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Original Article

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A Quantitative Retrospective Exposure Assessment for Former Chrysotile Asbestos Miners and Millers from Baie Verte, NL, Canada

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Abstract

Despite numerous studies of asbestos workers in the epidemiologic literature, there are very few cohort studies of chrysotile asbestos miners/millers that include high-quality retrospective exposure assessments. As part of the creation of the Baie Verte Miners' Registry in 2008, a two-dimensional job exposure matrix (JEM) was developed for estimating asbestos exposures for former chrysotile asbestos miners/millers. Industrial hygiene data collected between 1963 and 1994 were analysed to assess validity for use in a retrospective exposure assessment and epidemiologic study. Registered former employees were divided into 52 exposure groups (EGs) based on job title and department and mean asbestos concentrations were calculated for each EG. The resulting exposure estimates were linked to individual registrants' work histories allowing for the calculation of cumulative asbestos exposure for each registrant. The distribution of exposure for most EGs (82.6%) could be described as fitting a log-normal distribution, although variability within some EGs (55%) exceeded a geometric standard deviation (GSD) of 2.5. Overall, the data used to create EGs in the development of the JEM were deemed to be of adequate quality for estimating cumulative asbestos exposures for the former employees of the Baie Verte asbestos mine/mill. The variability between workers in the same job was often high and is an important factor to be considered when using estimates of cumulative asbestos exposure to adjudicate compensation claims. The exposures experienced in this cohort were comparable to those of other chrysotile asbestos miners/millers cohorts, specifically Italian and Québec cohorts.

Keywords: asbestos; asbestos exposure; chrysotile; exposure assessment; exposure estimation; exposure groups; mining

Introduction

It is well recognized that exposure to all forms of asbestos is associated with the development of malignant and non-malignant diseases, most notably asbestosis, mesothelioma, and cancers of the lung (IARC, 2012). Positive associations have also been observed between asbestos exposure and cancers of the pharynx, stomach, ovary, and colorectum (Institute of Medicine, 2006; Fortunato and Rushton, 2015). However, there has been much debate regarding the relative potency of the various types of asbestos (i.e. chrysotile as opposed to amphibole asbestos fibres) in the causation of lung cancer and mesothelioma. To address this debate, several meta-analyses have attempted to elucidate the potency factors for lung cancer and mesothelioma associated with exposure to different forms of asbestos fibres (Hodgson and Darnton, 2000; Berman and Crump, 2008a,b; Lenters *et al.*, 2011; van der Bij *et al.*, 2013). Data from epidemiological studies of workers exposed primarily to crocidolite, amosite, chrysotile, or to mixed fibres in various asbestos industries (i.e. textile, mining/milling, friction products, cement products, and insulation) have been used in these risk assessments. However, to assess the relationship between chrysotile asbestos exposure and disease risk, studies have primarily relied on the quantitative exposure assessment of the Québec miners' cohort (Liddell *et al.*, 1997). This has limited the evaluation of the risk of asbestos-related diseases in workers exposed to chrysotile asbestos only, especially with respect to industry type.

Generally, there has been a paucity of studies on chrysotile miners/millers. The existing literature consists primarily of studies of the Québec cohort (Liddell *et al.*, 1997), an Italian cohort (Du *et al.*, 2012), and more recently a Chinese cohort of chrysotile miners/millers (Wang *et al.*, 2012, 2013; Ren *et al.*, 2013). Furthermore, the published reports on these studies do not contain sufficient information to evaluate the quality of the data used in the exposure assessment or to draw conclusions regarding the reliability of exposure estimates that are often used for epidemiologic or compensation purposes.

In 2008, a new cohort of chrysotile asbestos miners/millers from Baie Verte Newfoundland, Canada was enumerated. The Baie Verte asbestos deposit was discovered in 1955 and mining began in 1963. From 1963 to 1990, the open pit mine was operated by Advocate Mines Ltd (a division of the Johns Manville Company) and Transpacific Asbestos Ltd using dry milling techniques to extract the fibres. In 1990, Terra Nova Ltd took over operations and utilized wet processing methods to extract fibres from the tailings. The mine/mill employed approximately 500 people at any given time over the operating years, with the exception of Terra Nova Ltd which employed 90 employees. Approximately 1.3–1.6 million tonnes of asbestos fibres were produced over the entire life span of the mine/mill (Rennie, 1999; AMEC, 2005).

In this article, we describe exposure patterns among a group of former employees of the Baie Verte chrysotile asbestos mine/mill. We also describe the methods used for reconstructing historical exposures and the development of a job exposure matrix (JEM) for this group of workers taking into account changes in job tasks, control measures, and process changes. Finally, we describe the statistical techniques used to evaluate the quality of the data used to develop the exposure estimates.

Materials and methods

Baie Verte Miners Registry

The chrysotile asbestos mine/mill in Baie Verte Newfoundland, Canada became active in the mid-late 1950s and began commercial operations in 1963. Production of asbestos continued for 31 years until the mine's final closure in 1994. In 2008, the Baie Verte Miners' Registry (BVMR) was established as a joint effort between the provincial Workplace Health, Safety and Compensation Commission, Memorial University, and the United Steelworkers Union of Canada. The purpose of the BVMR was to register as many of the former employees of the Baie Verte asbestos mine/mill as possible to gather information regarding vital status, employment history, medical history, and current health status in order to assist former employees and the provincial workers' compensation board in the compensation process. One of the key elements of the BVMR was the development of a retrospective exposure assessment using historical industrial hygiene data obtained from government, company, and union records, and the estimation of each registered employee's cumulative asbestos exposure. The details of the BVMR are described elsewhere (Bornstein *et al.*, 2013).

Exposure assessment

To estimate individual cumulative asbestos exposure, average asbestos concentrations for each job title in the departments within the mine/mill complex, for determined time periods, were calculated and incorporated into a two-dimensional JEM. Standard approaches proposed by Seixas and Checkoway (1995) as well as the Environmental Protection Agency (1994) were used to develop the JEM and to assess each registrant's exposure.

The BVMR's exposure assessment utilized two separate sources of industrial hygiene data. One source was from a study done at the mine/mill in the early 1980s (Edstrom, 1982) that used industrial hygiene samples collected by company and union representatives from 1966 to 1975 using the historical midget impinger method (Parsons *et al.*, 1986). The other source contained the results of airborne asbestos samples that were collected at the mine/mill from 1976 to 1994 using the National Institute for Occupational Safety and Health (NIOSH 7400) membrane filter method (1994). These sources will be described separately. As part of the BVMR, detailed employment history was obtained for each registrant and used in conjunction with the JEM to calculate estimates of cumulative asbestos exposure.

Industrial hygiene data: 1976–1994

Data for the time period 1976–1994 were obtained from monthly lists of routine air sampling results provided by the national office of the United Steel Workers of Canada, and an intensive 4-month government study carried out in 1980 (Louch, 1981). This included data from approximately 7000 personal and stationary samples collected by the company, the union, and the provincial government which were extracted, entered into a spreadsheet and reviewed for quality. The data were organized according to the job title and job code (see Supplementary Table S1, available at *Annals of Work Exposures and Health* online edition) of the individual wearing the sampling device, the department of the mine/mill where that individual worked, the year the sample was collected, and any other pertinent information noted in the records. Between 1976 and 1994, air samples were collected using the membrane filter method at a flow rate of 2 l min^{-1} for 1–2 h. Fibre counting was done according to NIOSH Analytical Method 7400. Approximately 11% of the sampling data were either averages of multiple samples collected on the same day for the specified job title (representing approximately 50–100% of the worker's shift) or were time-weighted averages (TWAs) of two to four samples per job title/person. TWA data came from the 1980 dataset with 85% of the data representing more than 80% of the shift of the person being sampled. Less than 2% of the samples were reported as 0 f ml^{-1} and were excluded from analysis.

In addition, the personal sampling data (n = 900) from the 1980 government study, as well as personal sampling data from company records for the years 1991–1994, were used to estimate the between-worker and within-worker components of variance for various job titles. These datasets contained repeated samples for multiple identified workers allowing for the calculation of the components of variance in the exposure data using analysis of variance (ANOVA) techniques. We also used the 1980 dataset to evaluate the reliability of the 1–2 h samples that make up the majority of the overall dataset.

Industrial hygiene data: 1963–1975

Data for the time period 1963–1975 were obtained from an unpublished study by Edstrom. In this study, Edstrom reports the results of stationary air samples collected by the company and government using the midget impinger method, and how these data were analysed and used to develop location-specific conversion factors for the various areas of the mine/mill complex where these samples were collected. These conversion factors were used to convert dust and fibre measurements to average asbestos fibre concentrations (f ml^{-1}) for each of the following locations: Pit, Crusher, Dryer, Screening, Refining, Bagging, Erection and Repair, and Other (e.g. lunchroom, offices). The average fibre concentrations, in conjunction with estimates of the amount of time workers in each job title spent in these various areas, were then used to calculate an area/time-specific estimate of exposure for the different job titles for each quarter-year from 1963 through 1975. These quarterly averages were converted to yearly averages in the JEM for the period from 1963 to 1975. The methods used by Edstrom in the calculation of the location-specific conversion factors are described by Parsons *et al.* (1986). The yearly area-specific conversion factors used to calculate exposure estimates for this time period ranged from 4.8 in the 'Pit', 1971, to 52.4 in 'Other' areas in 1973, and are reported by Parsons.

Exposure groups

Exposure groups (EGs) were defined according to job title and department and were used to define the vertical axis of the JEM. Time period defined the horizontal axis since airborne asbestos concentrations decreased over time as various control measures and changes in the refining process were implemented. Yearly average asbestos concentrations were calculated for each department and were examined graphically to identify groups of consecutive years that appeared to be similar in terms of exposure. These were then grouped into nine 'year categories' covering the years 1963–1994 which comprised the horizontal axis of the JEM. Year category groupings were supported by an evaluation of the timeline of changes in the mine/mill processes (Table 1) as ascertained from

Table 1. Process changes and control measures at the Baie Verte asbestos mine/mill.

Year	Control measures
1964	Drills used in Pit fitted with dust collectors
1970	Jute bags replaced with reinforced plastic film bags in packaging area; vacuum system installed in crusher/dryer building system
1972	Installation of ventilation in secondary crusher/dryer building to bring in outside air
1973	Dust masks made available to all workers
1975	Vacuum tables set up in mill for screen repair and at the dock for pallet repair
1976	Replacement of dust control equipment on paddle trammels; water added to tailings conveyor system to reduce dust emissions
1978–1980	14-Week worker strike; baghouse in secondary crusher/dryer building completed; automatic bag opener and refeed system installed in packaging area; car wash introduced; mobile lunch rooms; pressurized cabs for tractor operators; dedusters added to tailings system to recover fibres lost to tailings; mine 'dry' constructed with showers, double lockers and a change house; dust control system added to dry rock storage building
1988	Construction of wet mill begins
1990–1994	Wet methods used in processing of tailings

interviews by members of the BVMR team with former employees and a review of company records detailing technological changes, control measures, and production changes. The grouping of years was also supported by comparing the departmental yearly averages using a one-way ANOVA to assess the adequacy of the assigned year categories as predictors of exposure.

Personal samples were available for almost all the EGs and were preferred over stationary samples in assigning exposure estimates. The only exception was the 'Stevedore' job title for which stationary data were used since no personal samples were available (likely due to the fact that, for most of the mine's operating lifetime, stevedores were employed through an external contract rather than being directly employed by the mining company). Other job titles for which little or no sampling data were obtained (i.e. no personal samples or relevant stationary samples) were grouped with job titles that were deemed similar in terms of their physical location within the workplace and tasks performed according to the detailed job descriptions found in union records.

To create the EGs, relevant data for job titles that were considered to be similar with respect to the tasks performed or location of work were evaluated using independent sample *t*-tests to statistically compare average exposures (by year category) to ensure the adequacy of each grouping. Some job titles were subdivided according to the area within the department where the samples were collected. For example, 'Forklift Operator' was separated into two EGs—'Mill Forklift Operator' and 'Warehouse Forklift Operator'. A brief description of the departments can be found in Table 2.

The resulting JEM contained EGs along the vertical axis and calendar period (year categories) along the horizontal axis. The JEM was entered into an SPSS syntax file and linked to the work history records of each registrant through the job code (see Supplementary Table S1, available at *Annals of Work Exposures and Health* online edition) and year category fields in order to calculate a time-weighted estimate of exposure. The exposure estimates for all the work history records for each person (assembled primarily from company personnel files and information from miner's medical reports) were then summed generating a cumulative exposure estimate for each person based on his/her specific job history.

Data analysis

To validate the grouping of exposure data into EGs, the log-normal distribution model was used (Bullock and Ignacio, 2006). In this model, it is presumed that the underlying distribution for workplace exposure data is the log-normal distribution. This assumption was verified for each EG using the raw data from the 1976-to-1994 dataset and the IHStat™ statistical tool, which uses the Shapiro–Wilk test for log-normality, created by the American Industrial Hygiene Association for the evaluation of occupational exposure data (AIHA, 2010). Log-transformed data for each EG were also analysed for goodness-of-fit to the log-normal distribution using both the Kolmogorov–Smirnov and the Shapiro–Wilk tests of normality in SPSS. Cumulative probability plots and frequency histograms were used to visually inspect the data for log-normality. Descriptive statistics, including arithmetic means (calculated by the Minimum Variance Unbiased Estimate method) and Land's Exact 95% confidence intervals, and geometric standard deviations (GSDs) were generated for each EG for each year category.

For EGs that were found to have a bimodal distribution (through examination of the frequency histogram) non-parametric measures of the mean and variance, rather than the arithmetic mean, were used to estimate exposure. Sensitivity analyses were conducted to determine the difference in cumulative exposure estimates for workers in these job titles, depending on which of the two exposure

Table 2. Departments, process descriptions, and number of EGs at the Baie Verte asbestos mine/mill.

Department	No. personal samples	No. EGs	Description
Mill (M)	2778	23	Primary and secondary crushing of ore; drying of crushed material and storage while awaiting processing, screening, and packaging; workers exposed to dust in ambient air in all areas of the mill
Pit (P)	445	12	Open pit mine; ore blasted from bench and transported with shovels and loaders; workers exposed to dust in ambient air from drilling and tailings
Erection & Repair (E&R)	1118	12	Maintenance of vehicles, garage, cleaning of vehicles; workers exposed to dust in ambient air and from vehicles
Employee Relations (EmpRel)	73	1	Laundry services and janitorial services; this department was located in a separate building; workers exposed to dust on clothes during laundry duties and in ambient air
Office Services (OS)	41	1	Stores; located in E&R building, kept parts and materials needed for operation; exposed to dust in ambient air
Quality Control (QC)	289	2	Testing fibre grades; laboratory located in mill; workers exposed to dust in handling and collecting of raw material and in ambient air
Office	29	1	Office employees, located in various offices around mill, pit and E&R; workers exposed dust in ambient air
Total	4773	52	

scenarios was used to assign a value to the JEM. Also, data from both the 1981 government report (Louch, 1981) and the 1991–1994 documents were used to apportion the between-worker and within-worker variance using the ANOVA methods outlined by Ogden and Lavoué (2012).

Sample size was also used to evaluate the quality of the cells in the JEM for the period 1976–1994 for which raw data were available. This was based on criteria described by the EPA (1994) and the AIHA (Bullock and Ignacio, 2006) which suggest that 6 samples are the minimum required to judge the exposure acceptability of an EG, 10 measurements will provide a reasonable approximation of the exposure distribution, and at least 30 measurements are needed to conduct rigorous goodness-of-fit testing. Cells with less than 6 samples were considered to be 'poor' quality, 6–10 samples 'fair', 11–29 samples 'good', and cells with more than 30 samples were considered to be 'very good' (Bullock and Ignacio, 2006). That is, if an EG had more than 30 samples for a specific time period that cell in the JEM would be considered to be of 'very good quality' from a statistical perspective. On the other hand, if there were fewer than six samples available, the data in this JEM cell would be considered to be 'poor' quality.

Results

EGs

The total number of EGs was 52. The data for most EGs (n = 43) could be adequately described as fitting a log-normal distribution while a small number of EGs (n = 6) fit a normal distribution and three EGs were bimodal. GSDs ranged from 1.74 ('Forklift Operator-Warehouse') to 5.61 ('Senior Tester'), with 45% of the GSDs falling below 2.5, 35% between 2.5 and 3.0, 16% between 3.0 and 4.0, and 4% over 4.0. The vast majority of the GSDs in the Mill (92%) were below 3.0, while the Pit had 35% of its GSDs between 3.0 and 4.0, indicating more variation in exposure within EGs in the Pit than in the Mill. This may be due to the effect of weather on the dust levels in the Pit or to the variability of the amount of asbestos in the ore.

Using sample size as an indicator of the quality of the exposure estimates in each cell of the JEM a large proportion (89.8%) was found to qualify as 'good' or 'very good' quality (Table 3), whereas only 1% of all cells would be considered 'poor' quality. Also, there were only minimal differences across departments with respect to the percentage of cells that fell into the 'good' and 'very good' categories, ranging from 77.7% (QC) to 95.8% (E&R).

Three job titles ('Primary Crusher Attendant', 'Service Truck Driver', and 'Dry Rock Storage Attendant') were found to be represented by a bimodal distribution, rather than a log-normal or normal distribution, for at least one of the defined year categories. For example, Figs 1 and 2 show the frequency distribution and cumulative probability plot for 'Primary Crusher Attendant'. The data for this group were split into its two frequency

Table 3. Evaluation of the quality of the cells in the JEM (1976–1994) for each department of the Baie Verte asbestos mine/mill complex.

Department	≤6 samples/cell 'Poor'	>6 and ≤10 samples/cell 'Fair'	>10 and ≤30 samples/cell 'Good'	>30 samples/cell 'Very good'	Total # of cells
Mill	—	4 (8.2%)	14 (28.6%)	31 (63.3%)	49
E&R	—	1 (4.2%)	11 (45.8%)	12 (50.0%)	24
Pit	1 (6.35%)	2 (12.5%)	8 (50.0%)	5 (31.35%)	16
QC, OS, and EmpRel	—	2 (22.2%)	4 (44.4%)	3 (33.3%)	9
Overall	1 (1.0%)	9 (9.2%)	37 (37.8%)	51 (52.0%)	98

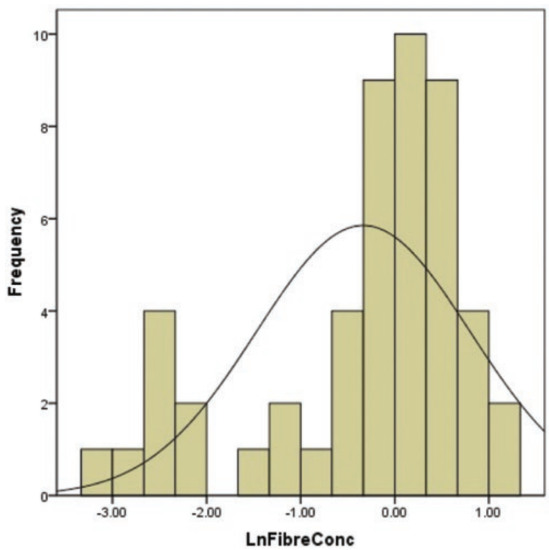

Figure 1. Frequency distribution for 'Primary Crusher Attendant' for the years 1980–1984, showing bimodality of the frequency distribution.

distributions and analysed separately. As shown in Table 4, the values that would be assigned to the cell of the JEM vary considerably depending on which of the two frequency distributions is used. If the lower peak is used, the value in the JEM would be 0.08 f ml^{-1}. This would mean that a person who spent 10 years during this time period working as a Primary Crusher Attendant would be assigned a cumulative asbestos exposure of 0.8 fibre-years ml^{-1} (i.e. 0.08 f ml^{-1} × 10 years = 0.8 f ml-years^{-1}). On the other hand, if we assign the value associated with the second peak (1.31 f ml^{-1}), the same person would be given a cumulative exposure of 13.1 fibre-years ml^{-1}, which is over 16 times greater than if we used the mean of the lower peak. In this case, taking into consideration the number of samples associated with each distribution (8 versus 42, respectively) and the exposure estimates for the year categories immediately before and after the time period in question, the higher peak was used to assign the value to the JEM. The same assumptions were made for the 'Service Truck Driver' and 'Dry Rock Storage Attendant' EGs for which the lower peaks also contained small sample sizes (n = 6 and n = 4, respectively).

From June to September 1980, the government collected 1004 asbestos samples at the mine/mill, with results provided for 970 (34 of the samples were not analysable). The sampling strategy was set to take sufficient consecutive samples to cover the full shift. The 970 samples represented 320 shifts with an average of 3 samples per 8-h shift, and 6 of the samples were single (TWA) samples only. The mean of the consecutive shift samples was calculated and compared with each of the individual samples that made up that mean. Of the 964 comparisons only 87 (9.0%) of the measurements had a difference from the mean that was greater than the error range of the NIOSH Method 7400 (i.e. less than −49% or greater than 213%). Thus, we are confident that the shorter duration samples are representative of the actual mean given the analytical error associated with the fibre counting analysis technique.

Exposure: 1963–1975

According to the data that were extracted from the 1982 Edstrom report, the highest exposures in the 1963–1975 time period were for the jobs 'Shuttle Operator', 'Primary Crusher Operator', 'Dryer Operator', 'Secondary Crusher Operator', and 'Dry Rock Storage Attendant'. All these jobs were located in the mill and had an average exposure of 66.55 f ml^{-1} at their peak in 1968. Overall, exposure during these years was highest in the Pit department (Table 5) and lowest in the Employee Relations department. Exposures in all departments peaked during 1967–1968 and gradually decreased over time (Fig. 3). This pattern can be attributed to the refinement of the process and higher production in the early years, followed by the implementation of

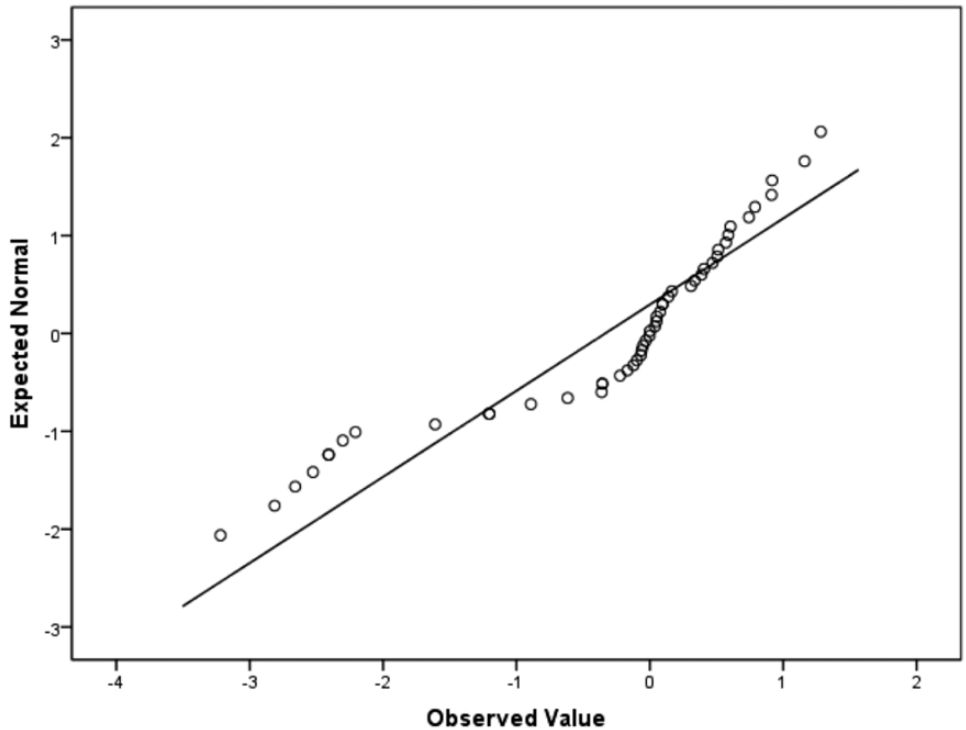

Figure 2. Cumulative probability plot for 'Primary Crusher Attendant' for the years 1980–1984, showing bimodality of the frequency distribution.

Table 4. Descriptive statistics for the two frequency distributions of Primary Crusher Attendant for the year category 6.

Statistic	Peak 1 (n = 8)	Peak 2 (n = 42)
Mean (f ml^{-1})	0.08 (0.07–0.10)	1.31 (1.12–1.58)
Log-normal	Yes	Yes
Geometric mean	0.08	1.09
GSD	1.39	1.83
95th percentile	0.13	2.96
Median	0.09	1.07
Mode	0.09	1.00–1.50
JEM value (f ml^{-1})	0.08	1.31

control measures (Table 1) in the mine/mill in the later years [particularly in the wake of the Selikoff report (Selikoff, 1976) and the strike which combined to reduce the airborne concentrations of asbestos fibres].

Exposure: 1976–1994

Generally, exposures decreased over time in all departments of the mine/mill complex (Fig. 3) and airborne concentrations of asbestos varied considerably between EGs and departments over the entire period (Table 5). The EG with the highest exposures during the 1976–1994 time period was 'Dry Rock Storage Attendant' with an overall average exposure of 3.19 f ml^{-1} and a maximum exposure of 18.8 f ml^{-1} in 1980. This position was responsible for regulating the flow of ore between the dry rock storage area (where ore was stored after it had been dried) and the mill. The average yearly concentration of asbestos fibres for this EG ranged from 7.45 f ml^{-1} in 1976 to 1.76 f ml^{-1} in 1990. Figs 4 and 5 show the frequency distribution and cumulative probability plot of the log-transformed data for 'Dry Rock Storage Attendant'. These graphs demonstrate the goodness-of-fit of the log-transformed data to the log-normal distribution. The lowest exposed job during the time period 1976–1994 was 'Backhoe Operator' in the Pit department with an average exposure of 0.08 f ml^{-1} and a maximum of 0.26 f ml^{-1} in 1982.

Components of variance

The analysis of the between- and within-worker variance was used to evaluate the reliability of the use of job titles in the creation of the EGs by comparing the exposure variability of individual workers with the exposure variability of an overall EG. Groups with less

Table 5. Average fibre concentration (f ml⁻¹) by department for all year categories.

Department	1963–1966[a]	1967–1968[a]	1969–1971[a]	1972–1974[a]	1975[a]	1976–1979	1980–1984	1985–1990	1991–1994
Mill	18.13	28.17	12.94	7.83	1.76	2.24 (1.90–2.58)	1.55 (1.45–1.65)	1.11 (1.04–1.19)	0.89 (0.77–1.02)
Pit	41.90	37.74	18.29	9.40	1.93	0.43 (0.32–0.54)	0.28 (0.23–0.33)	0.23 (0.17–0.29)	—
E&R	16.81	21.80	9.12	4.55	0.94	0.85 (0.63–1.08)	0.59 (0.50–0.68)	0.46 (0.40–0.52)	0.37 (0.31–0.45)
QC	12.99	22.19	8.87	6.12	1.56	1.17 (0.65–1.69)	0.91 (0.68–1.15)	1.03 (0.73–1.33)	1.32 (0.45–2.19)
EmpRel	6.12	8.81	3.69	2.15	0.44	—	0.16 (0.08–0.23)	0.06 (0.04–0.08)	0.09 (0.06–0.12)
OS	8.45	13.81	4.78	2.60	0.50	0.46 (0.16–0.76)	0.14 (0.07–0.21)	0.04 (0.02–0.06)	—

[a]95% confidence intervals are not given for the years 1963–1975 since raw data were not available.

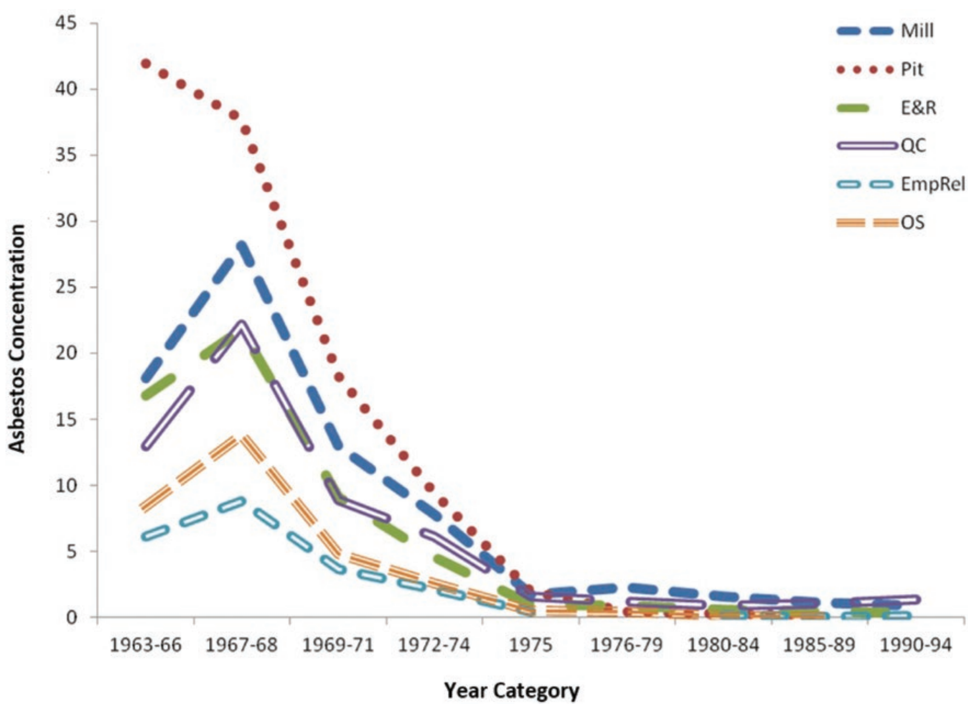

Figure 3. Yearly average concentrations of asbestos fibres, 1963–1994, in the various departments of the Baie Verte mine/mill complex.

than 20% between-worker variability are considered to be adequately representative of the exposure experienced by all members of that particular group and the value assigned to the JEM is considered to be appropriate for all workers within that EG (Bullock and Ignacio, 2006). On the other hand, EGs with more than 20% between-worker variability can be indicative of dissimilar exposures amongst members of that group and the value assigned to the JEM will likely underestimate some workers' exposure and overestimate that of others.

Overall, the EGs in the Mill department were the most consistent, with 11 of the 20 EGs analysed having less than 20% between-worker variability while the remaining 9 EGs ranged from 21% ('Dry Rock Storage Attendant') to 74% ('Janitor'). In the E&R department 7 of 13 EGs had less than 20%, with the others ranging from 27% ('Mechanic') to 99% ('Mobile Equipment Operator'). On the other hand, only two of seven jobs in the Pit satisfy this criterion with the remaining five EGs ranging between 31% ('Shovel/Loader Operator') and 84% ('Labourer'). This is consistent with the fact that most of the EGs in the Mill department had GSDs <3.0 (92%), while 35% of EGs in the Pit department had GSDs >3 thus indicating more variation.

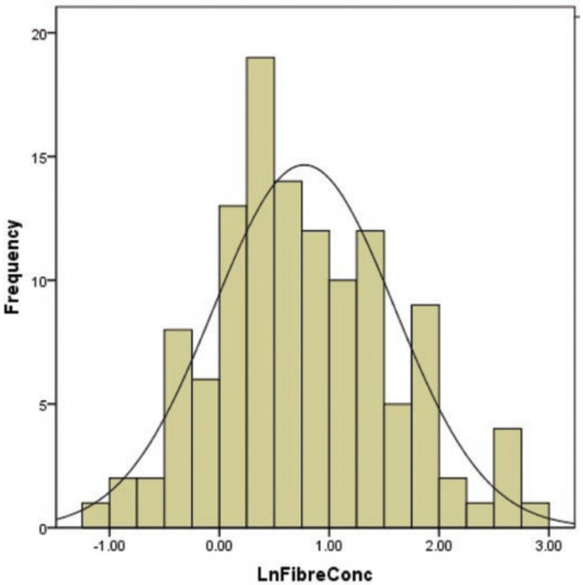

Figure 4. Frequency distribution for 'Dry Rock Storage Attendant', for the years 1980–1984, demonstrating the goodness-of-fit to the log-normal distribution.

The high between-worker variance found for some EGs may be explained in some cases by the small numbers of samples available for analysis (i.e. a small number of workers in the EG and/or few repeated samples per person). For example, 'Mobile Equipment Operator' in the E&R department, which had 99% between-worker variance, had repeated samples for only two people, and one of those people had only two samples and the other had four samples. In other cases, the EG contained jobs that were very mobile within the mine/mill complex (e.g. 'Labourer' in the Pit) and, therefore, exposures would have varied considerably between workers depending on where within the complex they were working when a sample was collected. Furthermore, the amount of between-worker variance was significantly different in the two datasets used (1980 versus 1990s) for some EGs. For instance, the percentage of between-worker variance was 67% for 'Plant Millwright' in the 1980 data but was found to be 0% in the 1990 data. This may be explained by the fact that the 1980 dataset included multiple intra-shift samples that were carried out over the duration of a shift (and therefore likely to be more representative of true exposure), whereas the 1990 data consisted of sample results that were only 1–2 h in duration and did not cover a full shift.

Overall, the use of job titles to create EGs and, thus, for the estimation of individual exposures, appears to be

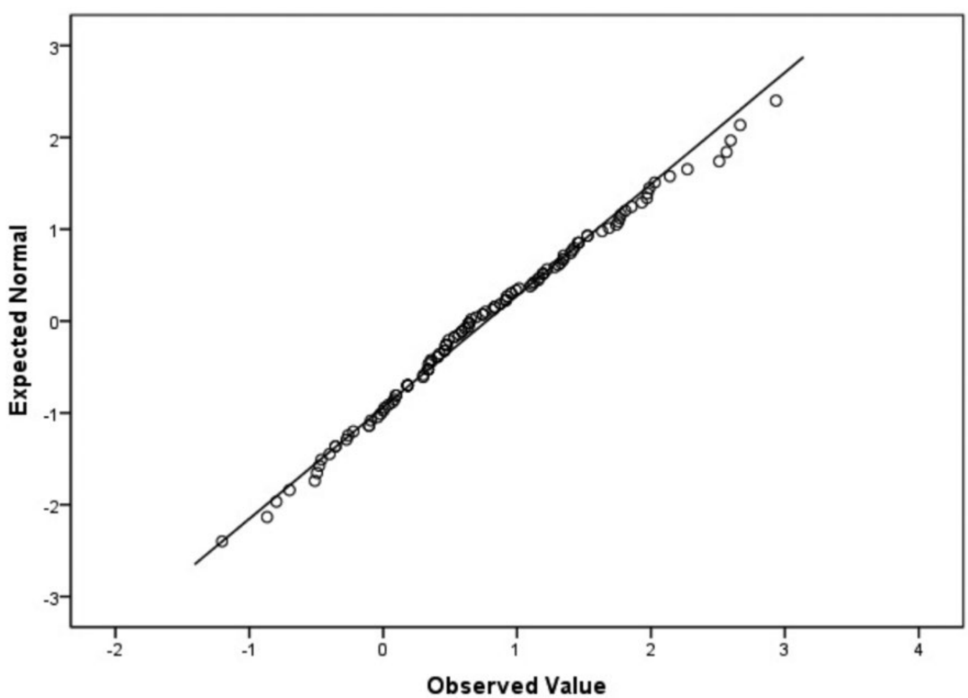

Figure 5. Cumulative probability plot for 'Dry Rock Storage Attendant', for the years 1980–1984, demonstrating the goodness-of-fit to the log-normal distribution.

appropriate for most job titles at the Baie Verte mine/mill. However, for those EGs for which the GSDs are high and the between-worker variance was greater than 20%, care should be taken, especially for the purposes of adjudicating compensation claims, since the value in the JEM may not be representative of the exposure of everyone in that group.

Discussion

The development of the BVMR has allowed for the estimation of exposure to chrysotile asbestos by former workers of the mine/mill. The development of the JEM was one of the first steps required in the retrospective exposure assessment and was instrumental in the estimation of cumulative asbestos exposures for the BVMR. The evaluation of the validity of the data used to estimate workers' exposure allows for the consideration of possible sources of bias and the potential for exposure misclassification. To assess the quality of such estimates, three factors based on criteria established by recognized organizations (EPA, 1994; Bullock and Ignacio, 2006; AIHA, 2010) were used in this study to ascertain whether the estimates are of high enough quality to be valid. The factors considered were: the number of samples used to compute the means for cells in the JEM; the goodness-of-fit of the exposure distributions of the EGS to the log-normal distribution; and, the proportion of between-worker variability in EGs.

In terms of sample size, we found that 89% of the cells in the JEM had a sufficient number of samples to be considered either 'good' or 'very good' quality to make a reasonable judgement of the exposure distributions of the EGs. As for the goodness-of-fit testing, we were able to ascertain that job title was an appropriate grouping mechanism for the creation of EGs for all but a few EGs whose frequency distributions were found to be bimodal. Finally, by evaluating the descriptive statistics for each EG (i.e. the normality of fit and measures of variation—GSD), and by assessing the components of variance (within- and between-worker components of variance) for the EGs with adequate data, we have a better understanding of the limitations of the exposure data for certain EGs and/or for some of the departments (i.e. the Pit) where exposures were more variable. These limitations must be considered when estimates of individuals' cumulative exposure are used to adjudicate compensation claims because exposures may have varied significantly in certain jobs and/or departments (e.g. 'Senior Tester', GSD = 5.61). The potential for exposure misclassification may also affect the results of an epidemiological study on this group of former asbestos workers.

Sample duration can also be a limitation associated with retrospective exposure assessment. In this study, many of the samples used in the construction of the JEM (i.e. the 1976–1994 dataset) were short samples (i.e. 1–2 h in duration) collected during the course of a worker's shift. This short sampling time was probably preferred because longer sampling periods led to an accumulation of dust on the filter which obscured the fibres and rendered them uncountable. To ascertain that samples are truly representative of a worker's exposure, good occupational hygiene practice would dictate that at least 80% of the shift duration should be sampled, preferably using multiple shorter samples over the span of the entire shift. In this case, approximately 11% of the values making up the overall dataset were averages or TWAs of multiple samples collected on the same day for the same job title and/or person. The limitations associated with the use of short samples are partially overcome by the averaging of many samples over the years covered by the time periods used in the cells of the JEM. Therefore, while a 2-h sample taken during a shift may not be representative of the exposure for that shift, taking repeated 2-h samples over a five period (which most of the JEM cells represent) may be a reasonable estimate of the exposure for that period of time. The exposure estimates in this article are not meant to be representative of a single day's exposure but rather of the concentration of asbestos fibres experienced by the workers in the specific job titles for the specified period of time. In addition, information obtained from the raw sampling reports indicate that each year multiple samples were collected for each job title while performing numerous tasks associated with that position. Therefore, the authors are confident that the tasks performed by each job title were adequately captured over the years in the sampling data, thus strengthening the position that the averaging of the shorter samples over long periods of time is representative of the exposure for that time period. Finally, the information contained in the 1980 allowed us to compare the mean of multiple individual samples collected for each job title to the individual samples that made up that average in order to evaluate the representativeness of the 1–2 h samples. Given that the sampling strategy of all sources (i.e. parent company, union, and government) was similar and unchanged over the years, this comparison demonstrated that the majority of the TWAs reported in the dataset was within the error range of the analytical method, giving us confidence that the shorter duration samples are representative of the actual means.

We have not been able to provide an equally rigorous evaluation of the quality of the exposure estimates for the period prior to 1976 because raw sampling data were unavailable. Edstrom (1982) used stationary samples to estimate exposure while the later dataset consisted of personal samples which are more representative of actual worker exposure. Therefore, it is possible that Edstrom underestimated exposure in the years between 1963 and 1975. The use of stationary samples is mostly problematic in cases where asbestos fibres are actually being disturbed (e.g. bagging of asbestos fibres) because the concentration of asbestos fibres in the breathing zone of the worker may be much higher than what is captured by a stationary sampling device. However, the reverse may also be true if a stationary sample is placed in an area where high levels of asbestos are found but where workers did not actually work resulting in overestimated workers' exposures. Another potential limitation of historical asbestos sampling data is the use of conversion factors to convert measurements of total airborne dust particles and fibres (reported in mppcf and mfpcf, respectively, and measured with the midget impinger method) into airborne fibre measurements (reported in f ml^{-1}). This conversion can introduce systematic bias because of the uncertainty associated with the conversion factor(s) and may lead to exposure misclassification which can bias the results of an exposure–response analysis towards the null hypothesis thus masking the true effect of asbestos exposure on the health outcome (Checkoway *et al.*, 2004). This type of bias is especially profound in studies that utilize a general conversion factor for all areas of the workplace. The conversion factors developed by Edstrom, however, were area-specific conversion factors thus reducing the amount of uncertainty associated with the conversion process. Furthermore, because cumulative exposure is calculated in the same manner for both diseased and non-diseased subjects, any exposure misclassification due to underestimation of exposure in the earlier time period would be non-differential in nature and would tend to bias the results of an epidemiological study of exposure–response towards the null hypothesis.

A further potential limitation of occupational exposure data is the bias that may be introduced by the sampling strategy employed by the person or group conducting the sampling. For example, the sampling strategy used by union, worker, or government representatives might have captured the worst-case exposure scenarios and may have overestimated the true exposure. On the other hand, sampling conducted by a company representative might have sought to capture best-case scenarios and may have underestimated true exposure. Parsons *et al.* (1986) completed an evaluation of the data collected by the three sources (i.e. parent company, operating company, and government) from 1965 to 1980. Although the agencies differed with respect to their reported average asbestos levels, with the government reporting higher levels than both sets of company samples, the variances of all three were found to be similar. The higher asbestos counts reported by government were most likely due to a higher magnification used in the analysis and because they sampled on the same day of the week, as well as the possibility that the government sampling strategy was more likely to be compliance based rather than exposure profiling. However, the similarity of the variances of all three sampling agencies showed that they sampled with the same precision, thus, the data from any one agency were of equal quality to that of another. As a result of the work conducted in the early 1980s by Edstrom and his team (and reported by Parsons in 1986) some changes were made to the sampling strategies of all three sampling bodies which would have further reduced bias from this source. Therefore, in the current study, the sampling data retrieved from the union records containing data from all three sources spanning the entire duration of the mine/mill operations is likely to have captured all possible exposure scenarios, thus reducing the overall amount of bias involved.

The exposure estimates calculated in the present study for the early years of the mine's operation are fairly consistent with exposures reported in the literature for other chrysotile mining/milling cohorts. Rubino *et al.* (1979) reported on the exposures of a chrysotile mining cohort from Balangero, Italy. Table 6 presents average exposures for both the Italian and the Baie Verte cohorts for two periods, 1961–1970 and 1971–1975. This table shows that, for the drilling and crushing processes, the exposures in the Balangero study are lower than our data for both time periods while the reverse is true for the bagging process. For the fibre separation processes, the estimates are very similar.

Table 6. Comparison of mean exposure levels from this study to Rubino *et al.* (1979).

Area (years)	Balangero, Italy (f ml^{-1})	Baie Verte (f ml^{-1})
Drilling (1961–1970)	14	37
Drilling (1971–1975)	5	8
Crushing (1961–1970)	14	31
Crushing (1971–1975)	3	12
Bagging (1961–1970)	20	11
Bagging (1971–1975)	6	5
Fibre separation (1961–1970)	21	22
Fibre separation (1971–1975)	8	7

Table 7. Comparison of mean exposure levels in Baie Verte to levels in five Québec mills reported by Nicholson *et al.* (1979) and Gibbs and du Toit (1979).

Area (years)	Québec (f ml^{-1}) Lowest to highest (Nicholson *et al.*, 1979)	Baie Verte (f ml^{-1})	Year	Québec (f ml^{-1}) 'Average mill' ('best'–'worst') (Gibbs and du Toit, 1979)	Baie Verte (f ml^{-1})
QC Lab (1973–1975)	9–20	4.9	1972	24 (3.5)[a]	7.5
Crushing (1973–1975)	26	11.7	1973	9 (3–50)	8.0
Dryer (1973–1975)	36	11.7	1974	8 (2–29)	8.0
Bagging (1973–1975)	9–16	4.5	1975	7 (1.5–9.0)	1.7
Shops (1973–1975)	10	2.1	1976	3.5 (1.5–4.0)	1.2
General Mill Air (1973–1975)	9–35	5.9	1977	2 (1–2)	0.9

[a]'Best' mill; no data given for the 'worst' mill for 1972.

When compared with data from the Québec chrysotile studies, the Baie Verte estimates are generally lower. The exposure levels reported by Nicholson *et al.* (1979, Table 7) in all areas of five Québec mills were much higher than the levels found by the present study for the same time period (1973–1975). Gibbs and du Toit (1979) also reported on exposure levels in the general mill air for the 'worst', 'best', and 'average' of the Québec mills. In 1972, exposure levels reported for the Baie Verte mine/mill fall somewhere between the levels found in Québec for the 'best' and for the 'average' mills, and in 1973 and 1974, the Baie Verte levels are in line with those of the 'average' Québec mill. However, the levels found in Baie Verte in the later years (1975–1977) are closer to those for the 'best' mills in Québec. These comparisons suggest that the exposure estimates for the Baie Verte miners/millers fall between that of the Italian and Québec chrysotile miners.

Conclusion

The current BVMR study is one of a small number of retrospective exposure assessments involving chrysotile asbestos miners/millers. This study demonstrates that exposures were very high (i.e. ranging from an average of 6–42 f ml^{-1}) in all areas of the Baie Verte chrysotile mine and mill in the early years of operation and gradually decreased over time. Our ability to analyse the quality of the available data, at least for the 1976–1994 period, allows us to be confident in the validity of the estimates used in the JEM for those years and in the resulting estimates of cumulative asbestos exposure. However, the potential for exposure misclassification resulting from the uncertainty associated with the use of stationary samples and the conversion of historical midget impinger results to fibre concentrations in the earlier data, as well as the lack of availability of the raw sampling data with which to accurately quantify this uncertainty, must be kept considered in epidemiological studies on this group of workers. This also applies to the use of estimates of individual cumulative asbestos exposure for the adjudication of compensation claims. While the exposure estimates are comparable to other similar chrysotile mining/milling cohorts in the epidemiological literature, future research into the sources of bias from the earlier industrial hygiene dataset would be useful in order to quantify the potential exposure misclassification.

Supplementary Data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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Conflict of interest

The authors declare no conflict of interest.

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Supplementary Information – Exposure Groups

A quantitative retrospective exposure assessment for former chrysotile asbestos miners and millers from Baie Verte, NL, Canada

TABLE S1. Exposure Groups

MILL	
Job title(s) included in the exposure group	**Job Code**
Primary crusher operator	M-01
Primary crusher attendant | Primary crusher helper	M-02
Secondary crusher operator	M-10
Dryer operator	M-11
Secondary crusher attendant	M-12
Baghouse attendant–sec crush & dryer | Baghouse attendant	M-15
Dry rock storage attendant | Dry rock operator	M-20
Shuttle attendant	M-21
Mill operator	M-22
Floor attendant | Mill attendant | Mill Cleaner	M-23
Pressure packer operator | Packaging operator/attendant | Packaging and shipping operator | Sewing machine attendant	M-30
Screen changer | Screener	M-41
Screen repairer	M-42
Labourer	M-43
Lift truck operator/driver – mill | Fork lift operator - mill	M-50
Tractor trailer operator | Warehouse van operator	M-51
Pallet repairer | Palletizing attendant|Pallet fabricator	M-52
Lift truck operator/driver – warehouse | Fork lift operator - warehouse	M-55
Janitor	M-60
Tailings operator | Tailings helper	M-70
Tractor grader operator | Dozer operator | Heavy equipment operator - Reclaim	M-72
Supervisor | Mill foreman | General supervisor	M-90
Wet mill operator	M-100
ERECTION AND REPAIR	
Job title(s) included in the exposure group	**Job Code**
Electrician | Electronic repairer | Instrument technician	ER-01
Linesman | Electrician-lines | Cable repairer	ER-02
Machinist	ER-10
Carpenter | Utility person	ER-20
Sheetmetal worker | Metalworker | Welder	ER-30
Service truck driver | Mobile equipment operator | Boom truck operator | Mobile crane operator	ER-40
Plant millwright | Industrial mechanic | Millwright apprentice | Maintenance helper	ER-50

Labourer-E&R | Labourer-garage | Janitor	ER-52
Millwright greaser | Mill greaser | Greaser	ER-61
Power center operator | Power center millwright	ER-70
Heavy equipment mechanic | Heavy duty mechanic | Garage mechanic | Heavy duty repair | Component mechanic | Tire repairer | Service attendant - light vehicles | Service attendant - mobile equipment	ER-80
Supervisor-E&R | Supervisor-garage | Supervisor-maintenance	ER-94

PIT

Job title(s) included in the exposure group	Job Code
Primary driller | Drill operator	P-01
Secondary driller	P-02
Blaster | Blaster helper	P-10
Explosives truck driver | Shovel operator | Production loader operator	P-12
Backhoe operator	P-22
Haul truck driver	P-30
Tractor grader operator | Mobile equipment operator-dozer | Mobile equipment operator-grader	P-40
Service truck driver | Service attendant | Dump attendant | Shuttle operator	P-41
Pump attendant | Pumpman	P-50
Labourer	P-52
Office janitor | Dry attendant – mine	P-60
Supervisor – mine | Shift supervisor | General supervisor - pit maintenance	P-61

QUALITY CONTROL

Job title(s) included in the exposure group	Job Code
Senior tester | Junior tester | Manager quality control | Quality control assistant | Quality control trainee	QC-01
Stevedore | Signal man | Winchman | Janitor - stevedoring	QC-04

OTHER

Job title(s) included in the exposure group	Job Code
Storeskeeper | Storesman | Supervisor stores	OS-01
Janitor-main office | Janitor-mine dry | Laundry attendant | Housing maintainer	A-01
Office clerk | Mine manager | Mill superintendent | Junior and senior industrial engineer | Industrial analyst | Draftsman-layout and detailer | Designer-assistant | Geologist | Supervisor - Mine engineering | Senior planner | Purchasing agent	BV-01