"Silica Exposure and Silicosis: Effect of Mixed Exposures"

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Final Report

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I. ABSTRACT

The quantitative relationship between exposure to crystalline silica and development of silicosis is uncertain despite a number of studies addressing the problem. The uncertainty is due to the following reasons: (a) the exposure reconstructions were based on sparse data with tremendous uncertainties; (b) dose reconstructions, to estimate the cumulative lung burden of the worker, did not account for retention and clearance of inhaled dusts; (c) exposure reconstructions for silica, a highly toxic dust, did not account for simultaneous exposures to less toxic dusts, (non-silica dusts). The purpose of this study was to obtain the quantitative dose-response relationship between crystalline silica and silicosis in a manner that addressed the above issues. The North Carolina Dusty Trades program provides a large dataset of human exposures to silica and non-silica dust and silicosis from 1935-1980. Pharmacokinetic modeling was used to estimate the cumulative lung dose of silica and non-silica dust and time to macrophage overload in the presence of this mixed exposure. A case-control study was conducted to compare silicotics and disease-free referents.

Conditional logistic regression models were developed to estimate odds ratios for the risk of silicosis for the given exposure metric. The independent and joint effects of cumulative silica and non-silica exposures and measures of lung burden were modeled to determine whether the cumulative non-silica exposure modifies the risk of silicosis among exposed workers. The cases had a much higher cumulative silica and non-silica dust exposure than the controls. The median silica exposures in the cases was roughly four times the exposure for the controls, however the non-silica dusts were less than twice as high. The median time from first employment to the estimated time of lung macrophage overload was much lower in the cases. The associations between silica exposure and non-silica dust exposure were maintained when these covariates were considered together in a model. This is consistent with and suggestive of the first study hypothesis that "*A cumulative exposure metric, which includes both silica and non-silica dusts, is more related to the development of silicosis than cumulative silica exposure alone*". These findings illustrate that the effect of silica exposures are modified by the presence of other dusts, and should be accounted for in the epidemiological analysis.

The time to overload was strongly associated with silicosis development when cumulative exposures to silica and non-silica dust were taken into account. The odds ratios for silica and non-silica dust exposure were, as expected, attenuated when this third metric of exposure was included in the model. Thus, our second hypothesis that "*The time to macrophage overload is a function of both silica and non-silica exposure, and is related to the development of silicosis*" is supported by this analysis of the data. When the months to overload was entered in the model, both silica exposures and months to overload were significantly correlated with development of silicosis. The longer it took for a worker to reach overload the lower the risk of silicosis. *These models offer additional evidence that the time to macrophage overload influences the development of silicosis, and that earlier exposure appears to be more important than later exposures.*

II. SIGNIFICANT FINDINGS

The cases had a much higher cumulative silica and non-silica dust exposure than the controls. The median silica exposures in the cases was roughly four times the exposure for the controls, however the non-silica dusts were less than twice as high. This is consistent with and suggestive of the first study hypothesis that "*A cumulative exposure metric, which includes both silica and non-silica dusts, is more related to the development of silicosis than cumulative silica exposure alone*". The median time from first employment to the estimated time of lung macrophage overload was much lower in the cases. This is consistent with and suggestive of the second study hypothesis that "*The time to macrophage overload is a function of both silica and non-silica exposure, and is related to the development of silicosis*".

The univariate analysis of silica and other dust exposures indicated strong associations between silica and other dust exposures and silicosis. This association was very similar for the cumulative lung burden and cumulative exposure. The time to overload indicates that the longer it took for a worker to reach overload the lower the risk of silicosis. The time to overload was strongly associated with silicosis development when cumulative exposures to silica and non-silica dust were taken into account. The odds ratios for silica and non-silica dust exposure were, as expected, attenuated when this third metric of exposure was included in the model. Thus, our hypothesis that "*The time to macrophage overload is a function of both silica and non-silica exposure, and is related to the development of silicosis*" is supported by this analysis of the data.

The pattern of association between silica exposure, non-silica dust exposure and silicosis was somewhat different when the data were evaluated on a continuous scale. The effect of silica on silicosis was consistent when adjusted for non-silica dust. The inclusion of an interaction term between cumulative silica and non-silica dust demonstrated significant effect modification of silica exposure by exposure to non-silica dusts. Thus, this supports our hypothesis that "*a cumulative exposure metric, which includes both silica and non-silica dusts, is more related to the development of silicosis than cumulative silica exposure alone*". When the months to overload was entered in the model, both silica and months to overload were significantly correlated with development of silicosis. *These models offer additional evidence that the time to macrophage overload influences the development of silicosis, and that earlier exposure appears to be more important than later exposures.*

III. SCIENTIFIC REPORT

a) SPECIFIC AIMS

The quantitative relationship between exposure to crystalline silica and development of silicosis is uncertain despite a number of studies addressing the problem. The uncertainty is due to the following reasons:

(a) the exposure reconstructions were based on sparse data with tremendous uncertainties;

(b) dose reconstructions, to estimate the cumulative lung burden of the worker, did not account for retention and clearance of inhaled dusts;

(c) exposure reconstructions for silica, a highly toxic dust, did not account for simultaneous exposures to less toxic dusts, (non-silica dusts).

These dusts have been shown, in animal studies, to impair lung clearance mechanisms and clearance rates by "particle overload" of macrophages, leading to pulmonary fibrosis and even lung tumors. Thus, mixed exposures can potentially affect the time to onset of disease following exposure.

The purpose of this study was to obtain the quantitative dose-response relationship between particulate-containing crystalline silica and silicosis, in a manner that assesses the uncertainties in exposure assessment, and accounts for lung clearance mechanisms that affect the cumulative lung burden and simultaneous exposures to non-silica dusts. A novel Bayesian methodology that synthesizes expert judgment and historical measurements was used for exposure reconstruction. Another innovation is the use of pharmacokinetic modeling for estimating the cumulative lung dose of silica and non-silica dusts. We address the following hypothesis, using the North Carolina Dusty Trades program, which is a large data set of human exposures to silica and non-silica dusts and silicosis cases from 1935-1980:

1. A cumulative exposure metric, which includes both silica and non-silica dusts, is more related to the development of silicosis than cumulative silica exposure alone.

2. The time to macrophage overload is a function of both silica and non-silica exposure, and is related to the development of silicosis.

3. The time to macrophage overload is a function of both silica and non-silica exposure, and modifies the time from first exposure to disease.

In order to answer the above questions, the following specific tasks were performed:

1. We estimated historical exposures for (a) silica and (b) non-silica dust for each job-code in the North Carolina Dusty Trades program for each workplace for the time period 1935-1980.

2. We combined this job-location-year exposure data matrix information with individual job histories for all study subjects, to calculate the cumulative exposure metric for silica and non-silica dusts along with the associated uncertainties.

3. We estimated lung burden as a function of time from first exposure, and time to macrophage overload due to total (silica and non-silica) dust exposure for each worker, using a lung deposition model, and pharmacokinetic data in the published literature on retention and clearance of inhaled dusts.

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4. We conducted a case-control analysis using the cumulative exposure and lung burden metrics, and compare with estimates from previous studies.

5. We evaluated the influence of time to macrophage overload on the occurrence of silicosis with reference to the exposure and lung burden metrics.

In each of the above tasks, the evaluation of the uncertainty in exposure and dose reconstructions to a mixed dust exposure was a key feature, since these can significantly alter the estimation of exposure- and dose-response relationships (odds ratios for silicosis), and the latency period of the disease. This was done within a Bayesian probabilistic framework that synthesizes sparse historical measurements, deterministic exposure models, and subjective expert judgments. Missing data were also estimated using various imputation algorithms. The overall uncertainty in these estimates was characterized, including analytical, environmental variabilities, and systematic biases in the measurements as well as estimation procedures.

b) BACKGROUND AND SIGNIFICANCE

Health risks of silica exposure

Exposures to the most common crystalline forms of silica observed in industrial settings (quartz, tridymite, and cristobalite) have long been associated with the development of silicosis, a fibrotic pulmonary disease, in workers (NIOSH, 1974; 1983; Rosner and Markowitz, 1991; Rom, 1994). The International Agency for Research on Cancer (IARC) recently also designated crystalline silica, in the form of quartz or cristobalite as a Group I Human Carcinogen (IARC, 1997). Some studies have hypothesized a link between the risk of lung cancer and silicosis, although this is still debatable (Simonato and Saracci, 1990; Pairon *et al.*, 1991; Goldsmith, 1994). Regardless of whether silicosis is one (or the only) pathway to lung cancer, elimination of silicosis will improve the overall health of workers.

OSHA has enforced its Permissible Exposure Limits (PELs) for crystalline silica (29 CFR §1910.1000; 29 CFR §1915.1000; 29 CFR §1926.55) for nearly 30 years. In 1996, the Agency initiated a Special Emphasis Program for crystalline silica designed to reduce the incidence of silicosis. Yet evidence of significant overexposures to crystalline silica continue in General Industry and other trades (NIOSH, 1999) due to a lack of effective workplace controls in many facilities. According to the National Center for Health Statistics, from 1968-1992 there were an estimated 14,313 deaths in the United States for which silicosis was either a causal or contributing factor. In a surveillance study designed to identify confirmed new cases of silicosis between 1993-95, NIOSH found 604 known cases of silicosis in just seven states (Ohio, Illinois, Michigan, New Jersey, North Carolina, Texas, and Wisconsin). The Centers for Disease Control estimate that there are about 300 deaths annually due to silicosis, three-fourths of which are estimated to occur among workers in general industry, construction, and maritime. *OSHA believes that its current PELs for crystalline silica deserve reexamination, and is proposing to revise its standard for crystalline silica* (Richard Fairfax, director, Directorate of Compliance Programs, OSHA, personal communication).

Development of a robust dose-response relationship for silicosis

Despite workplace standards, silicosis remains a fairly common occupational disease. This may be due to a lack of understanding of the exposure-response relationship in the development of silicosis, leading to continued overexposures to silica (NIOSH, 1996). While many

epidemiologic studies have looked at the relationship between occupational exposures to crystalline silica and silicosis, few have provided quantitative information about this relationship (Rice and Stayner, 1995), and none provide dose estimates or consider the effects of other dusts in the environment. Such studies are essential to estimate the risks from occupational exposures to silica and test the adequacy of current occupational health standards. Rice and Stayner (1995) reviewed six epidemiological studies of silicosis with environmental data, and found that these studies yielded widely varying cumulative risk estimates (by as much as a factor of 20) as well as estimates of no observed adverse effect levels (NOAEL) and lowest observed adverse effect levels (LOAEL). They attributed these enormous differences due to errors in exposure estimates, uncertainties in the quartz content of dusts, and differences in the definition of radiographic silicosis, and called for more research to better define the dose-response relationship.

Three issues need to be accounted for in order to obtain a robust quantitative dose-response relationship for silicosis:

(1) uncertainties in exposure reconstructions for silica and non-silica dusts based on sparse data with tremendous variability;

(2) retention and clearance of inhaled mixed dusts while obtaining cumulative lung burdens of workers;

(3) simultaneous exposures to less toxic dusts, (non-silica dusts) while reconstructing exposures for silica, a highly toxic dust.

The process of reconstructing exposure over long periods is fraught with a number of uncertainties and subjective biases: measurement criteria, instruments and analysis methods, workplace practices, plant processes, and plant-specific ventilation patterns change over time and thus modify exposures. Measurements of personal exposures are, at best, temporally sporadic, and for many time periods, not even available.

Esmen (1979) recognized these limitations, and proposed a methodology for projecting historical exposures from current estimates by a series of adjustments to the current data. These adjustments are based on changes in the process, physical parameters of the agent, and use of personal protective devices. However, subjective judgments would strongly influence these adjustments. Schneider *et al.* (1991) further explicated this approach by proposing the use of 'exposure modifiers' as input parameters to a deterministic exposure model, and using historic exposure data to adjust the model parameters. Researchers have used 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). More recently, Cherrie and Schneider (1999) have used structured subjective assessments for reconstructing exposures. While it is recognized that these techniques are subjective, there has been no effort to systematically use all these pieces of information in a logically consistent manner, that also evaluates and incorporates the uncertainties in exposure estimates.

Ramachandran and Vincent (1999) proposed a Bayesian framework for synthesizing objective but incomplete measurements, with subjective expert input based on historical information about workplace conditions. This was subsequently applied to estimating historical exposures in a nickel smelter. This innovative framework 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 was used for synthesizing expert judgment, historical information about workplace conditions, and incomplete measurements to determine exposure as a function of time and place. The end result was an exposure matrix by time and task-group, similar to that used by Stayner *et al.* (1992), except that exposures are represented as probability distributions, instead of averages. Such an exposure matrix can then be used directly for epidemiology. 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 and task-group, the exposure is represented as a probability distribution.

For a disease such as chronic silicosis that is caused by long term exposures and appear decades after first exposure, the health hazard is related to the amount of contaminant that the individual is exposed to, the kinetics of deposition and clearance of the inhaled material, and some measure of 'harmfulness' or potency of the contaminant. All of these are time-dependent quantities, and the integrated dose of 'harmfulness' at time t since the start of exposure may be expressed in a general form as

$$\text{Dose} = \int_{0}^{T} f\{E(t), R(t), G(t)\} dt$$

Here, $E(t)$ is the exposure history derived from measurements of dust 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 (Vincent *et al.*, 1988; Vincent and Donaldson, 1990). Most exposure-based epidemiology assumes that cumulative exposure, *i.e.,* $\int_{0}^{T} E(t) dt$, is a good measure of dose. This is an approximation that is only valid when $R(t)$ and $G(t)$ are unity. In recent years, a number of animal inhalation studies have enabled substantial progress to be achieved in understanding the retention and clearance mechanisms in the respiratory tract for toxic and non-toxic dusts, so that $R(t)$ is well defined. This will be described in more detail in a later section.

Although the parameter, $G(t)$, is just as important, it is more difficult to quantify. It is clear that the simplest models, that calculate dose as the cumulative exposure where each exposure is equally weighted, can be refined to better reflect the biology. Some early progress in this regard was made by linking the kinetic behavior of lung burden and cell response based on the cell lavage studies by Donaldson *et al.* (1988). From the results of inhalation experiments with rats for 'relatively innocuous' titanium dioxide and 'relatively harmful' quartz, they found that for TiO_2, $G(t)$ reaches a maximum soon after the particle contacts the lung and then quickly decays, whereas for quartz, $G(t)$ is high initially and remains so. 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 (Jahr, 1974). Thus, for silica, greater weight needs to be given to the effect of earlier exposures.

Epidemiologic studies of chronic diseases such as silicosis are hampered by uncertainties in the exposure assessment. Misclassification of exposure results in biased estimates of a dose-response relationship. The effects of exposure misclassification are often dismissed as biasing the results toward a null finding or attenuating an exposure response relationship, however it is usually impossible to determine the actual direction of the misclassification or bias. These problems are exacerbated when the analysis is describing the interaction of two or more correlated exposures, *e.g.* silica and non-silica dusts, on the occurrence of disease. Methods for conducting sensitivity analyses to describe the effects of misclassification are well known (Rothman and Greenland, 1998). Unfortunately the criteria used to evaluate misclassification are often subjective and may be biased by the evaluator's preconceived assumptions.

c) THE NORTH CAROLINA DUSTY TRADES PROGRAM DATA SET

Silica exposure occurs in a number of industries in North Carolina: quarrying and finishing of granite, rock crushing, foundry operations, and the mining and milling of mica/feldspar, kaolin, lithium, pyrophyllite, tungsten (hard rock), quartz and talc. The North Carolina Dusty Trades program was initiated in 1935, following passage of an act by the State legislature. Each workplace posing a risk of silica exposure was to be identified, exposure evaluated and all workers examined. The examination included a work history, chest exam, and X-ray. Workers free of silicosis were issued a work card valid for one year; the card was renewable at each required annual examination, if the worker did not show evidence of silicosis. The work history and examination records of anyone determined to have silicosis since the inception of the program are used in this project. Because of storage limitations, records of anyone free of disease and not examined in five years (presumed to have left the trades) used to be discarded until 1979. All industrial hygiene records have been retained and available.

Previous work with these data by one of the investigators has included selecting 331 silicotics employed in 1935 or later, identifying 672 matched controls for 216 of the cases (there are 888 workers in the entire study population), modeling the time to diagnosis among the cases diagnosed at Grade 1 (n = 229), conducting a case-referent study of silicosis and an investigation of the effect of various imputation methods on the exposure-response relation for silicosis (Rice, 1983; Rice *et al.*, 1984; Rice *et al.*, 1985; Rice *et al.*, 1988, Rice and Herring, 1995, Rice *et al.*, 1997). Cases were matched with up to four non-cases using the following criteria: race, year of birth within five years, year of hire within five years, and follow-up duration. Work histories for all cases and controls and industrial hygiene exposure measurements at any company (numbering approximately 400 in total) where one or more study subjects worked were computerized.

The work history consists of an identifier, date of birth, and race; and for each work site, a company and site (for multi-location employers) identifier, industry type, county, and job title. The variables in the industrial hygiene file include: date, mineral industry, county, number of employees, job, task, work location (underground/surface/mill), engineering controls, other controls, and analytical result. All of the jobs and tasks have been standardized into a common set of identifiers, specific to each mineral industry. The result is provided in millions of particles per cubic foot (mppcf) for 85% of the 15,000 measurements. The mppcf determinations resulted from short-duration (approximately 15 minute) samples collected in an impinger and counted using optical microscopy. This index of dustiness was used to evaluate exposure and the efficiency of engineering controls at specific locations in each workplace and could be used to estimate the time-weighted average exposure of a worker. The amount of dustiness considered

acceptable was scaled, using the silica content of the dust which was determined from samples of settled dust. Mineral-specific formulae were developed in collaboration with personnel familiar with the North Carolina dusty trades and used to combine the impinger measurements into estimates of exposure at the various jobs. For the remaining exposure data, samples were collected with the mass-respirable cyclone pre-sampler, and the results reported in mass concentration of particulate and percent silica. Each of these full-shift samples is directly linked to a job title.

Our data set also includes the work history listings for all cases and non-cases, and the results of any sampling survey at any work site of these subjects that was visited by a state industrial hygienist. The repository offers a unique opportunity to extend our understanding of factors that may affect the risk of silicosis (Rice and Herring, 1995). Specifically, the range of mineral matrices allows comparison with the results of other researchers, where exposure generally occurs in one type of industry only (*e.g.*, Vermont granite, Davis *et al.*, 1983; foundry, Rosenman *et al.*, 1996; hard rock mining for gold, Steenland and Brown, 1995). The use of the impinger to collect samples from 1935 until the mid-1970s provides information on exposure, by activity, which can only be inferred from cyclone data. Estimates of both total dustiness and silica exposure are available. While the validity of impinger data may be questioned by those unfamiliar with the technology, it can be noted that the original work resulted in a strong exposure-response relation and subsequent approaches to imputation have resulted in stronger relations. Moreover, exposures reconstructed from North Carolina granite operations were comparable to those measured in Vermont. The available data can be used to investigate the importance of all dust in the environment, and the silica. This has not been done and represents a mixed exposure that is very common in general industry and construction trades.

d) METHODS

This section consists of three parts: (1) A description of the procedures used for importing and cleaning the measurement data from the NC Dusty Trades data set, and estimating worker job exposures for different time periods by commodity. (2) A description of the methodology for exposure reconstruction for silica and non-silica dusts using a Bayesian approach; (3) A description of the methodology for dose reconstruction that accounts for the retention and clearance mechanisms for both silica and non-silica dusts, and the estimation of the time to macrophage overload for a given exposure history; (3) methodology for a case-control study to compare silicotics and disease free referents with respect to silica and non-silica exposure metrics, and time to macrophage overload.

a. Exposure Estimates based on Environmental Measurements Alone

i. Data collected using Greenburg Smith and Midget impingers

The impinger data runs from 1936-02-01 to 1979-07-01. In the impinger, air is drawn through a glass tube and impacted at high velocity on a wetted surface normal to the direction of air flow. The Greenburg-Smith impinger, used originally operated at 28.3 liters per minute (1pm). Samples were usually collected by placing the impingers on stands or holding them near workers. The glass construction and fluid sampling media made personal sampling difficult. (Rice,1983). The midget impinger replaced the Greenburg-Smith in the early 1940s. The midget impinger is almost identical in principle and design to the Greenburg-Smith impinger, except for its smaller size. Only a 12" head of water is required. The orifice at the bottom of the impinger is 1 mm,

passing 0.09-0.11 CFM of air at 12" H$_2$O vacuum. These impingers were designed for the sampling of small air volumes with a low jet velocity. This device was used in North Carolina till 1974. The impinger samples were collected for duration of 15 minutes and gave the task exposure. The results were reported in million particles per cubic foot (mppcf).

ii. Data collected using Cyclone Sampler

The cyclone sampler data run from 1970-06-01 to 1981-11-01. This device takes advantage of radial force to effect separation, the geometry of the unit determines the percent removal of a given size of particles from the sample air stream. Material passing through the cyclone is collected on a hydrophobic polymer filter having 5.0 μm pore size. This respirable fraction is weighed to determine total mass concentration in mg/m^3. This estimated the job exposure values for an eight hour work shift.

iii. Data Import

There are 888 workers in the entire study population with 672 matched controls for 216 of the cases. The occupational history consists the worker employment history and consists of the worker ID, the company for which the worker worked, the commodity (e.g., granite, quartz, etc.), the job (e.g., crush, drill etc.), the year he started the job, and the year the job ended. Each job is divided into one or more tasks. This data set also has records related to the number and types of tasks in each job for each commodity and percent time spent on each task within a job. Table1 gives the number of workers, jobs and tasks in each commodity. Appendix 1 shows the number of data points in each task and commodity.

The original data is contained in sets of three files for each commodity.

1   The .job file contains the jobs defined for the commodity

2   The .tsk file contains the tasks defined for the commodity.

3   The .jtt file contains the task loadings for each job.

These files were imported into Microsoft Access to create the Jobs, Tasks and JobTasks tables respectively. During the import a column was added to indicate the original commodity for each record. There were 265 distinct job titles across all of the 12 commodities and 76 task names. There were 1076 joint JobTasks records imported which were distributed by commodity (Table 2).

Commodity	No. of Workers	No. of Jobs	No. of Tasks
Asbestos	8	9	6
Foundry	263	63	20
Granite	100	52	19
Kaolin	72	37	24
Lithium	32	31	16
Micaspar	195	72	26
Other	65	47	22
Pyrophyllite	43	55	21
Quartz	7	10	12
Rock	45	37	11
Stone	204	47	17
Talc	21	10	12

Table 1. Number of workers, jobs, and tasks (1935-1980)

Commodity	Total Jobs in .job files	Jobs in 9/22/2000 IRB Memo	Total Tasks in .tsk files	Tasks in 9/22/2000 IRB Memo
ASBESTOS	9		6	
FOUNDRY	53	60	23	24
GRANITE	52	59	23	24
KAOLIN	37	38	28	29
LITHIUM	31	35	19	19
MICASPAR	60	65	37	37
OTHER	47	66	27	34
PYROPH	47	47	25	25
QUARTZ	10	11	15	15
ROCK	28	30	14	16
STONE	47	52	18	18
TALC	24	27	14	14

Table 2. Jobs and tasks in various commodities

The job and task numbers were replaced with their respective names and a new table, AnnotatedJobTasks was created. The Task name contained embedded information about the measurement type and the physical task location. Specifically, the first character of the task indicated whether the measurements for this task were made using personal devices (P) or area measurements (G for general). The second character was either S if the task was conducted on the surface or outside, M if it was located in the Mill and U if the task was performed underground. The AnnotatedJobTasks was then converted into the AnnotatedDetailJobTasks where two new columns were added to indicate the location and measurement type. The Task column was updated by stripping off the leading two characters. No anomalies were discovered in this process. There were still 1076 records and the new TaskLocation and MeasurementType columns all had suitable values.

iv. Data Format

The data set of impinger measurements contains 8,500 observations of raw exposure values measured as *million particles per cubic foot (mmpcf)*. The level of measurement is

1. Commodity. The type of material being handled, e.g. Stone, granite, etc.

2. Company. A number representing the company

3. Site. A number indicating the site where the measurement was taken.

4. Location. An indicator showing whether the location of the measurement was underground, above ground or at the mill.

5. Sample Type. An indicator of whether the measurement was a personal measurement near a specific, albeit unidentified, worker or a general measurement in the area the task was performed.

6. Task. The specific task for which the exposure measurement was collected.

The measurement data itself is composed of

1. The sample date of the measurement as year-month.

2. The exposure measurement in ln(mmpcf).

Unfortunately the data has some issues:

1. The measurements are not necessarily contemporaneous so we may have measurements for one task in the job in 1951 and 1962 and measurements for 1955 and 1958 for a second task in the same job. To deal with this we needed a method to mesh the data together from different time intervals.

2. In some cases we may need data values that lie outside of the range of observed data, for example, we may need an exposure value for a task in 1938 when the earliest measure that we have is for 1962. We needed a method for forecasting data outside of the observed dataset.

3. We did not have data for all of the tasks in a given job. For instance, a given job may have 3 constituent tasks but we may only have measurements for two of those three tasks available for a specific company. We needed a consistent and defensible method for filling in the missing data.

v. Aggregation of the Impinger Data

The impinger data contains information on the commodity, company, site, task, measurement type, task location, sample date and measured exposure. Several of these variables had some issues that were resolved in the following manner:

Problem: The impinger data contains information on the site for companies with multiple locations. Unfortunately, most of the employment history data doesn't specify a site for the worker's job history.

Solution: To deal with this issue, the data was aggregated across all of the sites for a given company.

Analysis: The job history file contains information on 7,680 distinct jobs held for 888 distinct workers. Of those 7,680 job records only 1024 contain information on a specific job site. The 7,680 jobs translate into 2,447 distinct commodity/company/site/task that are needed to calculate the job exposures. If we require a measurement to match on commodity/company/site/task we can only satisfy 198 of these requirements. When the sites are aggregated this increases to 648 of the required measurements.

Problem: Many of the aggregated sample values only have a single observation for the commodity, company and task for the sample date so no estimate of the variance of the observation is available.

Solution: Since the number of sample dates with more than 3 individual measurements is relatively small we chose to estimate the variance of the estimate using the following protocol.

1. Measurements for a given commodity, company, task, 5-year interval and location were grouped together to calculate a variance estimate.

2. Measurements for a given commodity, company, task and 5-year interval were grouped together to calculate a variance estimate.

3. Measurements for a given commodity, company and task were grouped together to calculate a variance estimate.

4. Measurements for a given commodity and company were grouped together to calculate a variance estimate.

5. Measurements for a given commodity were grouped together to calculate a variance estimate.

6. Measurements for the entire sample were grouped together to calculate a variance estimate.

For a specific measurement, the variance was estimated by examining the variance estimates by increasing degrees of aggregation. When a variance estimate was found that consisted of estimates from 5 or more data points was found, that estimate was used for the variance of the measurement. This process should provide a variance estimate among the most *similar* data points.

To summarize the rollup process, we started with the raw exposure value indexed by commodity, task, 5-year interval starting at 1930, company, location, sample year. If there weren't enough data points, we used 7 as the threshold number, the data was aggregated by "commodity, task, 5-year interval starting at 1930, company, location", then "commodity, task, 5-year interval

starting at 1930, company" , then "commodity, task, 5-year interval starting at 1930, commodity, task, 5-year interval starting at 1930" and so on until we were down to the overall average for the entire industry for all tasks for all time periods, etc. The only place this occurred was for asbestos.

Therefore the mean exposure value for each task for each commodity/task/time interval was calculated using the following formula:

$$M_i = \exp(Yb)\psi_n(V)$$

where Mi is the mean task exposure, Yb is the mean of natural logarithms of the sampling data, $\Psi n\ (V)$ is a function of sampling variance. (paper)

$$\psi_n(V) = 1 + \left(\frac{(n-1)V}{n} + \frac{(n-1)^3 V^2}{n^2(n+1)2!} + \cdots \cdots \right)$$

Where $V = \frac{1}{2}S_y^2$

S_y^2 is the sampling variance of Y.

Job title did not enter into the rollup process. When we needed an estimate of the job exposure at a particular company for a task we took the most detailed estimate for the task, time period, company, etc.

Problem: The impinger data contains records that seem to represent aggregate measurements. It also contains individual measurements for the same commodity, company, site, task and sample date. For example, the following table 9 individual measurements and 2 measurements aggregated into a single observation.

Solution: The aggregate measurements were dropped from the dataset.

Analysis: The sparse nature of the data makes it hard to calculate standard statistical measures. To deal with this problem it is necessary to construct proxy for these estimates. Ideally, this proxy should be as similar as possible to the data used to compute the estimate of the mean.

The get a measure of the sensitivity of the results to the selection of the threshold number of data points for the variance estimates the frequency distribution for thresholds of 3 – 7 data points.

Threshold/ Aggregation Level	3 pts	4 pts	5 pts	6 pts	7 pts
commodity task interval company location year	552	263	126	81	53
commodity task interval company location	1811	1395	1067	826	607
commodity task interval company	75	73	68	56	52
commodity task interval	2026	2533	2857	3007	3122
commodity task	316	479	600	717	834
commodity	51	88	113	144	163
All measurements	1	1	1	1	1

vi. Issues with Task compositions of Jobs

The next step was to verify that all of the tasks assigned to a given (commodity, job) tuple summed up to 100%. A query was run to identify any tuples where this wasn't the case and 54 cases were identified where the task loading wasn't 100% (see Table 3).

Subsequent information indicated that the overloaded jobs were caused by two aspects of the data. For 3 of the commodities (Micaspar, Pyroph and Rock), there were separate task loadings depending on whether the job was being done on the surface/outside or underground.

The second issue is the presence of a more refined breakdown for a single company in the Foundry commodity. In this case, a task like MOLD would be used by all of the foundry companies except for a single company which used MOLDFTG and MOLDPIPE. In most cases the percentage of time spent on MOLD was equal to the sum of time spent on MOLDFTG/MOLDPIPE.

To fix the first problem, the records in Micaspar/Pyroph/Rock were split into two sets of task records; one for the surface task and one for the underground task. In the original data, a given job could have three types of task records (mill, surface, underground). These were split into two tuples of records (mill, surface) and (mill, underground) and the latter was assigned to a new job record that had a U appended to the end of the name to indicate that it was an underground job.

For the most part this worked reasonably well and 176 of the bad (commodity, job, task) records were removed and 187 new split records were added. The one issue that arose was that 7 of the split (commodity, job) records had task loadings < 100%. These are shown in Table 4 below. In most cases a surface record had a matching underground record. In these 7 cases, there were

records for the surface with an entry for a 'yard' task which brought the (commodity, job) total to 100% for the surface records, but was missing for the underground records. If the yard record is added to the underground records, the problem goes away.

The second problem was dealt with in a similar manner. Split record sets were created with one record set containing the task distribution for companies using the (MOLD,GRIND) tasks and another set for those using the (MOLDFTG, MOLDPIPE, GRINDFTG, GRINDPIPE) tasks. In this case 47 (commodity, job, task) records were split into 56 new records. Two of the new jobs had loadings < 100% which were caused by the lack of (GRINDFTG, GRINDPIPE) records for the GRIND record (Table 5).

Commodity	Job	Percent Time
Foundry	CRANE	2
Foundry	FORE	1.67
Foundry	FURNACE	1.5
Foundry	HYSTER	1.5
Foundry	LABOR	1.34
Foundry	LINEFURNC	1.5
Foundry	LINELADLE	1.5
Foundry	MAINT	1.25
Foundry	MOLDPATRN	1.5
Foundry	UNKLABOR	1.67
Granite	SET	0.5
Granite	SETSAW	0.75
Granite	SETSHARP	0.75
Micaspar	BSMITHDRIL	1.5
Micaspar	BSMITHMUCK	1.5
Micaspar	COB	2
Micaspar	COBSCREEN	1.5
Micaspar	DRILL	2
Micaspar	GRINDRILL	1.64
Micaspar	MINEFORE	2
Micaspar	MINEMAINT	1.5
Micaspar	MINESUPT	1.5
Micaspar	MUCK	2
Micaspar	PUMPMUCK	2
Micaspar	PWDRILL	2
Micaspar	TRDR	1.25
Micaspar	TRDRCOB	1.75

Commodity	Job	Percent Time
Micaspar	UNKFORE	1.5
Micaspar	UNKLABOR	1.5
Other	BAKE	0.7
Other	BAKEFORE	0.7
Other	FORE	0.7
Other	FURNACE	0.7
Other	GRAPHFORE	0.7
Other	GRIND	0.875
Pyroph	DRILL	2
Pyroph	DRILLFORE	2
Pyroph	MINEENG	1.25
Pyroph	MUCK	2
Pyroph	PWDR	2
Pyroph	TIMBER	1.5
Pyroph	TIMBERFOR	1.25
Pyroph	TRDR	0.25
Pyroph	UNKFORE	1.5
Pyroph	UNKLABOR	1.5
Rock	DRILL	2
Rock	DRILLFORE	2
Rock	DRILLPWD	2
Rock	HOISTDRILL	1.5
Rock	MINEFORE	2
Rock	MUCK	2
Rock	PWD	2
Rock	TRDRILL	1.5
Rock	UNKLABOR	1.5

Table 3: Job-Task Loadings where percent times $\neq 100\%$

Commodity	Job	Percent Time
Micaspar	BSMITHDRILU	0.75
Micaspar	BSMITHMUCKU	0.75
Micaspar	TRDRU	0.5
Pyroph	TIMBERFORU	0.25
Pyroph	TIMBERU	0.5
Rock	HOISTDRILLU	0.5
Rock	TRDRILLU	0.625

Table 4: Erroneous Task Loading Created By SMU Split Correction

Commodity	Job	Percent Time
Foundry	LABORONE_COMP	0.67
Foundry	MAINTONE_COMP	0.75

Table 5: Erroneous Task Loading Created By FTG/PIPE Split Correction

Commodity	Job	PercentTime
Granite	SET	0.5
Granite	SETSAW	0.75
Granite	SETSHARP	0.75
Other	BAKE	0.7
Other	BAKEFORE	0.7
Other	FORE	0.7
Other	FURNACE	0.7
Other	GRAPHFORE	0.7
Other	GRIND	0.75

Table 6: Remaining Erroneous Task

In the current data set there are 18 (commodity, job) tuples with loading < 100% (Tables 4, 5, 6).

In Table 4, for TRDR (JobNo=51) in the micaspar.jtt file, the task GUMINE (TaskNo=4) has 25% time.

This would be a task with a 'General' measurement that was performed Underground. The full task list for Micaspar.TRDR is CRUSH.Mill = 25%; PIT.Surface = 25%; YARD.Surface=50%; MINE.Underground=25%. This gets split into two jobs during the SMU correction

TRDR = (CRUSH.Mill, PIT.Surface, YARD.Surface) = 100%

and

TRDR = (CRUSH.Mill, MINE.Underground) = 50%

We assumed that any job that didn't have tasks assigned to it was non-exposure. Likewise, when a job was composed of tasks that were less than 100% time we assumed that the missing time was non-exposed. The task-job weights came from expert estimates so presumably if they weren't there, they weren't exposed.

vii. Job Exposure Estimation

The task exposures were in units of ln(mmpcf). The formula used for conversion from mppcf to mg/m3 is as follows:

(mg/m3)= mppcf x 0.09

The process of estimating the job exposure levels is fairly simple. For each job there are a set of tasks and task weights (i.e., the time fraction spent performing each task) that allow us to aggregate the measurements for the underlying tasks into an estimate for the job.

$$E(job) = \sum_{i=1}^{N} E(task_i)\, t(task_i)$$

where Ei is task exposure and t_i is the time fraction spent on each task within a job.

The variance for the job exposure was estimated as

$$Var(job) = \sum_{i=1}^{N} var(task_i)\,[t(task_i)]^2$$

From 1970-1981, while the exposure measurements are in terms of 8-hour TWA gravimetric measurements (mg/m^3) for specific job titles, these had been converted to mmpcf. Therefore, the values had to be converted back into units of mg/m^3. These values were then used in the exposure estimates for specific jobs for specific years.

The impinger and cyclone measurements were thus combined to create job exposure tables for each job over the entire time period 1935-1981.

viii. Estimating silica and non-silica exposures

The job exposure concentrations (based on respirable dust) were multiplied by the fractional silica content to obtain respirable silica concentrations. The non-silica dust concentration was obtained as the difference between the respirable dust and respirable silica concentrations. The average fractional silica content in each commodity is provided in Table 7.

Commodity	Multiplier
Asbestos	0.2
Micaspar	0.2
Foundry	0.065
Granite	0.261
Kaolin	0.303
Lithium	0.232
Other	0.19
Pyrophyllite	0.346
Quartz	0.501
Rock	0.134
Stone	0.293
Talc	0.015

ix. Worker Exposure History Estimation

For each worker ID, the data set contained his employment history, i.e., information on each company/commodity that he had worked in, the job he performed, and the start year and end year of employment. Using the employment history and the job exposures estimated for each time interval (see previous section), we estimated each worker's exposure history. Table 8 below illustrates this process.

Table 8. Estimating worker exposure history from employment history and job exposure

Worker Id	Year	Commodity	Company	Job	GM (mg/m3)	GSD
41	1946-1950	Granite	66	Cut	2.60	4.66
41	1951-1955	Granite	NA	Cut	NA	NA
41	1956-1960	Granite	126	Cut	2.58	4.66

estimates.

b. Exposure Estimates using Bayesian Framework

i. The Bayesian Framework

We used a framework based on Bayesian inductive reasoning to retrospectively assess exposures to crystalline silica and non-silica dusts. In the Bayesian view, a measurement process serves to refine previous knowledge of physical parameters by adjusting their probability distributions (Little and Rubin, 1987; Makridakis *et al.*, 1984). If the physical quantity of interest is represented by f, and the measured data are represented by m, then the Bayesian expression for the updated probability distribution of f is

$$P_{post}(f/m) = \frac{P_o(f)P_L(m/f)}{P(m)}$$

where $P_o(f)$ is the probability distribution of f prior to making any measurements (the '*prior*'); $P_L(m/f)$ is the likelihood that given the true value f, the measurement m is observed; $P(m)$ is the probability that the measurement m is observed; and $P_{post}(f/m)$ is the updated probability that the physical quantity of interest is f, given that measurements m are observed (the '*posterior*').

The above framework is applicable to this project where subjective inputs such as expert judgments about the probability distribution of a particular parameter (such as silica and non-silica concentration under specified conditions) are synthesized with objective measurements of the same parameter. The updated probability provides a better estimate (*i.e.*, narrower probability distribution) of the parameter of interest than either the subjective prior probability provided by the experts or the objective - but sporadic and incomplete - measurements.

This probabilistic framework was first proposed by Ramachandran and Vincent (1999) 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. This illustrated that traditional methods, using only sparsely available historical measurements, result in estimates with large uncertainties. Retrospective exposure reconstruction based solely on sparse historical measurements leads to estimates with such large error bars as to be not useful for developing quantitative dose-response relationships for epidemiology. It is clear that this approach to reconstructing exposures provides better estimates since it incorporates all the available information, and not just the exposure measurements, in a logically consistent manner, and in many instances reduces the level of uncertainty associated with exposure estimates.

ii. Expert Selection

Recruitment of qualified professionals to interpret the data is crucial. Previous studies have used a number of approaches ranging from substantive contributions to the scientific literature (Wolff *et al.*, 1990), status in scientific community (Evans *et al.*, 1994; Siegel *et al.*, 1990) and peer nomination (Hawkins *et al.*, 1989). An important qualification is familiarity with workplace environments (Ramachandran, 2000). Another factor that was considered in assembling the team is to provide for a variety and balance of institutional perspectives, by including experts both from industry and academia. We identified four experts who possess considerable experience and expertise on different facets of this study. Probabilistic expert opinions were elicited from the four experts.

iii. Expert Judgment Elicitation

The selected expert presented his estimates of task exposures for each time interval of interest for each commodity in terms of a minimum and maximum value in units of mg/m^3. Thus, the prior was a uniform distribution between the minimum and maximum values.

This expert was very knowledgeable about the exposure levels in the NC Dusty Trades, and had been involved in numerous sampling campaigns in that program. He was also very aware of the various operations carried out in the dusty trades.

Process information has been developed for each of the industry types (mineral commodities); however, production levels, detailed ventilation data, and dimensions of each workplace are generally not included in the records. Many of the workplaces are no longer in existence. From the available records, we summarized known information on engineering controls, the use of protective equipment over the years when cases/controls worked at the site, and occurrences of work stoppages. In addition, the engineering files were searched again to obtain any additional, detailed information on plant/production area design. Health Department reports (*e.g.*, Vintinner *et al.*, 1941) and peer-reviewed literature (*e.g.*, Davis *et al.*, 1983; Dreessen, 1935; Porter, 1949; Renes *et al.*, 1950) also contain silica exposure assessment studies from similar industries in other states over the same period. These can be used to obtain baseline data. Emission factors will be obtained from the literature where available (NC Board of Health, 1939).

All this information for each workplace was summarized in the form of an information packet that was provided to the experts. Based on this information, the experts were asked to provide subjective probability distributions for exposures. It is important to note that, at this stage, the experts were not provided information on the actual historical concentration measurements. The information packets provided to the experts are in Appendix 2.

iv. Variance estimates for task exposures for Bayesian updating

The variance estimates in the data file come from the highest level of aggregation where there were 5 or more data points. The hierarchy and var_src values are:

1. commodity, task, interval, company, location, sample_year

2. commodity, task, interval, company, location

3. commodity, task, interval, company

4. commodity, task, interval

5. commodity, task

6. commodity

The location referenced is the location of the task rather than the location of the company site. So the aggregation can be described as

1. Variance of the raw data for the year, location, company and task.

2. Variance of the raw data for the 5-year interval for the location, company and task.

3. Variance of the raw data for the 5-year interval for all locations for the company.

4. Variance of the raw data for the 5-year interval. for all companies for the task.

5. Variance of the raw data for all companies for all time periods for the task

6. Variance of the raw data for all tasks in the commodity.

The intervals are 5 year periods starting from 1930. In (1) the interval value is redundant with respect to the year. Also note that when the variance lookup was done, it looked for the 5 year interval that contained the observed data rather than looking at a five year period surrounding the observation. This was done for computational reasons (it is easy to pre-compute all variance combinations) but could be changed to look at data in a 5-year window centered around the observation.

v. Combining Expert Judgment and Historical Measurements to obtain Task Exposure Estimates to Silica and Non-silica Dusts

Bayes' Theorem is used to determine posterior probability distributions for exposure histories as follows. Expert judgment is used to obtain prior probability distributions of exposure estimates at every point in time in the period of interest for each job code. These would be input as $P_0(f)$ in Bayes Theorem. A likelihood function for the actual historical measurements is evaluated using the variance in the measurements. This variance is obtained by the procedures described in the previous section. The expert priors and observed measurements are finally reconciled using Bayes' rule to yield posterior probability distributions for exposures for each task exposure.

The task exposures were then used to obtain job exposures and worker exposure histories as described in an earlier section (Sections 1g, 1h, 1i).

c. Lung burden estimation

i. Clearance of Deposited Particles from a Mixed Aerosol (Silica and non-silica dusts)

The clearance of deposited quartz particles depends primarily on the ability of the alveolar macrophages (AM) to detect, phagocytoze, and transport particles to the mucociliary escalator, where they are eliminated from the lung. However, the ability of the AM to remove particles from the alveoli becomes impaired at high particulate lung burdens - a condition described as 'overload' (Bolton *et al.*, 1983; Morrow, 1988). This depression in the clearance rate of particles due to AM overload leads to increased retention and accumulation of particles in the lung; the AM die and release particles into the pulmonary interstitium along with acute inflammatory mediators (Tran *et al.*, 1995). More AM are recruited if the inhaled quartz is not removed, these AM also undergo necrosis and release more particles into the interstitium. It is believed that this cyclic behavior produces chronic inflammation, and ultimately clinical symptoms of fibrosis.

A similar process of altered particle-retention kinetics caused by a depressed AM clearance has also been seen in a number of studies with particles of relatively low cytotoxicity (Morrow *et al.*, 1991; Muhle *et al.*,1990; Mauderly *et al.*, 1994; Bailey *et al.*, 1985). Morrow (1988) proposed that it is the volumetric loading of the AM that ultimately affects their clearance function, and a phagocytozed particulate lung burden of 6% of the normal AM volume is critical for the onset of overload. This corresponds to a volumetric lung burden of ~ 1-3 µl/g of lung tissue or ~ 1-3 mg/g of lung tissue, and is independent of the type of particle (at least for low toxicity particles).

More cytotoxic particles such as crystalline silica also affect clearance rates but at much lower lung burdens. Oberdörster (1995) emphasizes this distinction between more toxic quartz

and less toxic TiO_2, and cautions that not every impairment of AM-mediated particle clearance should be taken as a sign of overload. However, some studies show a clear relationship between clearance half-times in rats with the risks of radiological abnormalities in exposed workers (Soutar *et al.*, 1997).

The severe impairment of clearance induced by silica is correspondingly reflected in the high human risks of radiological abnormalities. For mixed exposures to more toxic quartz and less toxic TiO_2, the situation is more complicated, with some studies suggesting an increase in the clearance half times for the less toxic material as well (McMillan *et al.*., 1989).

Various models have been proposed for the kinetics of deposition and retention of dust in the lung to predict the accumulation of lung burden due to chronic exposures to mineral dusts. Early ideas in this regard assumed that given a constant level of exposure, the lung burden would reach a steady state value, representing an equilibrium between the mass being deposited and cleared. In this early model, the lung was represented by three compartments, described as *fast*-clearing, *medium*-clearing, and *slow*-clearing. The fast-clearance compartment was related to the ciliary clearance process in the tracheo-bronchial region, while the medium and slow compartments were related to macrophage clearance in the interstitium. Each of the compartments followed linear kinetics, *i.e.*, the instantaneous rate at which particulate matter was removed from a compartment was directly proportional to the mass present in that compartment. However, experiments using laboratory rats showed that after an initial non-linear phase, the lung burden increased steadily with time.

Based on these findings, Vincent *et al.* (1987) proposed an additional *sequestration* compartment from which particles are not cleared at all, but sequestered in the pulmonary interstitium. The model equations for the lung burden as a function of time predict experimental data for titanium dioxide exposures quite well. This model does not account for the physiological mechanisms that determine the differences in the rates of clearance of the compartments. Most importantly, the physiological role played by phagocytosis of dust particles and the breakdown of alveolar macrophages are not accounted for. Also, the real compartments in the lung are connected in series, rather than in parallel as in the model.

b. Dose Reconstruction and Calculation of Time to Macrophage Overload

The pharmaco-kinetic model will be used in the following manner. We will use the predictions of this model to estimate lung burden as a function of time. These predictions are, of course, for the rat lung. Thus we will obtain the rate of accumulation of silica and non-silica dusts separately in the rat lung. This will extrapolated to human exposures by appropriately scaling the rat and human breathing rates, as well as the lung burden per unit mass of lung tissue. Such an approach has been used with refractory ceramic fibers (Yu *et al.*, 1994, 1995, 1996, 1997). The following simple example will illustrate our approach.

Let us assume that the output of the exposure reconstruction procedure, described earlier, yielded the following exposure history for non-silica for a particular worker who retired in 1975. We will neglect associated uncertainties for the purposes of this example.

1935 to 1945	0.5 mg/m^3
1945 to 1955	1.1 mg/m^3

1955 to 1965	$1.2 \ \text{mg/m}^3$
1965 to 1975	$0.3 \ \text{mg/m}^3$

We will assume that the worker worked for 5 days/week, 48 weeks/year, and that the breathing rate for the worker is 20 liters/min (In reality, it varies between 12 and 25 liters/min), while that for the rat is 0.1 liters/min, and the human lung weighs 1 kg (range = 0.6 – 1.5 kg), while the rat lung weighs 2 g.

Number of days worked in each 10 year period = 10 x 48 x 5 = 2400 days.

The lung burden accumulation rate is 2-3 (μg/mg m^{-3})/day of exposure. This is the value obtained from rat studies. Expert judgment assesses this value needs to be multiplied by a correction factor to be applicable to humans. This multiplication factor ranges from 3-5. So, the lung burden accumulation rate is 6-15 (μg/mg m^{-3})/day of exposure for humans. A value of 8 (μg/mg m^{-3})/day was chosen for calculations in this study. (This value is assumed to be the same for silica and non-silica dust). Scaling the data for a human, the accumulation rate for the worker will be

$8 \, x \, \dfrac{20}{0.1} = 1600$ (μg/mg m^{-3})/day of exposure. Therefore the cumulative lung burden for the first

10-year period (1935-1945) is = [0.5 mg/m^3] x [2400 days] x [1600 (μg/mg m^{-3})/day] = 1920 mg, or a lung burden of 1.92 mg/g. Thus the total amount of dust retained in the lungs, and the lung burden for each time interval is:

Year	Dust retained	Lung burden
1935 to 1945	1920 mg	1.92 mg g^{-1}
1945 to 1955	4224 mg	6.14 mg g^{-1}
1955 to 1965	4608 mg	10.74 mg g^{-1}
1965 to 1975	1152 mg	11.89 mg g^{-1}
Cumulative Lung Burden		11.89 g

The cumulative lung burden of non-silica dusts in 1975 was 11.89 g. Since overload occurs at a lung burden of ~ 1 mg g^{-1}, this would have occurred around 1945. Thus, our dose metric is the cumulative dust retained in the lung (11.89 g), and the time to overload is 20 years. A similar analysis was performed for silica exposures as well.

We also corrected the above analysis to account for clearance during periods of no exposure for a given worker. The following assumptions were made:

1. If the previous exposure is over a time period of greater than 1 year, then during a no-exposure period the fraction retained is 0.8. So, if the lung burden prior to no exposure is Y_0, then the lung burden at the end of the no-exposure period is 0.8 Y_0.

2. If the previous exposure is over a time period of 6 months to 1 year, then the fraction retained is 0.7. So, if the lung burden prior to no exposure is Y_0, then the lung burden at the end of the no-exposure period is 0.7 Y_0.

3. If previous exposure is over a time period of 1-6 months, then the fraction retained is 0.5. So, if the lung burden prior to no exposure is Y_0, then the lung burden at the end of the no-exposure period is 0.5 Y_0.

e) RESULTS AND DISCUSSION

To analyze the relationship between exposure to silica and non-silica dusts, a case-control analysis of cases of silicosis and matched disease-free controls was conducted. The cases and controls for this analysis had been previously identified for earlier studies of this cohort. The population for this study includes all workers captured by the Dusty Trades program hired after January 1, 1930 or active in their first job as of January 1, 1935. Workers with relevant exposures prior to the initiation of the program were excluded to avoid an underestimation of exposure in these potentially higher exposed workers. The cases were 331 men diagnosed with silicosis from 1935 to 1980.

One to four controls from the same population and time period were selected for each case. Controls were matched by race, five-year birth interval, and year of hire within five years. The controls were also matched by a minimum duration of employment so that the person-time experience of the control population in the Dusty Trades screening program was representative of the cases. A total of 672 controls were identified for 216 of the cases. Eligible controls could not be identified for 115 cases. Two cases and forty-one controls did not have sufficient work history information to permit an exposure assessment and were subsequently dropped from the analysis. These cases tended to be older with longer tenure in the dusty trades. The Dusty Trades program had a policy in the early years of purging records of healthy individuals, thus the pool of eligible controls with complete records was limited for the older workers.

The case-control analysis estimated the risk of silicosis for given estimates of silica and non-silica exposures preceding the radiographic diagnosis of silicosis. Exposure estimates for the cases and controls were indexed to the date the case was first diagnosed with silicosis. Work histories and exposure estimates occurring subsequently were disregarded.

A descriptive analysis of the data initially characterized the exposure distributions for silica and non-silica dusts, estimates of total lung burden, and the estimated time to macrophage overload. The univariate and bivariate distributions of these covariates were evaluated for the entire population and compared between the cases and controls. Due to the matched nature of the study design and the indexing of the control's exposure to the date of diagnosis of the case, the matched design was maintained in the analysis. Conditional logistic regression models were developed to estimate odds ratios for the risk of silicosis for the given exposure metric, and 95% confidence intervals were calculated to describe the precision of these estimates (Breslow and Day, 1980). The independent and joint effects of cumulative silica and non-silica exposures and measures of lung burden were modeled to determine whether the cumulative non-silica exposure modifies the risk of silicosis among exposed workers.

The 214 cases and 631 controls included in the analysis were predominantly white (Table 9). The controls were more likely to be identified as smokers (62 vs 55%), however a larger proportion of the cases had missing information on this covariate. The prevalence of any tuberculosis was low, and a majority of the TB was not confirmed. The controls had more months of employment than the cases (Table 10), however exposure was truncated for the matched controls at the time

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of diagnosis of silicosis. The controls were also modestly younger than the cases; about two years on average.

Table 9. Characteristics of Cases and Controls

	Case		Control		All
	N	%	N	%	N
Smoking Status					
Non-Smoker	53	24.8	198	31.4	251
Smoker	117	54.7	392	62.1	509
No Information	44	20.6	41	6.5	85
Race, black or white					
White	163	76.2	465	73.7	628
Black	51	23.8	166	26.3	217
Tuberculosis status					
No TB detected	200	93.5	615	97.5	815
TB detected	14	6.5	16	2.5	30
Grade of the silicosis					
1	173	80.8	NA.	NA.	173
2	36	16.8	NA.	NA.	36
3	5	2.3	NA.	NA.	5
All	214	100.0	631	100.0	845

Table 10. Total months of employment and year of birth for cases and controls.

		Case	Control	Total
Total months of	N	214	631	845
employment	Mean	396.6	462.7	445.9
	Median	411.0	481.0	464.0
	Min	138.0	103.0	103.0
	Max	614.0	696.0	696.0
Year of Birth	N	214	631	845
	Mean	1917	1919	1918
	Median	1916	1918	1917
	Min	1897	1901	1897
	Max	1945	1948	1948

As would be expected, the cases had a much higher cumulative silica and non-silica dust exposure than the controls. The median silica exposures in the cases was roughly four times the exposure for the controls, however the non-silica dusts were less than twice as high (Tables 11-12). This is consistent with and suggestive of the first study hypothesis that "*A cumulative exposure metric, which includes both silica and non-silica dusts, is more related to the development of silicosis than cumulative silica exposure alone*". The minimum exposures for the cases were suggestive of exposure misclassification, as the lowest exposure were among the cases. In concordance with the exposure distributions of the cases and controls, the median time from first employment to the estimated time of lung macrophage overload was much lower in the cases, 121 vs 181 months. (Table 13). This is consistent with and suggestive of the second study hypothesis that "*The time to macrophage overload is a function of both silica and non-silica exposure, and is related to the development of silicosis*".

Table 11. Total lifetime cumulative silica, non-silica dust, and total dust exposure in mg/m^3*months for silica cases and matched controls from the North Carolina Dusty Trades cohort.

		Case	Control	All
Total Silica exposure mg/M^3*months	N	214	631	845
	Mean	5390.6	3251.3	3793.1
	Median	3309.4	863.9	1325.4
	25th Percentile	915.4	333.4	365.1
	75th percentile	8451.3	3404.9	4647.8
	Min	4.8	16.4	4.8
	Max	26579.8	88356.0	88356.0
Total Non-silica dust exposure mg/M^3*months	N	214	631	845
	Mean	19464.6	12431.4	14212.6
	Median	10707.4	5456.4	6267.7
	25th Percentile	3817.6	2996.7	3176.0
	75th percentile	29043.8	11308.1	14847.6
	Min	31.3	207.2	31.3
	Max	107281.1	353424.2	353424.2
Total dust exposure mg/M^3*months	N	214	631	845
	Mean	24855.2	15682.7	18005.7
	Median	14040.3	6664.5	7690.6
	25th Percentile	5174.4	3585.0	3728.8
	75th percentile	38263.2	14229.2	19773.9
	Min	36.1	252.8	36.1
	Max	133860.8	441780.2	441780.2

Table 12. Total Working Lifetime Cumulative lung burden (mg/Kg lung tissue) of silica, non-silica dusts, and total dusts for silica cases and matched controls from the North Carolina Dusty Trades cohort.

		Case	Control	All
Silica (mg/Kg of lung tissue)	N	214	631	845
	Mean	8609.7	5194.0	6059.0
	Median	5285.3	1382.3	2097.4
	25th Percentile	1371.1	530.5	576.6
	75th percentile	13522.2	5408.1	7436.6
	Min	3.9	21.0	3.9
	Max	42527.6	141369.7	141369.7
Non-silica (mg/Kg of lung tissue) (non-silica dust)	N	214	631	845
	Mean	31089.2	19859.3	22703.3
	Median	17131.9	8708.7	10028.3
	25th Percentile	6108.1	4751.8	5054.6
	75th percentile	46470.1	18087.4	23748.3
	Min	25.0	302.6	25.0
	Max	171649.7	565478.7	565478.7
Total dust (mg/Kg of lung tissue)	N	214	631	845
	Mean	39698.8	25053.3	28762.4
	Median	22326.7	10629.0	12304.9
	25th Percentile	8279.0	5727.8	5966.1
	75th percentile	61221.1	22766.8	31638.2
	Min	28.9	323.6	28.9
	Max	214177.3	706848.4	706848.4

Table 13. Time in months from first employment in the Dusty Trades to the estimated time of lung macrophage overload for silica cases and matched controls from the North Carolina Dusty Trades cohort.

		Case	Control	Total
Number of month since first employment when overload occurred	N	205	595	800
	Mean	143.2	204.9	189.1
	Median	121.0	188.0	172.5
	25th Percentile	54.0	111.0	95.0
	75th percentile	196.0	285.0	270.5
	Min	1.0	1.0	1.0
	Max	523.0	591.0	591.0
Months from Overload to Diagnosis	N	205	NA	205
	Mean	253.0	NA	253.0
	Median	246.0	NA	246.0
	25th Percentile	154.0	NA	154.0
	75th percentile	359.0	NA	359.0
	Min	12.0	NA	12.0
	Max	536.0	NA	536.0

The univariate analysis of silica and other dust exposures indicated strong associations between silica and other dust exposures and silicosis (Table 14). This association was very similar for the cumulative lung burden and cumulative exposure. Accordingly, additional adjusted analyses were done only with one exposure metric of cumulative lung burden. The time to overload indicates that the longer it took for a worker to reach overload the lower the risk of silicosis. This finding is in agreement with the results for exposure. The associations between silica exposure and non-silica dust exposure were maintained when these covariates were considered together in a model (Table 15). Interestingly, the effect of non-silica dust on silicosis was maintained when adjusted for cumulative silica exposure. The time to overload was strongly associated with silicosis development when cumulative exposures to silica and non-silica dust were taken into account. The odds ratios for silica and non-silica dust exposure were, as expected, attenuated when this third metric of exposure was included in the model. Thus, our hypothesis that "*The time to macrophage overload is a function of both silica and non-silica exposure, and is related to the development of silicosis*" is supported by this analysis of the data.

Table 14. Crude odds ratios for silicosis by quartiles of silica and non-silica dust lung burden and cumulative exposure and number of months to overload for silica cases and matched controls from the North Carolina Dusty Trades cohort.

Exposure	Quartile	OR[1]	95% CI
Cumulative silica lung burden mg/kg lung tissue	1	1.0	
	2	1.5	0.9-2.6
	3	2.4	1.4-4.2
	4	6.5	3.5-12.0
Cumulative non-silica lung burden mg/kg lung tissue	1	1.0	
	2	0.6	0.3-1.1
	3	2.1	1.2-3.8
	4	5.4	2.9-10.2
Cumulative silica Exposure mg/M^3*months	1	1.0	
	2	1.4	0.9-2.6
	3	2.5	1.4-4.2
	4	6.5	3.5-12.1
Cumulative non-silica Exposure mg/M^3*months	1	1.0	
	2	0.7	0.4-1.2
	3	2.2	1.2-4.0
	4	5.8	3.1-10.8
Time to overload	1	1.0	
	2	0.9	0.6-1.3
	3	0.7	0.6-1.3
	4	0.6	0.4-0.9

1: Odds ratios estimated with conditional logistic regression thereby accounting for age, period of employment, and duration of follow-up in the Dusty Trades Program.

Table 15. Adjusted odds ratios for quartiles of silica and non-silica dust lung burden and number of months to overload for silica cases and matched controls from the North Carolina Dusty Trades cohort.

Model	Covariates	Quartile	OR[1]	95% CI
1				
	Cumulative silica lung burden mg/kg lung tissue	1	1.0	
		2	1.3	0.7-2.3
		3	2.4	1.2-4.7
		4	2.3	1.0-5.7
	Cumulative non-silica lung burden mg/kg lung tissue	1	1.0	
		2	0.4	0.2-8.2
		3	1.2	0.6-2.5
		4	2.7	1.1-6.8
2				
	Cumulative silica lung burden mg/kg lung tissue	1	1.0	
		2	0.9	0.5-1.7
		3	1.6	0.8-3.2
		4	1.5	0.6-3.8
	Cumulative non-silica lung burden mg/kg lung tissue	1	1.0	
		2	0.4	0.2-0.7
		3	0.7	0.3-1.6
		4	1.2	0.5-3.4
	Time to overload	1	1.0	
		2	0.5	0.2-0.9
		3	0.2	0.1-0.4
		4	0.1	0.04-0.3

1: Odds ratios estimated with conditional logistic regression thereby accounting for age, period of employment, and duration of follow-up in the Dusty Trades Program. The odds ratios are also adjusted for the other terms in the model.

The pattern of association between silica exposure, non-silica dust exposure and silicosis was somewhat different when the data were evaluated on a continuous scale (Table 16). Due to the highly skewed distribution of exposure, these models used a natural log-transformation of the silica and non-silica dust exposure metrics. The effect of silica on silicosis was consistent when adjusted for non-silica dust. The inclusion of an interaction term between cumulative silica and non-silica dust demonstrated significant effect modification of silica exposure by exposure to non-silica dusts. Thus, this supports our hypothesis that "*a cumulative exposure metric, which includes both silica and non-silica dusts, is more related to the development of silicosis than cumulative silica exposure alone*". When the months to overload was entered in the model, both silica and months to overload were significantly correlated with development of silicosis. *These*

models offer additional evidence that the time to macrophage overload influences the development of silicosis, and that earlier exposure appears to be more important than later exposures.

Table 16. Interaction of cumulative silica, non-silica dust lung burden mg/kg lung tissue, and time to overload as continuous covariates for silica cases and matched controls from the North Carolina Dusty Trades cohort.

Model	Covariates	OR[1]	95% CI
1	Log Cumulative silica lung burden	1.484	1.193-1.845
	Log Cumulative non-silica lung burden	1.050	0.786-1.403
2	Log Cumulative silica lung burden	0.679	0.363-1.273
	Log Cumulative non-silica lung burden	0.543	0.313-0.946
	Interaction (silica*non-silica) (p-value for interaction 0.0179)	1.086	1.020-1.157
3	Log Cumulative silica lung burden	1.332	1.065-1.667
	Log Cumulative non-silica lung burden	0.777	0.563-1.072
	Months to overload	0.991	0.988-0.995

1: Odds ratios estimated with conditional logistic regression thereby accounting for age, period of employment, and duration of follow-up in the Dusty Trades Program. The odds ratios are also adjusted for the other terms in the model.

In future analyses, the estimated time to macrophage overload will be included as a time-dependent covariate to evaluate the effects of silica exposure before and after macrophage overload. The odds ratios estimates for silica exposure will be made on linear and categorical scales, based on the intensity and duration of exposure. Separate models will be developed with an exposure lag period of one year to account for disease induction in the interval between the index date and the previous screening.

Limitations of Study

Similar to all observational studies, the proposed research has limitations that cannot be fully addressed in the study design, but must be considered when interpreting the data.

- The diagnosis of silicosis was made through a Workers' Compensation system screening program. For the annual screening, small films are used and if warranted a standard 14 x 17 inch film is obtained for final diagnostic purposes. The standard-sized films have been read using the early system of Grades 1-3 (Gardner *et al.*, 1930). While this is not the generally accepted scheme, it has been consistently used over the full duration of this program. The use of medical screening data to determine the onset of silicosis has some other limitations. Participation in the screening program may have varied over time and the frequency of screening may have been influenced by job classification. The diagnosis of silicosis was made using a subjective scoring system based on the radiographic evidence. The quality of the radiographs and any bias of the reader may have lead to missed diagnoses of silicosis in the controls or delayed diagnosis in the cases. Misclassification of silicotics as controls would lead to an underestimate of risk for that given exposure level. Delayed diagnosis of the cases would result in an overestimation of the exposure needed to initiate disease.

- The onset of silicosis is insidious. The cases were identified using screening methods that may be confounded by other personal habits such as smoking and occupational exposures. The direction of this bias is unknown.

- Exposures that workers experienced prior to employment in the industries captured by the Dusty Trades Program are not measurable, thus some workers may have had exposures that could not be accounted for.

- More than 400 companies have been included in the Dusty Trades. Sampling could not be conducted at all companies each year, and for some operations, a state employee may never have conducted a survey. This is especially true at crushed stone operations, that were often short-term, mobile set ups to support road construction. None-the less the original work resulted in a strong exposure-response relation. Imputation methods have provided stronger relations. The methods proposed in this research will provide additional insights.

Strong exposure-response relations for silica and the development of silicosis have been described in this population. Thus it represents an important resource for extending exposure-response studies to dose evaluations, and the testing of hypotheses regarding macrophage overload and mixed exposures in working populations. The results will increase our understanding of the determinants of silicosis, and provide guidance for further computer updates and analyses of the North Carolina Dusty Trades experience.

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Appendix 1. Number of measurements for each task/commodity

Commodity	Task	Number of Companies	Minimum Number of Data Points	Maximum Number of Data Points	Average Number of Data Points
Asbestos	DRILL	1	1	1	1.0
Foundry	CORE	32	1	6	1.7
Foundry	CUTOFF	13	1	3	1.5
Foundry	FURNACE	8	1	4	1.9
Foundry	GRIND	46	1	12	4.8
Foundry	GRINDFTG	1	1	1	1.0
Foundry	GRINDPIPE	1	2	2	2.0
Foundry	GRINDPORT	36	1	12	4.1
Foundry	GRINDSTAT	40	1	10	3.9
Foundry	GRINDSTATF	1	1	1	1.0
Foundry	MACHSHOP	4	1	3	1.5
Foundry	MOLD	54	1	14	5.9
Foundry	MOLDBENCH	52	1	13	5.4
Foundry	MOLDBENCHF	1	2	2	2.0
Foundry	MOLDBENCHP	1	1	1	1.0
Foundry	MOLDFLOOR	47	1	11	4.7
Foundry	MOLDFLOORF	1	2	2	2.0
Foundry	MOLDFLOORP	1	6	6	6.0
Foundry	MOLDFTG	1	3	3	3.0
Foundry	MOLDPIPE	3	1	3	2.0
Foundry	MULL	29	1	10	4.3
Foundry	OFC	3	1	1	1.0
Foundry	PATTERN	1	1	1	1.0
Foundry	POUR	30	1	5	1.4
Foundry	SBLAST	16	1	2	1.3
Foundry	SHK	43	1	11	3.0
Foundry	SHOP	12	1	2	1.3
Foundry	WHEELABRTR	31	1	8	2.6
Foundry	YARD	1	1	1	1.0
Granite	BAG	1	14	14	14.0
Granite	BURN	2	2	6	4.0
Granite	CHIP	27	1	15	5.0
Granite	CRUSH	3	1	8	4.0
Granite	DRILL	8	1	17	4.5
Granite	LATHE	1	1	1	1.0
Granite	LAYOUT	15	1	10	3.5
Granite	LETTER	12	1	2	1.3
Granite	LOAD	2	1	2	1.5
Granite	PIT	3	1	2	1.3

Granite	PITCH	17	1	8	2.5
Granite	POINT	25	1	20	4.3
Granite	POLISH	12	1	10	2.5
Granite	SAW	9	1	10	2.3
Granite	SBLAST	29	1	18	6.7
Granite	SHED	23	1	14	5.1
Granite	SHOP	6	1	2	1.2
Granite	SURFACE	7	1	6	2.3
Granite	YARD	5	1	3	1.4
Kaolin	BAG	1	17	17	17.0
Kaolin	CAST	1	8	8	8.0
Kaolin	CENT	1	5	5	5.0
Kaolin	CRUSH	1	1	1	1.0
Kaolin	DRY	1	10	10	10.0
Kaolin	FLOAT	1	2	2	2.0
Kaolin	GLAZE	3	1	4	2.3
Kaolin	GRIND	3	1	2	1.3
Kaolin	JIG	1	1	1	1.0
Kaolin	LOAD	3	1	7	3.0
Kaolin	MILL	3	1	2	1.3
Kaolin	MIX	3	2	10	4.7
Kaolin	MUCK	1	1	1	1.0
Kaolin	OFFBEAR	1	1	1	1.0
Kaolin	PRESS	3	1	10	4.3
Kaolin	SCREEN	1	4	4	4.0
Kaolin	SHIP	2	1	8	4.5
Kaolin	SHOP	1	1	1	1.0
Kaolin	SILO	1	1	1	1.0
Kaolin	THROW	2	1	3	2.0
Lithium	BAG	1	6	6	6.0
Lithium	BALL MILL	1	1	1	1.0
Lithium	CRUSH	2	1	7	4.0
Lithium	DRILL	2	1	10	5.5
Lithium	DRY	1	3	3	3.0
Lithium	LOAD	1	2	2	2.0
Lithium	MAGSEP	1	1	1	1.0
Lithium	PEB MILL	1	1	1	1.0
Lithium	SHIP	1	1	1	1.0
Micaspar	BAG	24	1	14	7.5
Micaspar	BATCH	1	10	10	10.0
Micaspar	BOLT	2	1	3	2.0
Micaspar	CENT	1	8	8	8.0
Micaspar	COB	9	1	2	1.1
Micaspar	CRUSH	14	1	16	4.4
Micaspar	DRILL	30	1	6	1.6
Micaspar	DRY	22	1	12	4.2
Micaspar	DSCHG	2	1	2	1.5
Micaspar	DUMP	1	1	1	1.0
Micaspar	EXLONE	4	3	11	5.3
Micaspar	FIRE	9	1	3	1.4
Micaspar	FLOAT	9	1	4	1.8
Micaspar	GRIND	17	1	11	3.6
Micaspar	JIG	1	1	1	1.0
Micaspar	LAB	2	1	3	2.0
Micaspar	LOAD	14	1	4	2.0
Micaspar	LOADMILL	5	1	6	2.6

Micaspar	MACHSHOP	2	1	1	1.0
Micaspar	MAJAX	2	3	4	3.5
Micaspar	MICAHS	9	1	6	2.4
Micaspar	MILL	21	1	10	3.4
Micaspar	MINE	6	1	2	1.3
Micaspar	MUCK	20	1	5	1.7
Micaspar	OFC	3	1	2	1.3
Micaspar	PIT	2	1	1	1.0
Micaspar	PRESS	5	1	2	1.6
Micaspar	SANDPLANT	1	1	1	1.0
Micaspar	SCREEN	19	1	7	2.6
Micaspar	SHED	2	1	4	2.5
Micaspar	SHIP	1	1	1	1.0
Micaspar	SHOP	7	1	2	1.6
Micaspar	SILO	2	1	1	1.0
Micaspar	WRHS	11	1	3	1.7
Micaspar	YARD	4	1	2	1.3
Other	BAG	3	1	9	4.7
Other	BAKE	2	1	4	2.5
Other	CRUSH	3	2	4	3.0
Other	DRILL	1	2	2	2.0
Other	DRY	1	1	1	1.0
Other	GRIND	2	1	1	1.0
Other	MAGSEP	1	1	1	1.0
Other	MILL	2	1	2	1.5
Other	MIX	1	3	3	3.0
Other	MUCK	1	1	1	1.0
Other	OFC	1	1	1	1.0
Other	POLISH	3	1	2	1.7
Other	SAW	1	2	2	2.0
Other	SCREEN	3	1	2	1.7
Other	SHOP	1	2	2	2.0
Other	SURFACE	2	1	2	1.5
Other	WEIGH	1	1	1	1.0
Other	WRHS	1	2	2	2.0
Pyroph	BAG	5	5	18	11.2
Pyroph	BIN	3	1	11	5.0
Pyroph	CRUSH	4	1	10	6.3
Pyroph	DRILL	4	3	8	5.0
Pyroph	DRY	5	1	13	5.8
Pyroph	EXTRUSION	1	7	7	7.0
Pyroph	GRIND	4	2	7	4.8
Pyroph	LAB	1	3	3	3.0
Pyroph	LOAD	5	2	14	7.0
Pyroph	MILL	5	5	17	9.4
Pyroph	MINE	3	1	8	4.0
Pyroph	MUCK	3	1	8	4.3
Pyroph	OFC	2	1	1	1.0
Pyroph	PIT	1	2	2	2.0
Pyroph	SHIP	1	2	2	2.0
Pyroph	SHOP	2	1	2	1.5
Pyroph	YARD	2	1	3	2.0
Quartz	BAG	1	9	9	9.0
Quartz	CRUSH	1	2	2	2.0
Quartz	DRILL	1	1	1	1.0
Quartz	DRY	1	1	1	1.0

Quartz	FIRE	1	1	1	1.0
Quartz	LOAD	1	1	1	1.0
Quartz	MILL	1	7	7	7.0
Quartz	MUCK	1	1	1	1.0
Quartz	PIT	1	1	1	1.0
Quartz	SCREEN	1	1	1	1.0
Rock	CRUSH	3	1	9	4.3
Rock	DRILL	4	1	9	4.0
Rock	GRIND	2	2	9	5.5
Rock	MINE	4	1	6	3.0
Rock	MUCK	4	1	8	3.5
Rock	SHOP	1	1	1	1.0
Rock	TABLE	1	7	7	7.0
Rock	YARD	1	1	1	1.0
Stone	CATHOLE	6	2	11	5.0
Stone	CRUSH	31	1	24	5.4
Stone	DRILL	27	1	23	4.5
Stone	DRY	3	1	4	3.0
Stone	LAB	3	1	2	1.7
Stone	LOAD	13	1	12	3.6
Stone	MIX	3	1	1	1.0
Stone	OFC	2	1	1	1.0
Stone	PIT	16	1	11	2.8
Stone	PUGMILL	3	1	6	3.3
Stone	SCREEN	14	1	12	3.5
Stone	SHOP	4	1	5	2.3
Stone	SWITCHRM	9	1	7	3.2
Stone	TOWER	5	1	5	2.6
Stone	TUNNEL	4	2	5	4.3
Stone	WAREHS	3	1	3	2.0
Stone	YARD	9	1	8	1.9
Talc	BAG	2	1	13	7.0
Talc	CRUSH	3	1	2	1.3
Talc	DRILL	3	1	5	2.7
Talc	DUSTER	1	1	1	1.0
Talc	GRIND	3	1	8	3.3
Talc	MINE	1	4	4	4.0
Talc	MUCK	3	1	5	2.3
Talc	PACK	3	1	9	3.7
Talc	SAW	3	1	15	6.0
Talc	SHOP	1	1	1	1.0
Talc	YARD	1	1	1	1.0

Appendix 2. Information Packets Provided to Experts

Crushed Stone

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Quarrying Techniques:

After removal of the over burden by bulldozer, stone quarries are deepened to as much as 200 feet and worked horizontally. Drilling and blasting methods are adapted to local conditions; several types of drills are used (jack hammer, plug, wagon, well).

Large blocks remaining after the initial blast may be reduced by additional blasting or dropball. Compressed air is commonly used to clear dust from the drill holes. **Muckers, car and truck loaders and general laborers** do much of materials handling work. Large buckets are loaded by **power shovel operators and hoist men.** Other quarry jobs include **blacksmith and tool grinder** who supply the proper drilling equipment.

Crushing techniques:

At the plant, stone is fed sequentially to a primary and secondary crusher. Each is monitored by a **feeder operator or crusher attendant** who general stone yard works if the crusher is not operating. In the past a **cat - hole man** monitored where the crusher discharges to a conveyor to maintain smooth operation at the transfer point and shovel spilled material back onto the conveyor. **Machinists, carpenters and oilers** work in close proximity to the crusher .The crushed stone is sized by screening and loaded into trucks or cars. **The car loader** may assist in crusher repair and pumping, as needed. A **superintendent** oversees the quarry and crusher. **Laboratory personnel** test the stone on-site.

Throughout the crushed stone industry, **the laborer** is the predominant job.

Environmental Control Measures:

- **1928-** Cat-hole men received respiratory protection in 1928 at one quarry .Drillers used respirators at some locations when operating dry.

- **Early 1930s-** Wet drilling was introduced at some quarries but dry drilling

-

- Continued to be used into the 1960s.

- Spray bars reduced dust at the crushers; however, use was intermittent due to disrepair, particularly during winter and spring months.

- **Intrinsic Emission:**

Quartz Content:

Location	n	Arithmetic Mean and Standard Deviation (% SiO2)
Plant	51	29.32 ± 14.40

- **Principal Producers of Crushed Stone in North Carolina.**

Company	Quarry Location
Bryan Rock and Co.	
Lassiter quarry	Rolesville
Neverson quarry	Sims

- Buchanan Stone Co.   Greensboro

  Grey stone granite quarries Co.

     Greystone quarry   Greystone

- Lambert Brothers, Inc.

     Pelham quarry   Pelham

- Piedmont Quarries Co.

     Winston- Salem quarry   Winston- Salem

     Guil quarry   Stokesdale

- Superior Stone Co.

     Mcleansville quarry   Mcleansville

     Woodleaf quarry   Woodleaf

- Whitlow Brothers

     High point quarry   High point

     CC quarry   Jamestown

- State of North Carolina   Various localities

- **Handling:** Drilling and blasting operation at the quarry and also the use of compressed air to clear dust from the drill holes. Breaking and crushing operations at the plant.
- **Local Control:**

1928- At some sites Drillers and cat-hole man used respiratory protection.

Early 1930s- At some quarries wet drilling was used.

Job Title Summary

Job Title	Location	Other possible duties
Driller Jack hammer Plug Wagon Well	Quarry	Compressed air blowout, blasting
Mucker	Quarry	Car and truck loader
Laborer	Quarry	Muck, drill, crusher attendant
Crane operator	Quarry	
Power shovel	Quarry	
Hoist operator	Quarry	
Blacksmith	Yard and shop	

Tool grinder	Shop	
Pumper	Quarry	
Crusher attendant	Crusher plant	Yard work 25%
Cathole man	Crusher plant	
Screen attendant	Crusher plant	
Car loader	Crusher plant	Repair crusher, load, pump
Superintendent	Crusher plant and quarry	
Machinist	Shop	
Carpenter	Crusher plant	
Oiler	Crusher	
Laboratory	Crusher plant	
Officer personnel	Crusher plant	

Dimension Stone (Granite)

The Quarrying Process

Basically, granite quarrying involves cutting channels on all sides of large, rectangular sections of granite called quarry blocks. These blocks usually have an open face, and once the ends and backs of the doorstep-like ledges are channeled loose, horizontal lift holes are drilled along the bottom of the open face. The holes are then loaded with primer cord explosive and the resulting blast has just enough force to break the quarry block from the bed of the quarry. Then jackhammers drill 3-in.-deep holes about 6-in. apart the length of the block and steel wedges and shims are inserted in the holes. The wedges are hit with sledgehammers and the long length of granite cracks loose. This section is then cross-cut by further drilling and wedging into individual saw blocks, usually three to four feet wide, three to four feet high, ten to twelve feet long, and weighing nine to ten tons. The dimensioned saw blocks are removed by derrick or mobile crane and shipped to monument plants for processing. Small pieces are moved with a towmotor by a **banker.** A steady supply of steel at the drill site is maintained by **the steel carrier**. **A tool boy** grinds and carries tools and bits to the **driller; blacksmiths** repair and form drill bits. After careful examination, the granite selected for finishing is started on its way through the various manufacturing processes.

The Manufacturing Process (Sawing Methods)

To transform the huge block of rough granite into smaller pieces for manufacturing, the block must be sawed into "slabs".

The Polishing Process

After most slabs are sawed, they are polished to a high gloss by automatic or manually-operated machines which grind, hone and buff the granite surfaces with water and abrasive grit or polishing bricks.

In a manually-operated system, the slab is placed flat in a large wooden box called a "bed" which is lined with heavy sheet metal to repel the water and abrasive during the polishing process. The **operator** manually guides a heavy revolving "scroll" wheel over the slab as abrasives and water smooth and hones the surface of the stone. The scroll wheel is removed and another steel circular emery ring wheel is attached.

Three different grades of emery abrasives are used. Large grains of silicon carbide are first used; then follow a medium grain, and the last grain is very fine, giving the slab a smooth honed finish. An experienced **polisher** will know when the granite has reached the stage where he will remove the emery wheel and attach a heavy buffing wheel which has thousands of tiny compressed felt pads inserted between steel rings. These soft pads

are coated with a mixture of water and tin or aluminum oxide powder, and slowly guided over the entire slab until a brilliant mirror-like polish has been accomplished. From the time the scroll wheel was first attached, to the final application of the buffing wheel and powder takes about 45 minutes.

Shaping a Monument

The slabs then move via bridge crane or roller conveyor to the Breakout Department. Shop tickets specifying the sizes and shapes of an individual monument are taped to the large slab and the **breakout man** uses chalk to line off the slab to conform to the monument sizes required by the shop tickets.

The **stonecutter** uses a special pencil to line off the granite pieces to the specific monument size. His hammer strikes the pitching tool and pieces spawl off as he shapes the monument to the previously applied monument dimension line.

The shaped unit then moves to a profile grinding machine which grinds the top or ends to conform to a given shape. This machine traverses across a wooden pattern or "profile" of the monument shape, which may be straight, oval, serpentine, concave or some other configuration.

After the top and ends are shaped, the monument moves to the Top and End Polishing Department where a mirror-like polish is applied to the top and/or ends by small polishing heads.

The Sandblast Engraving Process

The monument then goes to the **Engraving Department** where the fascinating artistic process of carving symbols and letters in granite is accomplished. First, liquid glue is applied to the surface so that a sheet of rubber-like stencil will bond to the granite securely. While the glue dries, the stencil is carefully spread then pressed onto the polished surfaces. In the meantime, **a draftsman** has been preparing a pattern or "layout" of the exact size and contour of the monument. He has used a thin tracing paper in making this "full size detail" which will contain the family name, inscriptions, floral or other design. Metal letters of proportioned sizes have been selected form the variety of lettering styles available. As the paper is rubbed with a flat object, the carbon will imprint the letters on the backside. The draftsman now layouts the carved floral design. This requires an artistic talent for he must be exact in every minute detail in getting the correct size leaves and flowers or other ornamentation in proportion to the size memorial to be carved.

The full-sized layout is placed over the rubber stencil, the carbon backing is rubbed and transfers the carving and lettering to the stencil. Next, a rubber cutter guides his razor sharp knife along the tiny lines made by the carbon reproduction. As each line is cut, the stencil is pulled from the surface and discarded leaving the sections of granite underneath exposed to the sandblast abrasive.

The monument is next moved to the **metal sandblast room**....powerful lights insure that the **operator** has a perfect view of each line. The operator stands outside the room, his hands protected by heavy rubber gloves. He holds the large rubber air hose inserted into a 4-in. long, tapered ceramic nozzle through which abrasive exits under 100 pounds of air pressure. The operator sprays abrasive evenly into each exposed area of the granite while the uncut stencil portions reflect and protect the polished surface. Through his years of experience, the sandblast operator knows when the correct depth has been achieved to bring out the contrast and beauty of the letters and the shape-carved flower designs.

When this has been completed, the monument is moved by overhead crane and deposited on the wash rack. Live steam removes the remaining glue and tiny particles of stencil. A soft fiber brush is used for the final cleaning. The monument dries thoroughly and is carefully wrapped in heavy paper or plastic to protect the highly polished surface from scratches while enroute to its destination.

Environmental control measures:

Before 1930- Exhaust ventilated tools were in place in one shed. Respirators were frequently provided as interim protection as plants installed exhaust ventilation.

1936- Dust samples collected revealed that occasionally the surfacing machine operator is exposed to an excessive amount of dust even when the exhaust was in operation.

1939- North Carolina cutting sheds revealed that surface cutters occasionally were exposed to as much as 752 million particles of granite dust per cubic foot of air; pneumatic hand tool operators were exposed to as much as 100 million particles; and that the air of sand blast rooms may contain more than 1 billion particles of sand dust per cubic foot of air. No roof ventilators were there. In many small plants the sandblast operator used virtually no protection against the inhalation of dust. In one of the small sheds the sandblast operator wore only a handkerchief over his nose. In several small plants only a hood was used, and although this device protected the worker against the cutting action of the flying sand, it did not keep out the fine dust. In some plants the operator worked inside the sand blast room, where he was protected by a positive pressure air helmet.

1946- No local exhaust ventilation for the surfacers and all pneumatic tools. No sandblast cabinet was there to permit the operator to be stationed outside. Nose type respirators instead of the dust type approved the US Bureau of Mines.

1949- No proper protective measures were there for sandblasting. No exhaust hoods for stone cutters.

1951- No dust collector was used and the dust laden air was exhausted directly to the atmosphere outside the shed.

1961- Exhaust system not so efficient. No respirators for drillers. Pointing, grinding and drilling operations were done in open shed with no proper exhaust ventilation.

1962- Dry carborundum wheel was used and the operator did not wear the proper respirator.

1963- Poor exhaust ventilation. The bagging machine exhaust had very poor face velocity due to deterioration of the complete collecting system.

1964- Pure sand was used as an abrasive in the lettering booth. Chipping of small stones was done without an exhaust

- **Intrinsic emission**

    Quartz content –

Location	n	Arithmetic mean and Std. deviation (%SiO2)
Plant	44	25.38 ± 14.59
Surface	6	27.02 ± 16.77

- **Principle Producers of Dimension Stone in North Carolina**

Company	Quarry Location

- Harris Granite Quarries Co.

Balfour quarry	Granite quarry (Central Piedmont)
Carolina quarry	Granite quarry (Central Piedmont)

- J.A. Logan Granite Co.

Faith quarry	Faith

- North Carolina Granite Corp.

Mt. Airy Quarries	Mt. Airy

- Salisbury Granite Industries, Inc.

Collins-Durax Quarries	Granite quarry (Central Piedmont)

- **Local Controls**

  Not Available

- **Handling**

  Drilling and blasting during quarrying and use of pneumatic hand tools, surfacers and polishers (types of machines) during the finishing operation.

- **Particle size distribution:**

Size Range	Particle Count	Size Range	Particle count	
<0.5	10	<0.24*	0	0
0.5-0.99	86	0.25-0.49	8	10
1.0-1.49	79	0.5-0.74	48	47
1.5-1.99	17	0.75-0.99	52	39
2.0-2.49	1	1.0-1.24	46	67
>=2.5	7	1.25-1.49	16	12
		1.5-1.74	12	11
		1.75-1.99	2	6
		2.0-2.24	9	0
		2.25-2.49	3	1
		>=2.5	6	7

* Two sets of data

Job Title Summary:

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Job Title	Location	Other possible duties
Drill/blast	Quarry	
Breaker	Quarry	
Banker	Quarry	
Steel carrier	Shop and quarry	
Water boy	Quarry	
Blacksmith	Quarry and shop	
Tool boy	Quarry and shop	
Derrick operator	Quarry edge	
Truck driver	Various	
Sawyer	Shed or yard	
Hand tool operator	Shed	
Surface machine	Shed	
Polisher	Shed	
Layout	Shed	Cut rubber, hand chisel
Letterman	Shed	Power hand tools
Crater	Shed	Saw work cleanup
Shipping	Shed	
Sandblast	Shed	Cutstone33-50%
Foreman	Shed	All jobs
Combination	Shed	3 hour sandblast 1 hour layout 4hour polish
Setter	Cemetery	

Feldspar

Mining and milling techniques:

In each mining method, some drilling may be required by the miner to loosen the less weathered material. Pick and shovel work predominated in early, small operations. Feldspar cobbed from the material mucked at the mine site was forked into wheel barrows and loaded into trucks for transport to the mill. Larger activities requiring frequent drilling employed **steel carriers and a blacksmith.**

Raw ore was crushed and dried to remove moisture prior to grinding. Magnetic separators removed iron-bearing impurities; quartz was removed by air classification after milling. Feldspar was shipped either in bags or boxcars. In the latter case, loaders assured even distribution in the boxcar during filling. **Oilers, mechanics and general laborers** completed the mill crew.

The development of froth floatation made the recovery of feldspar from alaskite possible. This technique renders the feldspar aerophilic, causing it to rise to the ₅₃surface in the froth when air is bubbled through. A

pulp is first formed by the wet grinding of the ore to at least 48 mesh and dilution to 25-45% solids. Reagents are added to modify the surfaces and to coat the feldspar with an aerophilic pulp. The recovered feldspar is then washed, dried and milled.

An example of the plant operation in the year 1958 is as follows:

Raw ore was initially delivered to a primary crusher. After leaving this crusher it was conveyed on to a stock pile fro storage until removed from below, via a tunnel belt, and delivered to secondary crushers, located in an adjacent isolated building. These crushers received their ore and in turn processed it for delivery above and into storage bins supplying the plants extensive floatation system. While passing through the floatation system the feldspar is separated and removed into separate silos for drainage.

After drainage is completed feldspar is screwed out of the bottom of the silo and conveyed into rotary driers. Upon completion of the drying process water is re-added and feldspar is again washed into drainage silos for re-entry into the rotary driers and eventually conveyance above and into the "batch room" where the various sized feldspar is separated and stored into the hoppers.

As different mixtures are desired chutes are pulled on designated hoppers and the material is mixed via a system of open belts. These belts eventually convey the mixture into the "mill room" where six dry roller mills grind it down to the finished product. Upon completion of this phase of operation the material is elevated up and into its designated silo for storage until needed for bagging.

The bagging operation occurred in two areas and under contrasting conditions. In one area, located inside the plant, one man operated an enclosed exhausted valve-type bagging machine. The second area was located at the base of the storage silos on the outside where a movable unexhausted valve-type bagger was used.
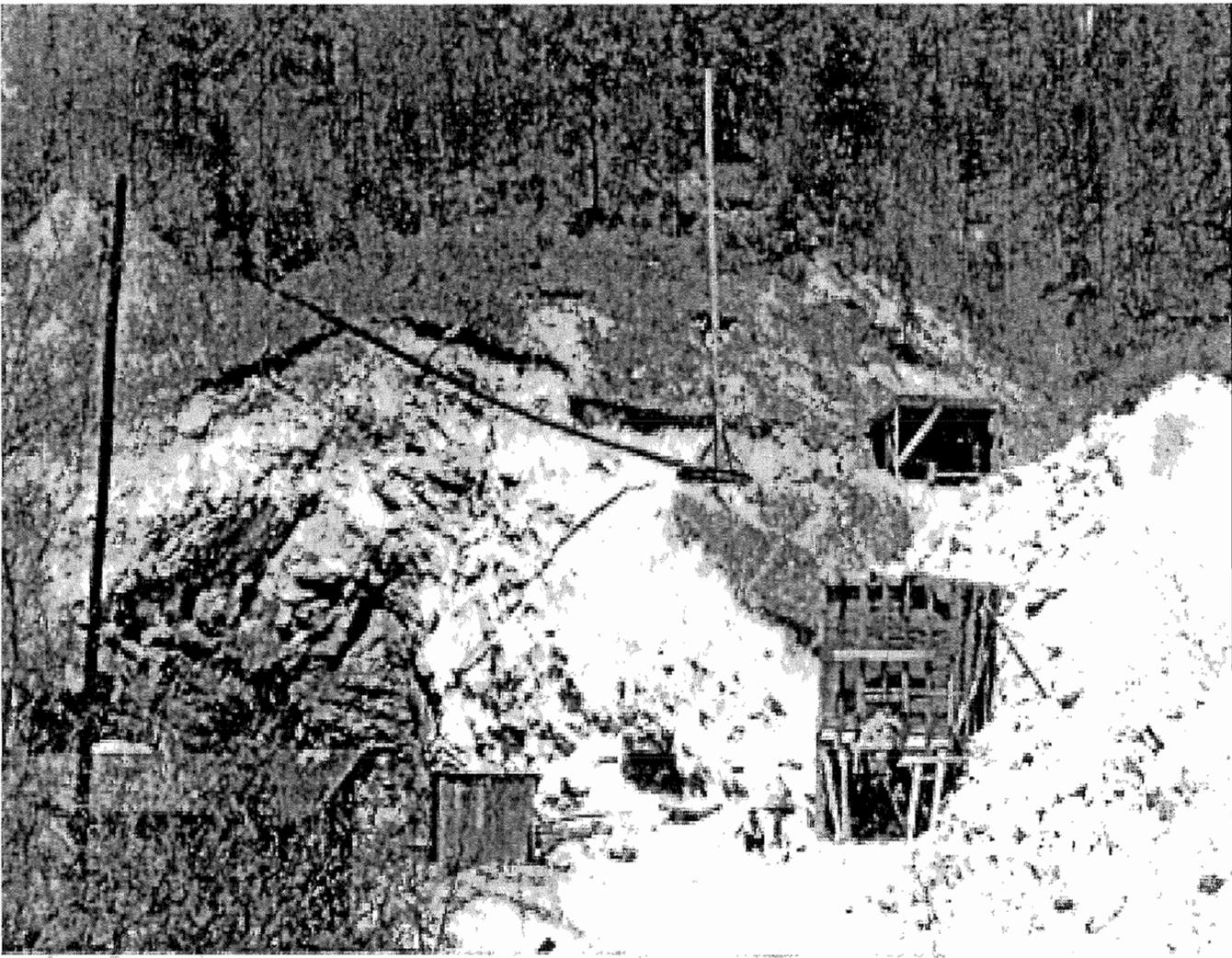
B. Cox No. 1 mine. Upper part of main working at left, beneath derrick boom.

- **Environmental Control Measures:**

1930s- Respiratory protection was available to many workers engaged in loading, crushing, oiling and mill operations.

1940- The roll mills were not enclosed in the metal housing .

1942- A mine in this period could be 100 feet deep and reached only by a shaft. This mine could have as many as 8 men employed. Wet drilling was used. Presence of carbon monoxide in some of the mines showed the absence of sufficient ventilation.

1943- No wet drilling.

1958-The exposure to the clean up man was above the maximum allowable concentrations because of use of brooms instead of vacuum type cleaner. No proper exhaust ventilation in the crusher and drier house.

1961- No proper dust respirators.

1962- No proper respirators.

- **Intrinsic Emission:**

  Quartz content:

  Location   n   Arithmetic mean and Std. Dev. (%SiO2)

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- **Principle Producers-** Not Available
- **Handling:** Drilling and crushing operations were performed during the mining and milling.
- **Local Control:**

  1930s- Respiratory protection was available to many workers engaged in loading, crushing, oiling and mill operations.

- **Particle size distribution:** Not Available

Job Title Summary

Job Title	Location	Other Duties
Driller	Underground or surface	Drill, pic and shovel
Mucker	Underground	
Forker	Underground	
Cobber	Underground	
Steel carrier	Mine and shop	
Blacksmith	Surface and shop	
Shovel operator	Pit	
Truck driver	Surface	
Crusher operator	Mill	
Drier operator	Mill	
Mill operator	Mill	Load mill
Magnetic separator	Mill	
Grinder	Mill	
Flotation operator	Mill	
Loader/bagger	Mill	
General labor	Mill	bag, crush, sweep
Oiler	Mill	
Repairmen	Mill	
Mechanic	Mill	
Laboratory	Mill	

Foundry

Production Techniques:

Patterns and cores were used to form the molds into which molten metal is poured. The pattern was packed in specially prepared sand and then removed, leaving the impression in sand box. The compound high in silica content had been used as a parting material. Most metal was heated in cupola furnaces, although electric arc furnaces were in use in some foundries.

When the casting had hardened, a **shake-out worker** or **general laborer** removed the outer box, allowing

the casting to fall free of the sand. In North Carolina, much of the shakeout was done on the foundry flour. Completely cooled castings were cleaned in tumblers or shot booths, and then ground on wheels. Some castings may be specially polished, electroplated or painted at the foundry. **General laborers and yard men** perform any of the above tasks, except molding.

Environmental Control Measures:

1936- A foundry could have as many as 26 employees. The plant could be housed in a frame structure that was approximately 50 feet by 60 feet. Additions to this main structure accommodated bench molding, core making, and the pattern shop. In this main structure was located the cupola, the tumbling mill, emory wheel, revolving steel brush, the core baking oven and the two molding floors. The structures were of loose construction and permit free circulation of air through them. In the tumbling mill operation much fine dust escaped into the atmosphere. The emory wheel and revolving steel brush upon which castings were cleaned were located only about 6 feet from the mill. The castings cleaning devices were not isolated from the other foundry operations. The men engaged in cleaning castings did not wear respirators while at work. There were no devices employed for the control of dust.

1936- Plants generally had three exhaust ventilation systems serving respectively the tumbling mills in the casting cleaning department, the grinders in the stove mounting department and the grinding and buffing wheels in the finishing department. Some of the general observations in one of the foundries during that period were that the fine dust escaped from dust collectors and air filters. Much of it blew back to the stove mounting department and into the foundry building. The tumbling mills in the casting cleaning department discharged much burnt sand onto the floor and into the air during the first few minutes of the operation after loading. All grinders in the stove mounting department were operated with the top part of the hoods thrown back. These practices reduced the efficiency of the exhaust ventilation system. None of the exhaust duct connections to mills and grinders were provided with blast gates.

1938- Sand blasting was employed for cleaning castings in many plants, but in no instance was the worker adequately protected to prevent inhalation of silica dust except where commercial sand blast cabinets were employed for cleaning small machine parts. The universally employed safeguard was a canvass helmet with which in a few plants a common type filter pad respirator was used. In none of the plants the positive pressure air line helmet was employed. None of the foundries were mechanized in North Carolina to the extent that some of the large ones were in other states. Molding was confined to floor and bench work. All shakeout work was done with hand.

Cores were removed manually. There were no automatic sandblasting units or barrels in use. In only one plant the tumbling barrels and grinding wheels were adequately exhausted. In all only 6 plants out of 32 surveyed at that time had attempted to control dust by exhaust ventilation.

1939- An examination of foundry revealed that the most flagrant sources of dust were mechanical sand conditioning, casting shakeout and casting cleaning. It was found that the dust concentrations for sand conditioning exceeded 100million particles and one was as great as 527 million.

1942-Sand blasting exposed the worker operating the sand blast equipment to an atmosphere containing 324.3 million particles of dust per cubic foot of air. Much of this fine dust was quartz sand used in sand blasting and some of it was molding sand. Workers grinding castings a short distance from the sandblasting operation were exposed to 48 million particles of dust per cubic foot of air. The grinding wheels were not hooded and exhausted. There was no ventilation in the brass molding room.

1947- Workers did not wear the approved dust type respirators during the shake out operations.

1950- High exposure in the casting cleaning department.

1960- No forced dilution fans.

1965- Employees working in the casting cleaning and grinding room of the foundry were subjected to a definite health hazard.

Intrinsic Emission:

Quartz Content:

Location	n	Arithmetic mean and Std. Deviation
Plant	82	32.39±8.52

- **Principle Producers-** Not Available

- **Handling:**

Patterns and cores are used to form the molds into which molten metal is poured. When the casting has hardened, a shake-out worker or general laborer removes the outer box, allowing the casting to fall free of the sand.

- **Local Controls:**

1938- Only one plant had exhaust ventilation and no person doing abrasive blasting was adequately protected.

- Particle size distribution: The median particle size of various samples ranged from 0.5 to 2.3 microns.

Job Title Summary

Job Title	Location	Other duties
Pattern maker	Pattern shop	Mold
Core maker	Pattern shop/ foundry floor	Mold
Sand mixer	Foundry floor	
Molder, helper	Foundry floor	Cut/ temper sand, shake out prepare cores
Shakeout	Foundry floor	
Tumbler	Cleaning area	Cut /temper sand, shake out
Sandblast	Cleaning area	Cut /temper sand, shake out
Cupola tender	Cupola	Clean casing, assist molder yard work
General laborer	Various	All jobs, except mold
Yardman	Yard	Material handling
Shipping	Foundry floor	
Office/ clerical	Office	
Superintendent	Various	All jobs

Kaolin

Mining and Milling techniques:

In 1930s kaolin was mined from pits by hydraulic methods and sluiced to nearby plants, or removed by power shovel. Around 1980s power shovels were used exclusively. The kaolin is recovered from the crude ore, consisting of clay, quartz, fine muscovite mica and minor amount of garnet and biotite by washing .Various settling techniques are used to remove quartz and garnet. The slurry is screened to separate mica, and kaolin is removed from suspension by flocculation. The sludge is pumped to filter presses. **Off-bearers** remove cakes to steam-fired drying racks. **Clay** 58**throwers** break the drying cakes, allowing the clay to

fall through the lattice of drying racks into storage bins below. The kaolin is loaded into box cars or bagged. An example of the plant operation in the year 1938 is as follows:

The crude ore was scraped out of the pit bank with a power shovel and dumped in a pile near the manhole, through which the ore was shoveled onto a conveyor belt. The conveyor belt carried the ore into the plant. Here a series of wet screening and washing operations separated the kaolin. The kaolin, freed from practically all impurities, left the preliminary processing department suspended in water. This suspension was treated with filtered alum and passed through a series of settling tanks. The alum precipitated the kaolin.

The settled kaolin was pumped to stock tanks. From the stock tanks the kaolin which was now in the form of thin aquas sludge, was pumped to filter presses for dewatering. The moist filter-pressed cakes of kaolin were transferred by hand to wheeled dryer racks which, when full were transferred to drying kilns. Upon their removal from the drying kilns, the kaolin filter- press cakes were conveyed to an elevator that discharged on to an overhead conveyor belt which delivered the kaolin to the storage building. The dried cakes were removed manually from the dryer cars, usually by two men who threw them into the elevator feed hopper. Near the top of the hopper there was a grating which served to break up the cakes as they were thrown into the hopper. This was the only operation in the plant that exposed worker to dust, all prior processing being done wet. The figure below shows a kaolin mine.
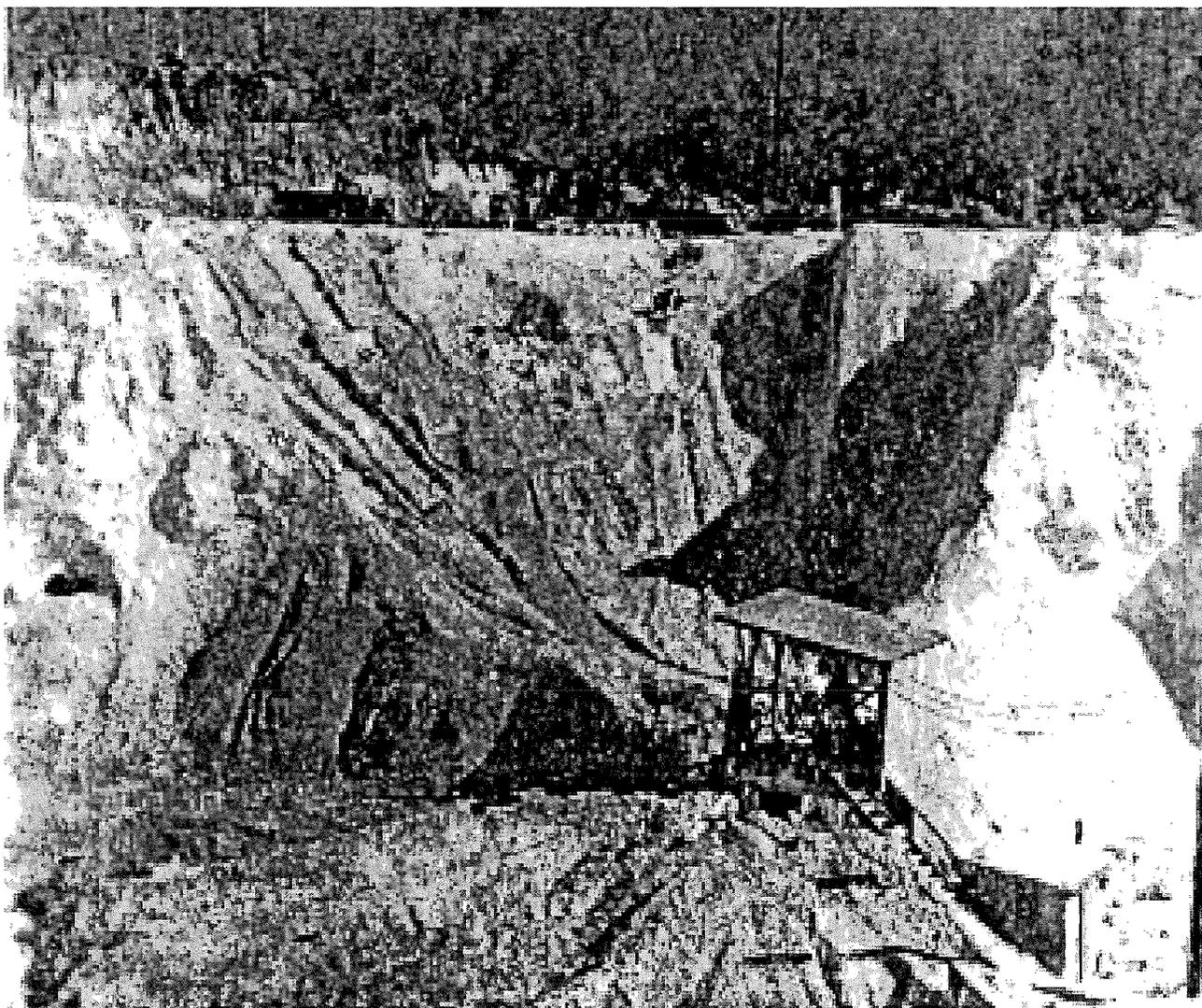

Fig. 2.—Mine of Kaolin, Incorporated, near Spruce Pine, N. C. Note thick overburden of stratified gravel, sand, and clay in left background.

- **Environmental Control Measures:**

  Late 1930s- Respirators were available in dusty trades.

  The use of water in recovering the kaolin limits dust generation prior to drying of the cakes.

  1938-The men who removed kaolin cakes from the dryer car and threw them in the elevator feed hopper were exposed to 83 million particles of dust per cubic foot of air.

  1942- Kaolin was delivered by trucks to a covered bin at a railroad siding. The discharge chute from the bin delivered to a conveyer belt loader which was set up in the box car. Thus mechanism delivered the material from the car door to the end of the car. A man attending this conveyor was exposed to 169 million particles of dust per cubic foot of air.

- **Intrinsic Emission:**

  Quartz Content:

Location	n	Arithmetic mean and Std.Dev. (%SiO2)
Plant	17	30.27±15.20

- **Principle Producers-** Not Available

- **Handing:** Use of hydraulic methods and power shovels in mining.

- **Local Controls:**

  Late 1930s- Respirators were available in dusty trades

- **Particle Size distribution:**

Size Range	Particle count
<0.99	153
1.0-1.49	29
1.5-1.99	13
2.0-2.49	1
2.5-2.99	3
>=3.0	1

Job Title Summary:

Job Title	Location	Other duties
Driller	Surface	
Shovel operator	Surface	
Truck driver	Surface	Unload
Settling tank	Washing plant	
Screener	Washing plant	
Floatation	Mill	
Filter press operator	Mill	
Off bearer	Mill	
Clay thrower	Mill	Off bearer
Loader/bagger	Mill	

Superintendent	Mill	
Maintenance	Mill	All over

Pyrophyllite

Mining and Milling techniques:

In 1980s underground mining jobs included **driller, timber and mucker. Miners** usually mucked and set timers and drilled occasionally. **Muckers** loaded the raw mineral into trammer cars. **The cager and hoist operator** supervised transfer of the ore to the surface. In early mining operations, mules pulled cars which were dumped into large hopper; cage cars were loaded from this hopper by the **chute puller**. Pit mines are worked by conventional mechanical means and ore is trucked to the mill.

Ore is crushed and screened prior to milling. The miller oversees pulverizers and air separator. The finished product is bagged or loaded into rail cars for bulk delivery. Mill support jobs include **hand truck men, cleanup, oiler, lab workers, engineers and repair crew.** The figure below shows a pyrophyllite mine.

- **Environmental Control Measures:**

    1933- Respiratory protection was made available in one plant under a pay incentive program. Use varied by area; bagger consistently used the masks.

    Mid 1930s- Some wet drilling was introduced.

    1936- Plant ventilation had been constantly upgraded since 1936.

    1945- Local exhaust ventilation was not effective

    1958- No adequate dust respirators.

    1960- Respirators were present but most of them were not fitted with appropriate dust filters.

    1964- Employees used respirators not approved by the U.S. Bureau of Mines. Some of the common problems were bursting bags and spillage from the same, exposure from loading old stock out of storage. Exposure from loading into boxcars and closed trucks. Exposure due to sweeping the floor of the plant.

B. Open Pit Mine

- **Intrinsic emission:**

  Quartz content:

Location	n	Arithmetic mean and Std. dev. (%SiO2)
Plant	30	49.05±17.22
Surface	1	53.90
Underground	1	20.00

- **Principle Producers-** Not Available

- **Handling:**

  Drilling operations are performed during mining

  - **Local control:**

  1930s- Respiratory protection was made available in one plant. Bagger consistently used the masks. Some wet drilling was introduced.

Particle Size Distribution:

Particle size range	Particle count
<0.5	5
0.5-0.99	109
1.0-1.49	48
1.5-1.99	6

2.0-2.49	10
2.5-2.99	7
3.0-3.49	9
3.5-3.99	2
>=4.0	4

Job Title Summary

Job title	Location	Other duties
Driller	Underground	
Trammer	Underground	
Chute puller	Underground	Muck 33%
Mule driver	Underground	
Cager	Underground	Drill
Hoist man	Surface	
Truck driver	Surface	
Power shovel	pit	
Crusher attendant	Mill	
Screener	Mill	
Miller	Mill	
Laborer	Mill	
Hand truck man	Mill	
Oiler	Shop and mill	Half- time in shop
Inspection	Mill	
Bagger	Mill	
Foreman	Mill	All over
Watchman	Mill and surface	
Laboratory	Mill	
Cleanup	Mill	
Magnetic/clerical	Mill	

Quartz

Mining and Milling Techniques:

Quartz is mined from veins and pegmatites for use as exposed aggregate in architectural concrete, oscillator plates, and prism sand other optical products. The development of froth floatation process resulted in recovery of quartz as a byproduct.

Several industries produce quartz as a byproduct. The recovered quartz is either in-house or bagged and shipped elsewhere for grinding.

- **Environmental Control Measures:**

  Since quartz processing may be intermittent, control of employee exposure is generally accomplished by use of respirators. Plants in continuous operation employ wet techniques.

  1970- Water was not used in the crushing operation. Operators did not use the respirators.

- **Intrinsic Emission:** Not Available

- **Principle Producers-** Not Available

- **Handling**: sent elsewhere for grinding.

- **Local control:** Respirators were available

- **Particle size distribution:** Not Available

Job Title Summery

Job Title	Location	Other duties
Grinder	Mill	
Bagger	Mill	

Lithium

Mining and Milling techniques:

Spodumene, a lithium ore, is loosened by blasting in benched pit mines. Waste and crude ore trucked out of the pit for crushing. After treatment similar to that described for feldspar, the lithium mineral is separated from other rock by froth floatation. Some grades are further concentrated by sizing and magnetic separation. The acid leach process has also been applied. Mill feed is heated to convert the ore mineral to the more soluble form; after cooling, the ore is ground in the presence of acid and roasted to produce lithium sulfate. The sulfate is leached from the ore and lithium carbonate and lithium hydroxide recovered from the liquor.

- **Environmental Control Measures:**

  1962- Respirators were made available to employees.

  1974- One company retrofitted its crusher with wet dust suppression equipment.

- **Intrinsic Emission:** Not Available

- **Principle Producers-** Not Available

- **Handling:** Blasting and crushing operations are performed in the mines.

- **Local control**

  1962- Respirators were made available to employees.

- **Particle size distribution:** Not Available

Job Title Summery:

Job Title	Location	Other duties
Driller	Pit	
Mining supervisor	Pit	

Drop ball	Pit	
Shovel operator	Pit	Shovel maintenance
Oiler	Pit or crusher	
Truck driver	Surface	
Primary crusher	Crushing plant	
Secondary crusher	Crushing plant	
Screener	Crushing plant	
Grinder/Classifier	Mill	
Flotation	Mill	
Sizing	Mill	
Magnetic separation	Mill	
Kiln	Acid leach plant	
Acid treat	Acid leach plant	
Recovery	Acid leach plant	
Welder	Shop	
Electrician	Shop	

Talc

Mining and Milling techniques:

Work performed by under ground mining personnel conforms to typical underground mining job titles. The duties of a miner may include mucking, timbering, and drilling with jack hammer and core drills. Ore loosened by drilling is hand shoveled into tram cars or buckets for transport to the surface. Drill helpers work on the surface carrying steel and bits.

General laborers may also do support work at the surface and drive trucks to the mill. In open pit operations, shovel operators load trucks which transport the ore to the mill. Materials in blocks, which will be marketed as slabs or crayons are sawed to the desired dimension by hand at slab, finish and dowel saws. A sawyer also called a cutter operates all three types of saws as required. A primary crusher, followed by roll mill is generally used to pulverize talc to 100-200 mesh. All mill work is supervised by the mill operator; inspectors and lab personnel are in charge of quality control. Finished crayons are boxed for shipment by packers; crushed talc is bagged.

An example of plant operation in the year 1958 is as follows:

The raw ore, from the mines was dumped into three bins with one supplying the crayon section and the other two supplying the bagging plant. The ore from the two bins connected to the bagging plant, was conveyed into the hopper feeding a

"Raymond Mill". Here the talc was ground into a fine powder with the larger particles being delivered directly via air ducts into a storage hopper above the bagging machine, while the finer particles were funneled into the "socking leg collector" where they were collected and then delivered to the storage hopper. This fine powder was then bagged and stored in the plant awaiting the removal.

The raw ore from the single bin, supplying the crayon section was chuted onto a platform containing a "rough cut or circular bench saw" which gives a rough shape to the block. A single slabbing or smaller bench saw then shaped the blocks for introduction into the stocking machine which was an automatic abrasive wheel cutter. This machine reduced the blocks to Crayon slized slabs which were then fed into a "crayon

machine" for production of square pencil-like strips of talcs. Some of these rectangular sized crayons were then packaged, while others were fed into a 'rounder" used in making a more polished crayon. Women worked in adjoining room where they packaged the crayons. This area was separated from the main work room by a wall, containing several small chutes through which the finished crayons were delivered for packaging.

- **Environmental Control Measures:**

  1937- Respiratory protection was introduced at saws in some mills.

  1955- Wet Drilling.

  1959- No adequate respiratory protection.

  1960 -Poor exhaust ventilation for the bagger.

  1962- Poor house keeping practices.

  1972- Blow back of waste material in the crayon room.

- **Intrinsic emission:**

  Quartz Content:

Location	n	Arithmetic mean and Std. Dev. (SiO_2)
Plant	3	1.49 ± 0.06

- **Principle Producers-** Not Available

- **Handling:**

  Drilling in mining operations.

- **Local Control:**

  1937- Respiratory protection was introduced at saws in some mills.

  1955- Wet Drilling.

- **Particle size distribution:** Not Available

- **Job Title Summery:** Not available

Hard Rock Mining – Tungsten

Mining and Milling Techniques:

The under ground **miller** drills and blasts ore and rock loose from the mine .Ore is loaded into cars by the **mucker** for transport to the surface. **Muckers** also care for the tools and the laying and clearing of track.

All ore crushing and concentration was done in the mill. The jaw crusher was followed by screens, jig and table separation. Froth floatation was used to remove sulphides. After drying, a magnetic separator removed iron-bearing impurities.

- **Environmental control measures:**

  Natural water entering the North Carolina tungsten mine assisted in dust suppression.

  1952- A new crusher with better enclosure and ventilation was installed in the mill.

  1952- Respirators were made available at the same time.

- **Intrinsic emission:**

  Quartz content:

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Location	n	Arithmetic Mean and Std. Dev. (%SiO_2)
Plant	1	13.40
Underground	1	20.00

- **Principle Producers-** Not Available

  - **Handling:**

    Drilling, blasting and crushing operations were carried out in the ore.

  - **Local Control:**

    1952-new crusher with better enclosure and ventilation was installed and respirators were made available.

  - **Particle size distribution:**

Size Range	Particle count
<0.5	40
0.5-0.99	127
1.0-1.49	26
1.5-1.99	7
2.0-2.49	0
2.5-2.99	0
>=3.0	0

Job Title Summary

Job Title	Location	Other duties
Drill	Underground	
Mucker	Underground	Look after tools, lay and clear track.
Crusher man	Mill	Monitor conveyors
Tableman	Mill	
Drier	Mill	
Magnetic separator	mill	
Watchman	Surface and mill	

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