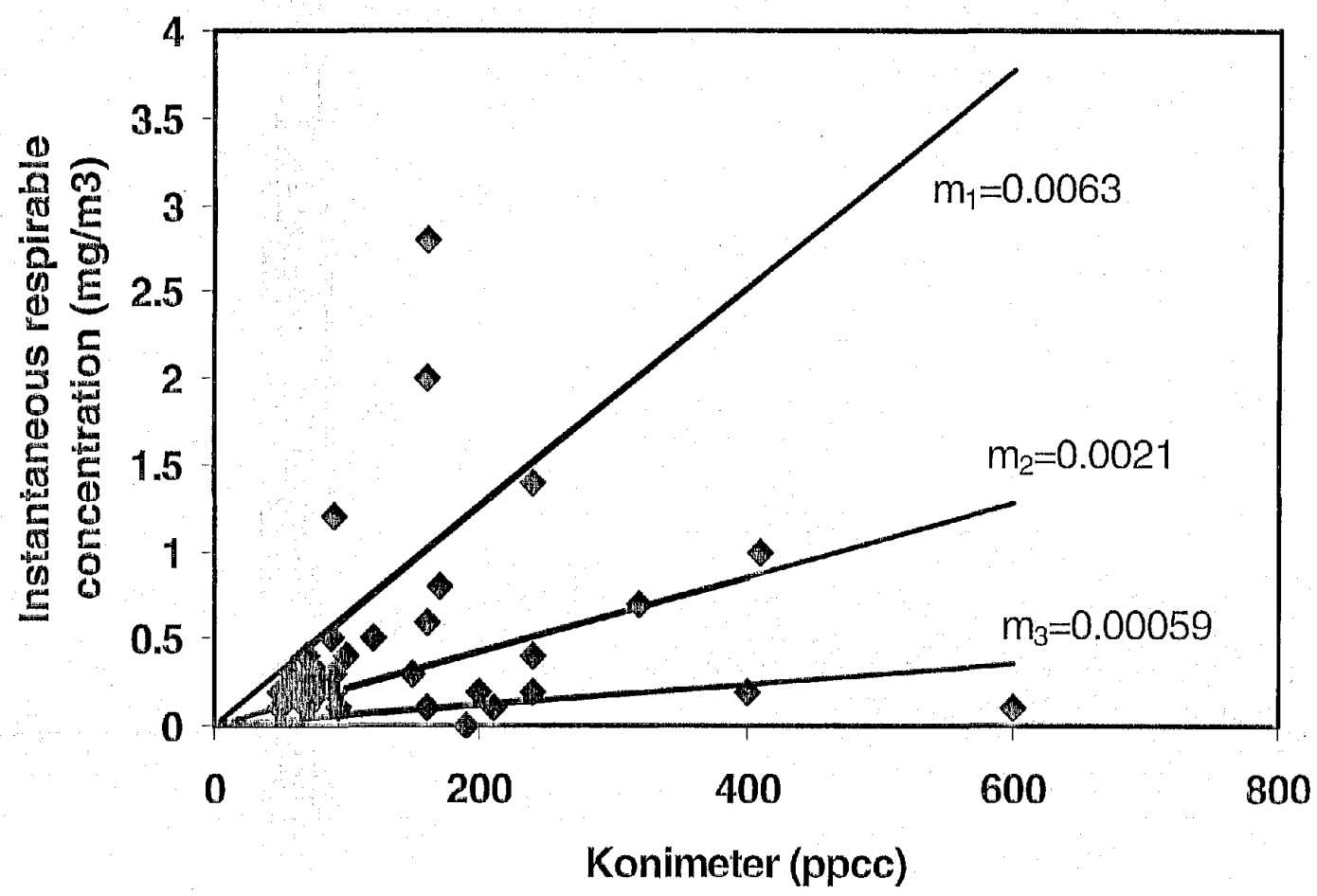

Figure 3. Cumulative probability of errors (in terms of number of standard deviations) for a normal distribution and for most physical environmental data (Shlyakhter, 1994).

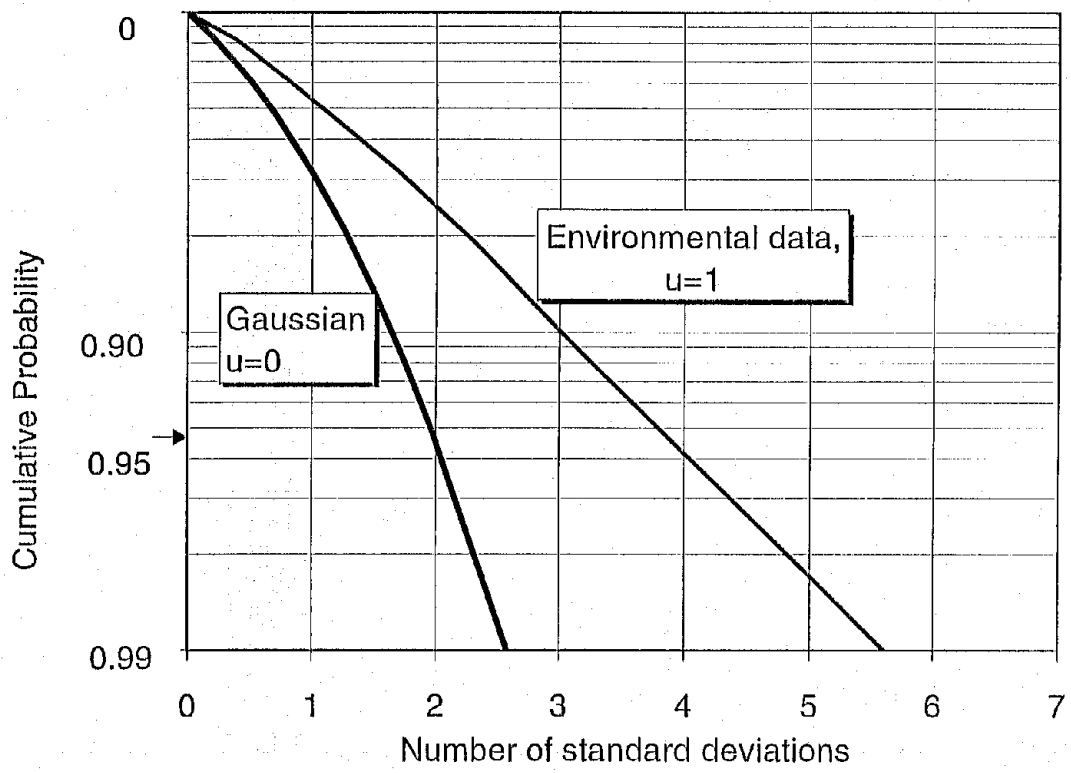

Figure 4. Historical measurements after conversion to inhalable concentrations. The error bars include both spatial and temporal variability and are corrected for systematic biases.

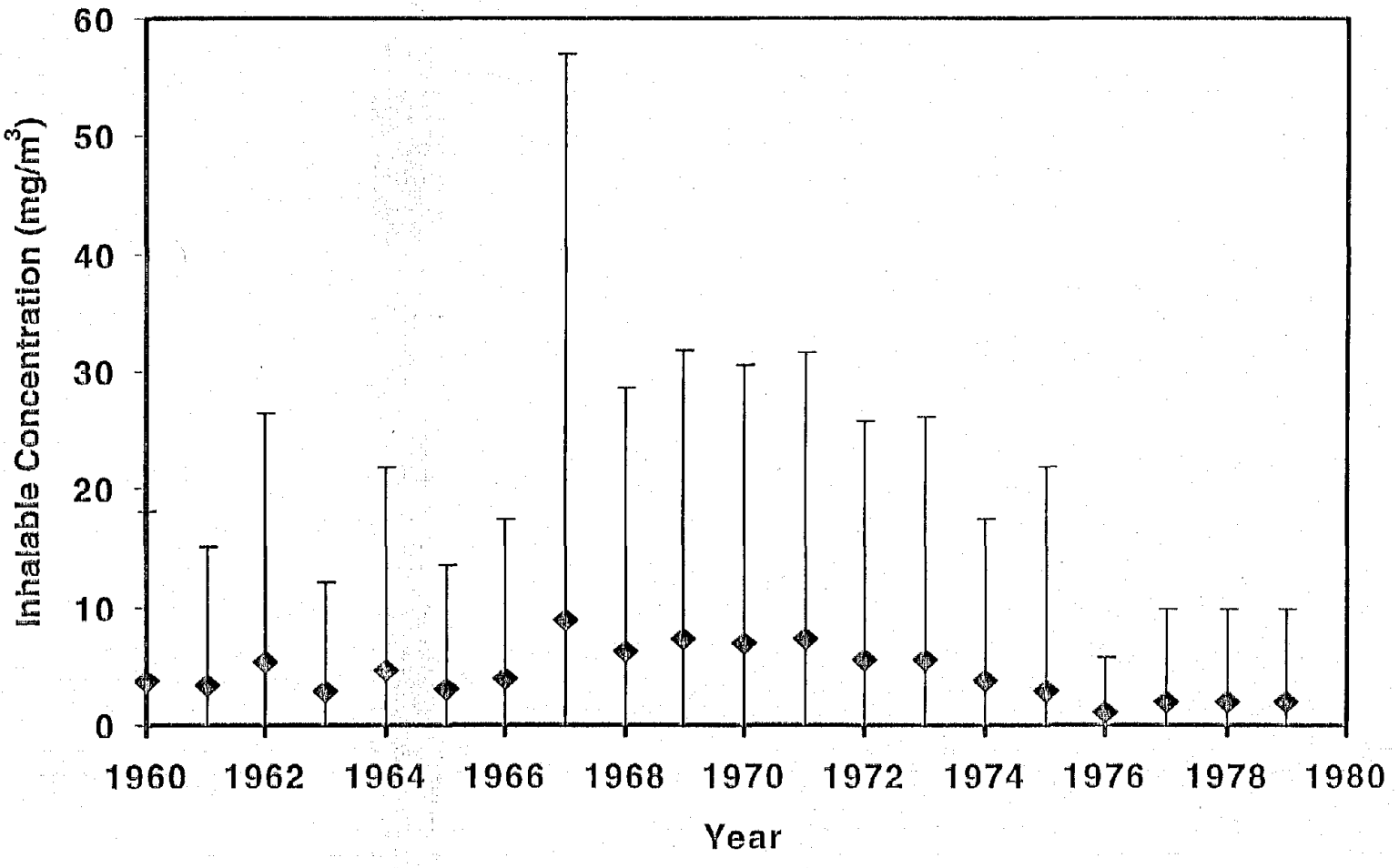

Figure 5. Exposure history of job code 827 (skimmer converter) for inhalable aerosol in the nickel converter operations.

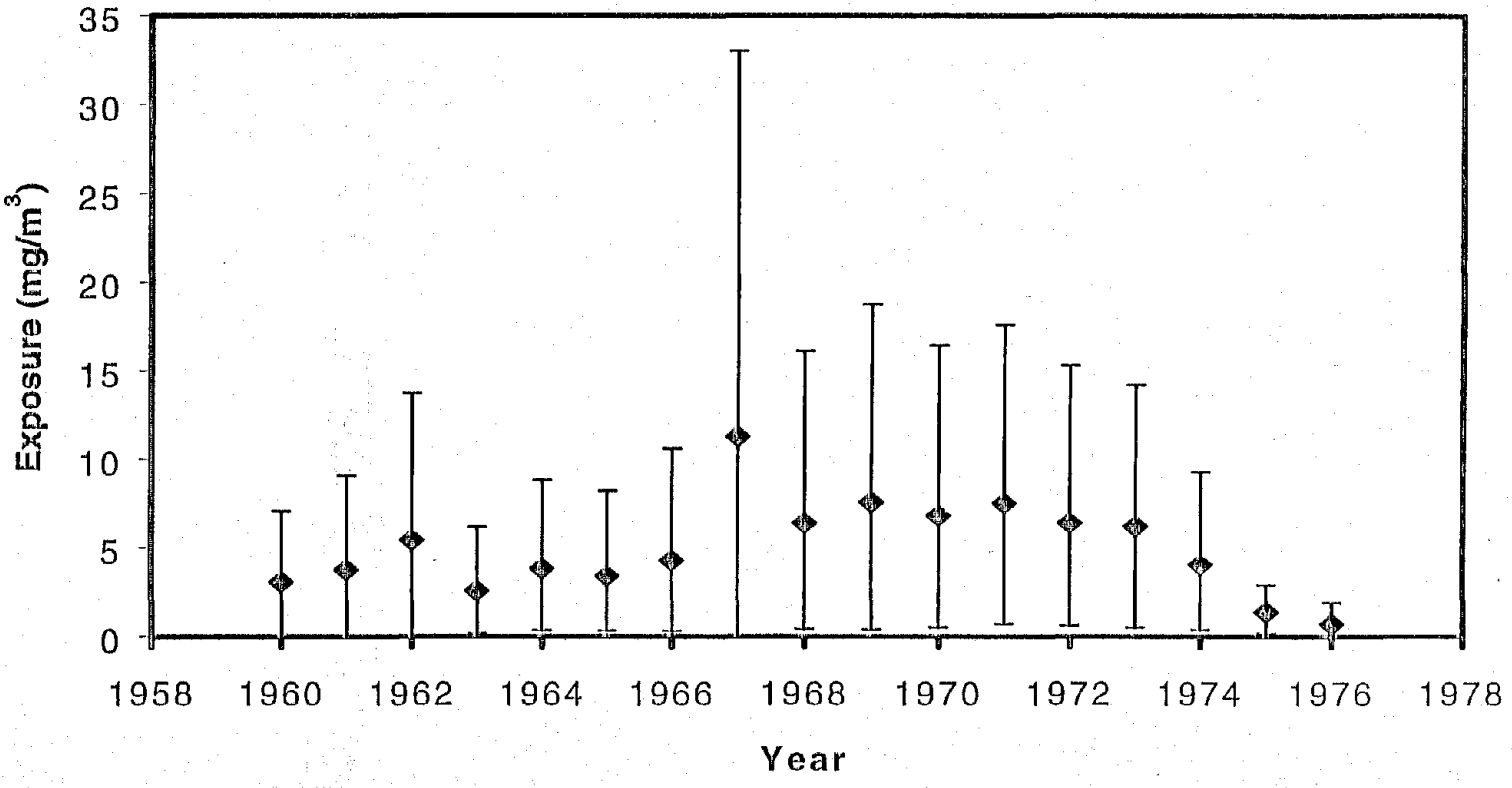

Figure 6. Plan view of converter building showing the converter aisle with 19 converters and the ventilators. Stations 1, 49, 56, 57, 59, and 60 are some of the locations where historical measurements were made.

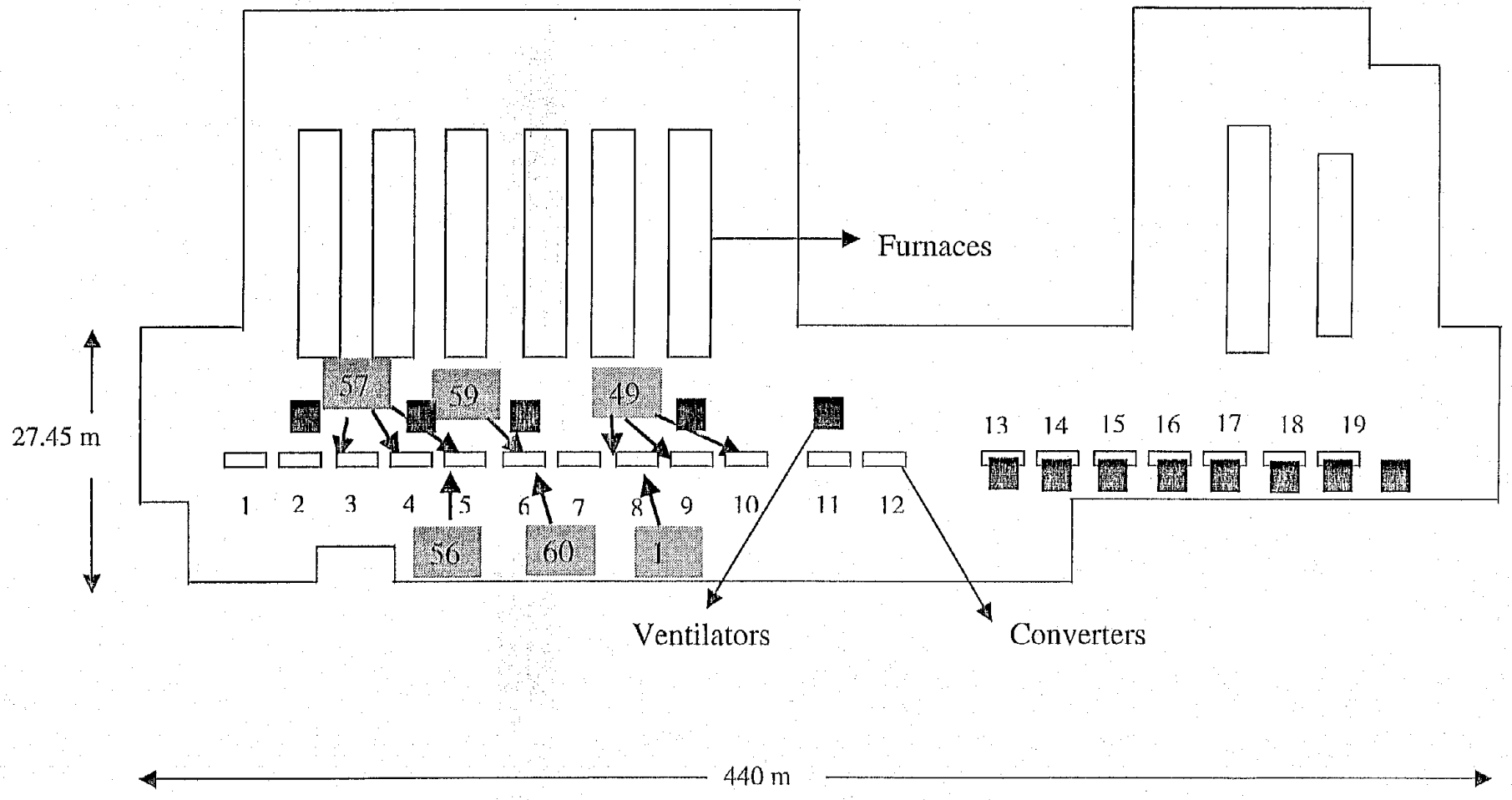

Figure 7. Layout of converter building showing the nickel and copper converter sections and their ventilators.

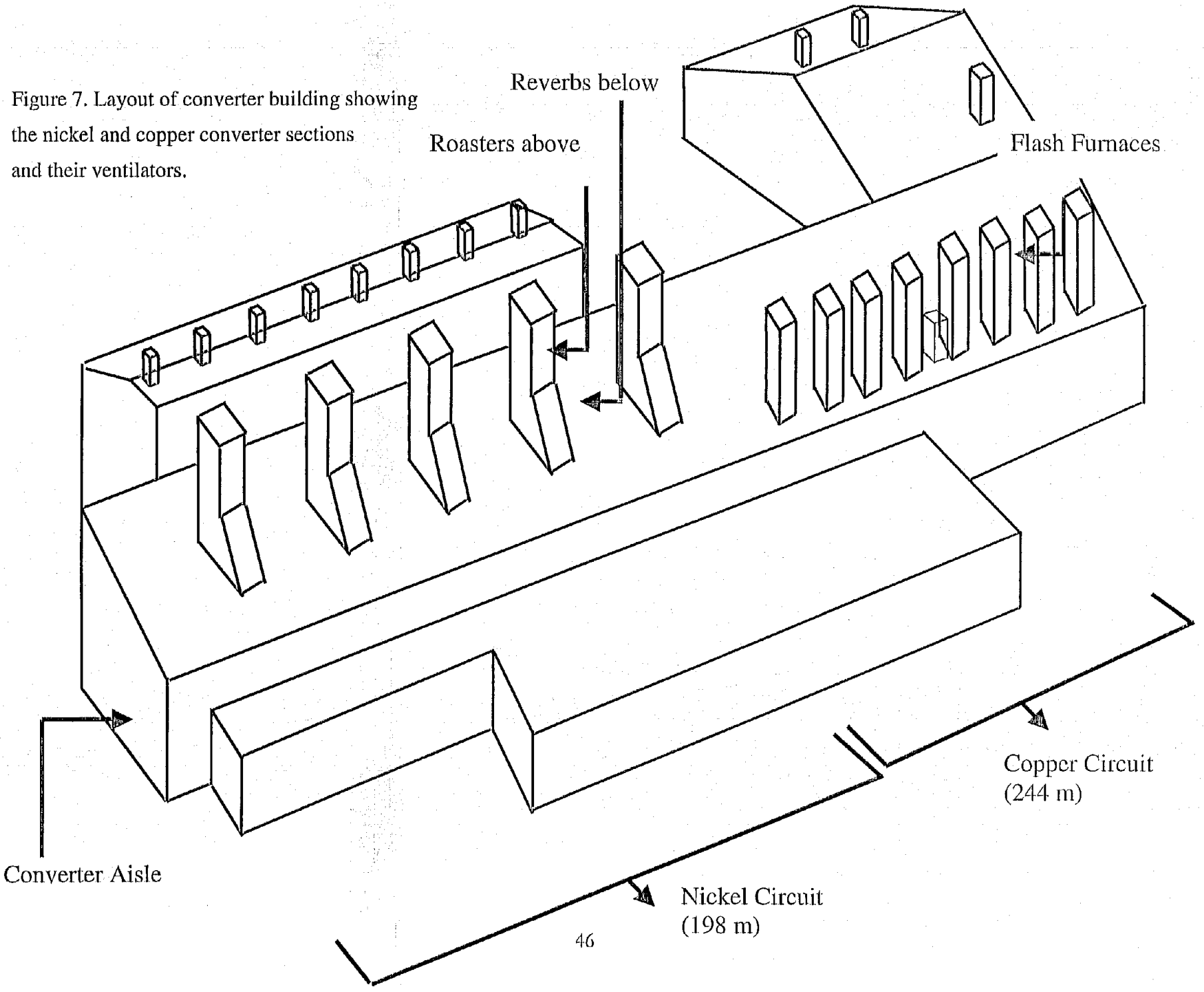

Figure 8. Schematic of ventilation flows through the flue ducts to the Cottrell electrostatic precipitators in 1971. The diagram does not include air flow through the roof ventilators.

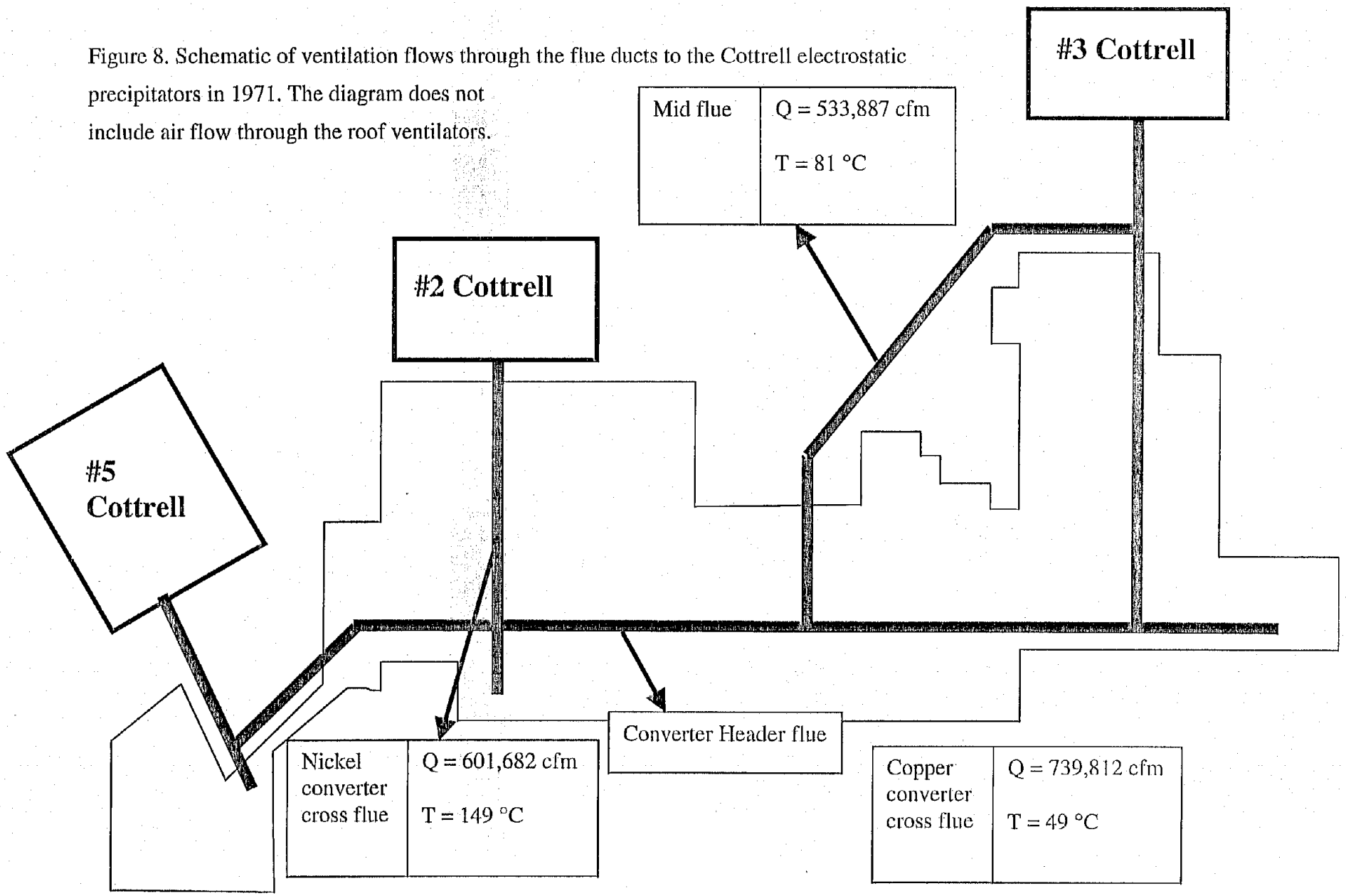

Figure 9. Distributions of input and output parameters for Monte Carlo sampling to determine expert priors. Input parameter distributions include production rate (tons/year), flow rate (m^3/min), and emission factor (kg/ton of matte), and the output parameter is the aerosol concentration (mg/m^3).

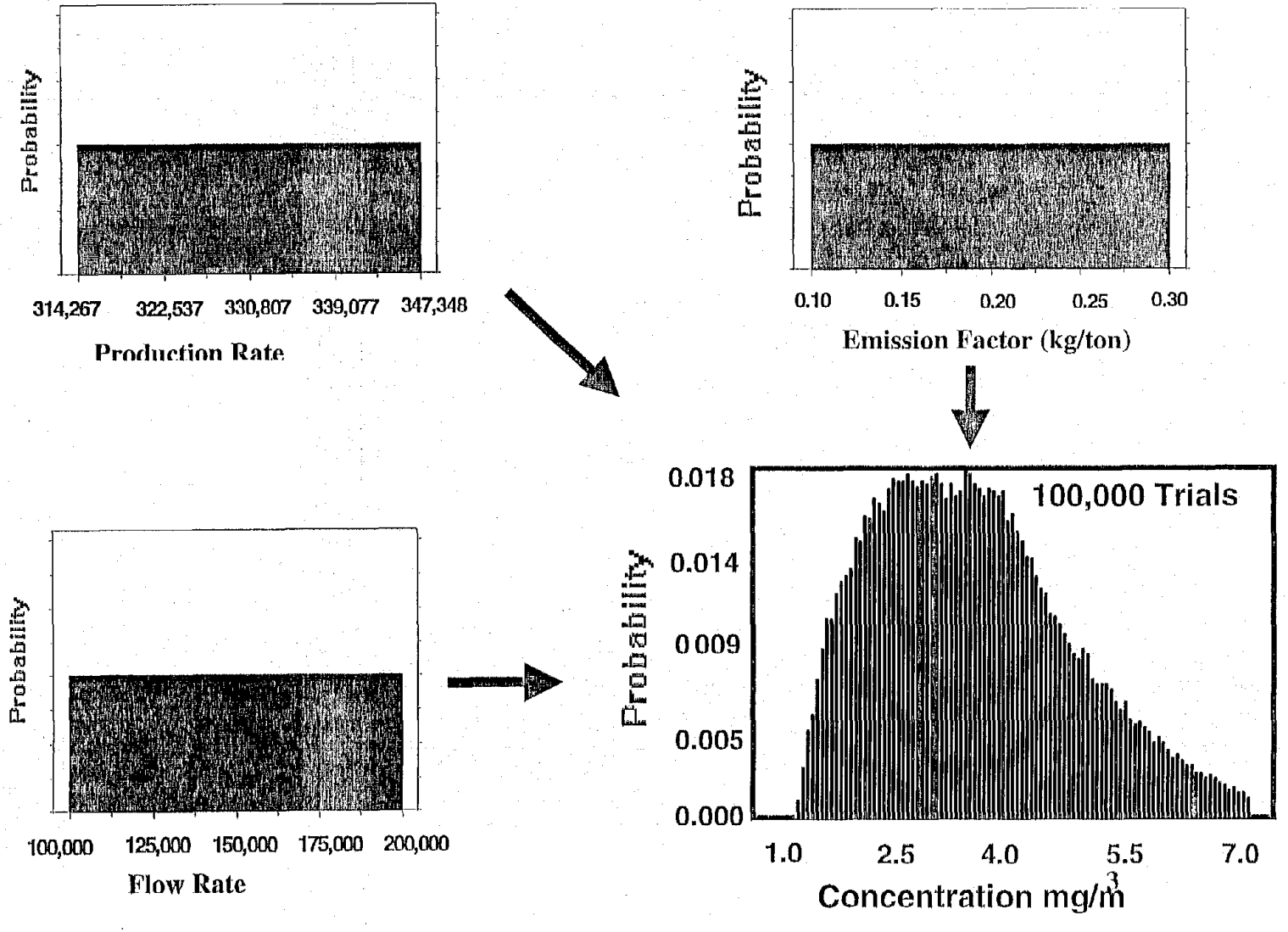

Figure 10. Outputs of Monte-Carlo simulations using expert inputs to a predictive model for inhalable nickel concentration. 100,000 sample runs were performed to obtain the distribution of model outputs for each year, using the set of input parameters provided by each expert. These are the expert prior probability distributions. The error bars represent the range between the 2.5th and the 97.5th percentiles of the outputs.

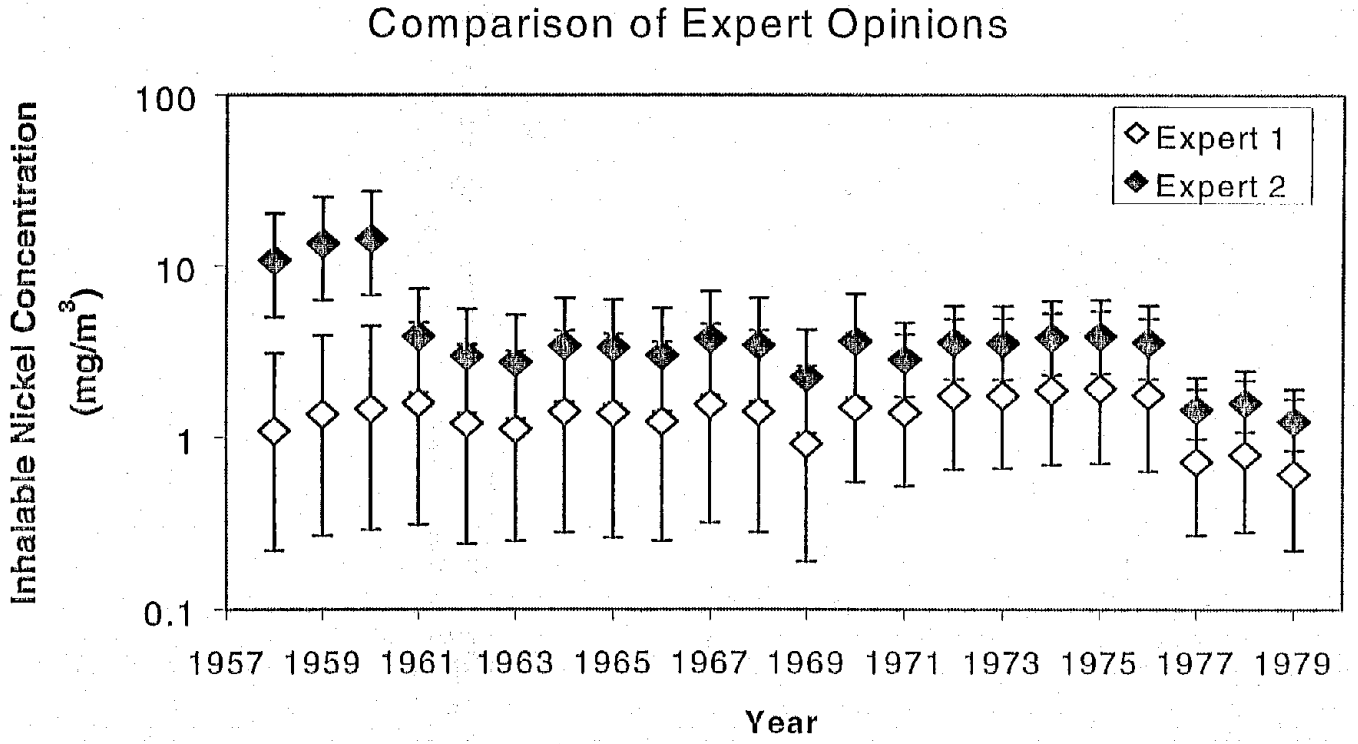

Figure 11. Posterior probability distributions for the building air concentration of inhalable nickel. The error bars represent the range between the 2.5th and the 97.5th percentiles.

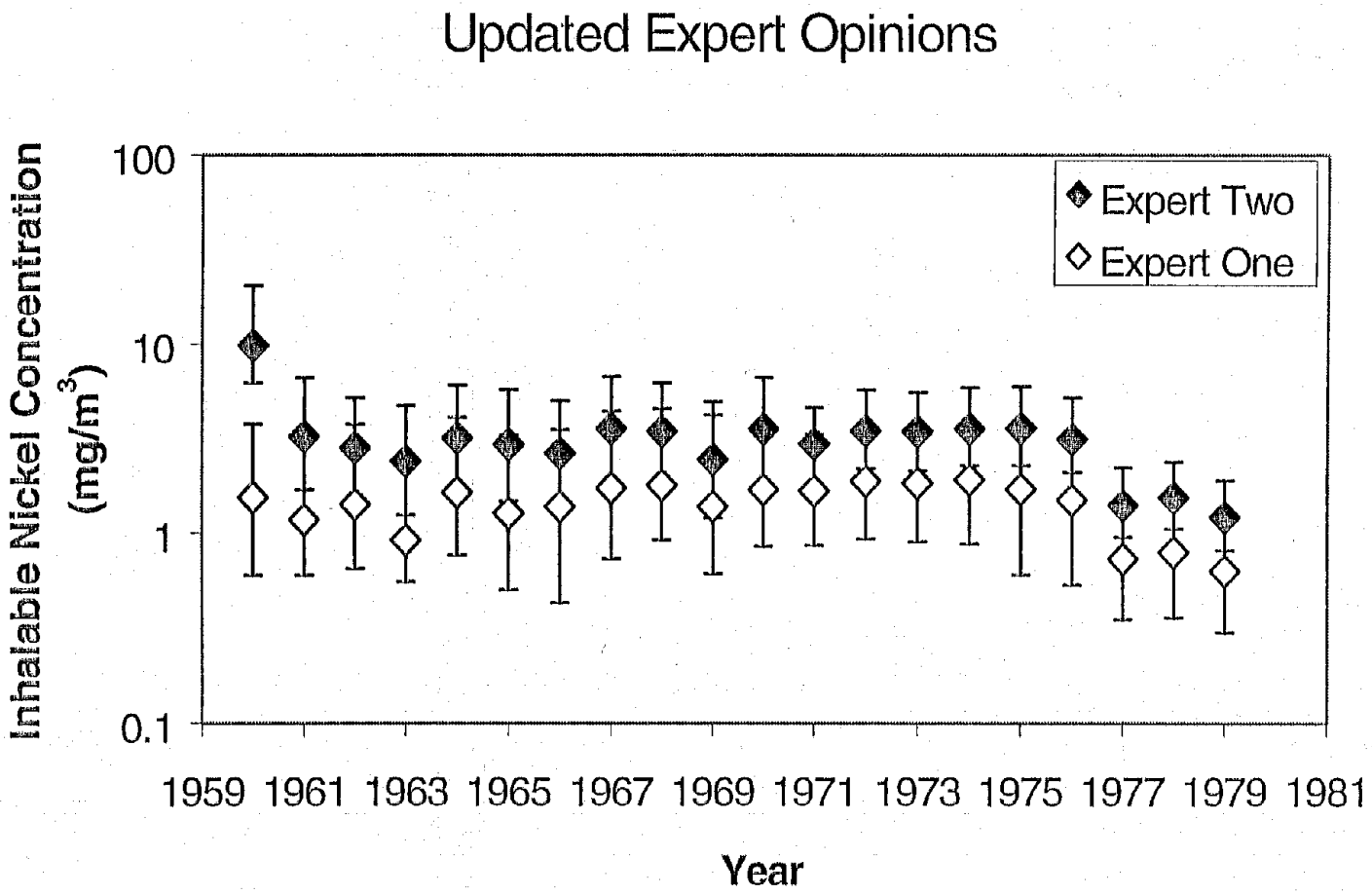

Figure 12. Cumulative probability distributions for the prior (Expert 2), the posterior, and the historical measurements for 1976.

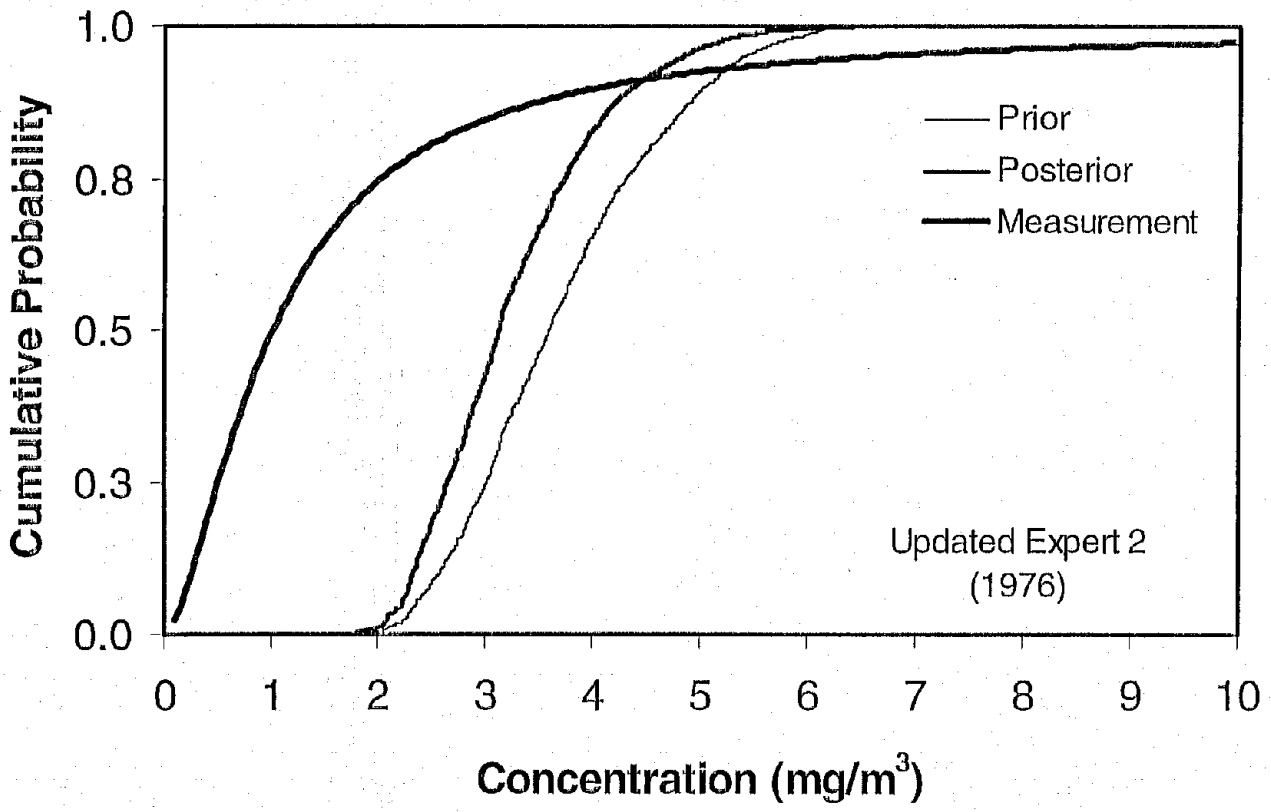

Figure 13. Comparison of posterior probability distributions (for both experts) with historical measurements. The error bars represent the range between the 2.5th and the 97.5th percentiles.

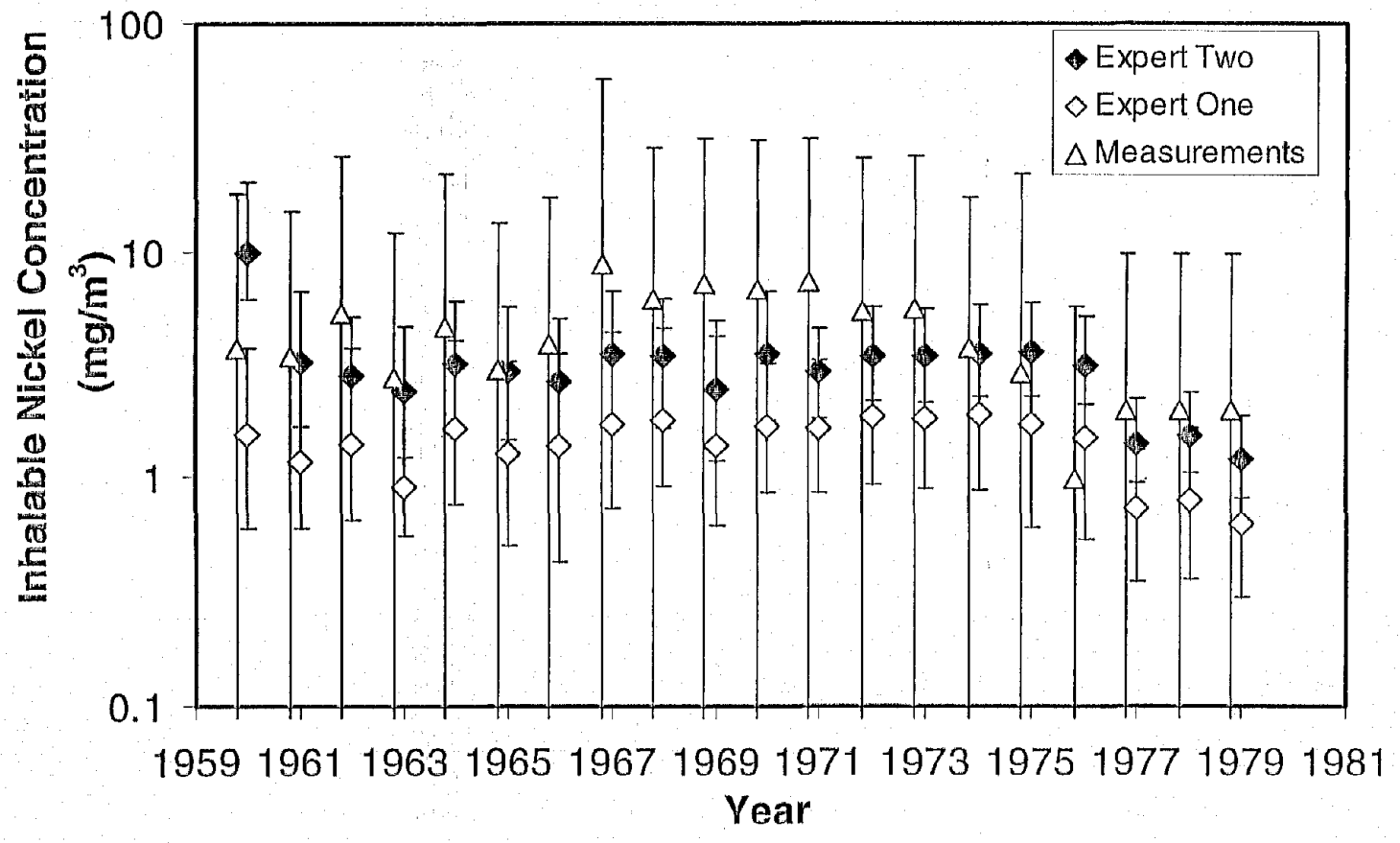

Figure 14. Comparison of posterior probability distribution of exposure history of job code 827 (skimmer converter) for inhalable nickel aerosol with conventional exposure history.