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Time-weighted exposure measurements are frequently available for use in occupational epidemiology studies of exposure–response relationships. Generally, these measurements must be combined and extrapolated over time to develop job-specific exposure estimates. A stepwise strategy for the development of exposure estimates from time-weighted data is described. Elements include describing the distribution of the data, exploring trends over time, calculating estimates, and methods of categorizing the estimates. The process is applied to more than 2200 time-weighted exposures from the beryllium processing industry collected from 1950 through 1978. The data were approximately lognormally distributed, requiring the calculation of the mean of the log-transformed data, and subsequent estimation of the arithmetic mean exposure for each job title at the five facilities. Few trends in exposure estimates over time were detected in the data, which may be a result of the small number of data points for each job. Exposure estimates were categorized by several methods; criteria for selecting a specific scheme included (1) having one group with mean exposure at or near the current allowable exposure level, (2) ensuring that the groups were statistically separable, and (3) minimizing the gaps between confidence intervals. The resulting exposure estimates were generally consistent with the range of previously published values describing industry-wide exposures, or those at a single plant. Thus the estimates derived from the uniform procedures described do not appear to be biased, compared with estimates calculated historically. For a specific job title, exposures varied across each facility. Acquisition of additional data from existing company and archive sources would probably increase the number of job titles for which exposure data are available and improve the utility of these data for studies of potential health effects. SEILER, D.H.; RICE, C.; HERRICK, R.F.; HERTZBERG, V.S.: A STUDY OF BERYLLIUM EXPOSURE MEASUREMENTS, PART 1: ESTIMATION AND CATEGORIZATION OF AVERAGE EXPOSURES FROM DAILY WEIGHTED AVERAGE DATA IN THE BERYLLIUM INDUSTRY. APPL. OCCUP. ENVIRON. HYG. 11(2):89–97; 1996.

Beryllium production was first begun in 1921 by Charles Brush II in Cleveland, Ohio.[1] By the late 1940s the Atomic Energy Commission (AEC), which oversaw beryllium production because of its strategic uses, recognized that acute exposure to beryllium caused severe pulmonary disease.[2] Soon after, the AEC developed a protocol for monitoring breathing zones of workers and the general air in process facilities.[3] Today, several researchers have hypothesized that exposure to beryllium may be a risk factor for lung cancer.[4] The National Institute for Occupational Safety and Health (NIOSH) has undertaken a cohort mortality study of beryllium refinery employees in an attempt to resolve the question of cancer development from beryllium exposure.

The work reported is a review of more than 2200 available full-shift exposure measurements housed at NIOSH. These data represent measurements collected by various agencies and constitute an initial data set for the study of beryllium exposures. Through study of these data, an evaluation can be made of the adequacy of the data set to support the epidemiologic study through the development of an exposure estimate for persons employed at jobs sampled at each facility. A strategy for exposure estimation from these time-weighted sampling data is detailed. Identified deficiencies in the available data set are described.

Background

Production Techniques

Beryllium is extracted from beryl ore and converted to beryllium hydroxide by either the fluoride or sulfate method for the production of alloy, oxides, ceramics, and pure metal.[5] Alloys are fabricated in a variety of forms and used in tooling dies, bearing sleeves, and overseas cables. Beryllium oxides and ceramics are used in resistor cores, laser tubes, and as circuit chip carriers. Metallic beryllium has a wide range of military applications, which include use in missile, inertial guidance, and other weapon parts. In the United States beryllium processing has been conducted principally in Ohio and Pennsylvania. The Reading, Pennsylvania, facility has operated since 1935 for the extraction of beryllium oxide, production of copper alloys, and fabrication. The Hazelton, Pennsylvania, facility extracted beryllium oxide to form beryllium metal for fabrication from 1958 to 1978. The Elmore, Ohio, foundry began operation in 1953 for fabrication operations and ceramic production and is still in operation. An extraction and foundry facility in Luckey, Ohio, operated from 1950 to 1958. A Lorain, Ohio, extraction, conversion, and fabrication facility was on line from 1935 to 1948. Various shops in the Cleve-

Operation or Operating Areas	Time per Oper.	Oper. per Shift	Time per Shift	Number of Samples	Concentration ug/Be/m^3 Low	High	Ave.	Conc. Time Total Time (T x C)
GA Lathe Area (center)	225	1	225	6	.23	3.37	1.02	229.5
GA Shoe Change Room	6	1	6				2.66	16.0
GA Locker Room	12	1	12				.17	2.0
GA Cafeteria	30	1	30				.15	4.5
GA General Plant	30	1	30				1.20	36.0
BZ Install & Remove Billets in Lathe	6	5	30	2	4.71	14.82	9.77	293.1
BZ Pick Billets	60	2.5	150	3	1.50	3.71	2.26	339.0
BZ Change Chip Pickup Drum	5	3	15		1.74	12.82	8.42	126.3

* Respirator

$\frac{\Sigma(T \times C)}{T} = 2.96$ ug Be/m^3 $\Sigma T = 498$ $\Sigma(T \times C) = 1478.1$

FIGURE 1. Typical DWA calculation sheet.

land, Ohio, area were the sites of conversion of beryllium oxide to metal and machining operations from 1948 to 1972. Environmental data were available for all facilities except Lorain.(6) Sampling results in the Cleveland-area plants did not include notation of the specific facility (Perkins, St. Clair, and Chester); therefore, all exposure data are grouped into the Cleveland data set.

Air Sampling

Companies producing beryllium products under the aegis of the AEC, now the Department of Energy, were required to evaluate workplace exposures. Although a variety of sampling devices have been used over the years, high volume samplers were the most common. Air was drawn through a 4-inch Whatman No. 41 filter paper at a flow rate of 20 ft^3/min. Samples were collected in the breathing zone for approximately 2 to 5 minutes during specific tasks. Area samples were also collected at work locations away from direct emission sources, such as control panels, lunch room, and clothing change areas.

For each job, air sampling technicians collected general area (GA) or breathing zone (BZ) samples for the tasks in the job title. A study of the time required for an average worker to perform each task was conducted for each job title within the plant. The arithmetic average of the samples at each task or location was calculated and then weighted by multiplying by the amount of time spent performing each activity. The time-weighted results for each of the GA and BZ sample locations were then summed and divided by the total work time to calculate the worker's daily weighted average (DWA).(7) The AEC protocol included quarterly monitoring for the calculation of DWAs. An example of a DWA calculation sheet for billet picking and chipping lathe operator is displayed in Figure 1. This format, adapted from a AEC report, was commonly used to calculate workers' exposures. Limits of detection, the laboratory performing the analysis, and other quality control data were not included.

Methods

Introduction

The data used in this study were acquired from the files of the Industry-Wide Studies Branch of NIOSH, and had been collected by multiple agencies, including NIOSH, the Public Health Service, and the AEC; limited in-house company data were also included. In order to use the data, it was necessary to transfer information from the paper records to a computer file. Information abstracted included plant identifier, date, type of sample, job title, task duration of the sample, analytical results, and the organization performing the sampling. Once computerized, a stepwise strategy was followed to describe the distribution of the data, explore evidence of trends in the data over time, calculate estimates of exposure, and categorize the exposure estimates. All data analyses were conducted using SAS®.

Description of the DWA Data Set

Based on historical process information, conversations with current and former plant personnel, and observations during walk-through surveys at the Reading, Pennsylvania, and Elmore, Ohio, facilities, the job titles listed on the environmental records determined to include the same duties in each of the facilities were placed in uniform title groups. For example, many of the job titles began with EO (extraction oxide), while others began with OE (oxide extraction); thus, both types of titles were combined to form a single job title, oxide extraction. Whenever possible, new titles were assigned which were consistent across plants.

Several studies have shown that environmental data follow a logarithmic distribution.(8,9) Taking an arithmetic mean of lognormally distributed data can result in a biased exposure estimation;(10) therefore, it was first necessary to determine if the values were normally or lognormally distributed. Calculated DWA values for both the data set as a whole and for each plant were evaluated for normality. As shown in Results, the data were approximately lognormal; therefore, all subsequent methods descriptions are appropriate for lognormally distributed data.

Trends in the Data

According to the AEC protocol, beryllium industry personnel were to collect air samples on a quarterly basis. Sampling was used to quantify exposures and to identify areas where concentrations exceeded the 2 $\mu g/m^3$ exposure limit first recommended in 1949 and currently in effect.(11,12) For areas identified to present elevated airborne levels, engineering controls would be implemented to reduce exposure. A series of resampling efforts would follow soon after the controls were in place to document that exposures in these areas had been reduced. Sampling might also have been used to identify the deterioration of engineering controls and determine the need for maintenance or repair. These situations would be reflected in the sampling results as an increasing or decreasing trend in the data or a sudden change in concentration.

The possibility of increasing or decreasing trends in the data was investigated by uniformly plotting the log of all DWA values for each job title by plant versus time. By plotting exposure levels at each job title by plant, gradual increases and decreases in exposure levels could be identified. Also, dramatic reductions in exposure levels over time could be observed. Plots of exposure for job titles with at least one data point above 2 $\mu g/m^3$ were of particular interest, since exposures above this level would probably be the focus of engineering controls.

Each job- and plant-specific data plot was examined to characterize the different types of data distribution present. Five categories were defined *a priori*: grouped (all data within ±1 log unit); two-level (separable into groups by two perpendicular lines and one point greater than 2 $\mu g/m^3$); scattered (more than four values scattered across more than ±1 log unit); limited data (three or fewer points); and line data (four or more points generally following a linear function). Plots characterized as grouped or scattered indicated that the data showed no visual trend over time; limited plots contained insufficient numbers of data points to assess trends. The existence of two statistically different mean exposures in the two-level plots was evaluated by examining the 95 percent confidence intervals to determine if the groups were statistically separable, using the formula for small-sample groups with a frequency distribution approximately normal.[13] Line data, which could be a result of increasing or decreasing concentration over time, could be evaluated by linear regression.

After the plots were assigned to one of the five categories, the plots were evaluated by a second, independent rater who was blind to the initial determinations; the interrater agreement was analyzed by calculating the Kappa statistic to assess reliability of the ratings.[14] A large Kappa statistic would indicate that the rules were stated clearly.

Exposure Estimation

The next step was to calculate exposure means from the logarithmic data points for each job title. The majority of plant-specific job title exposures included less than 30 data points, and 207 of 491 job titles were represented by one data point; therefore, small sample size statistics were necessary to calculate an estimate of the arithmetic mean (M_a):

$$M_a = \exp(Y)\,\Psi_n(V)$$

where Y is the mean of the natural logarithms of the sampling data. The factor $_n(V)$ is a function of the sample variance,

$$\Psi_n(V) = 1 + \frac{(n-1)V}{n} + \frac{(n-1)^3V^2}{n^2(n+1)^2!} + \frac{(n-1)^5V^3}{n^3(n+1)(n+3)3!} + \ldots$$

$V = 1/2\ Sy^2$, where Sy^2 is the sample variance of Y.[15] Because of the small numbers of samples for many job titles, job-specific variance estimates were unstable when defined; therefore, the following variance values calculated for each plant were used for Sy^2: Cleveland, 1.3; Elmore, 1.1; Hazelton, 0.6; Luckey, 1.4; Reading, 1.5. The value of M_a for each job was used as the estimate of exposure.

Categorization of Exposure Estimates

Quantitative exposure estimates are frequently categorized for the analysis of exposure–response relationships.[16,17] For this DWA data set, two approaches for selecting categories were considered. The first involved separating the data set into quarters (quarter) or fifths (fifth) by using the calculated cumulative percentages from the frequency listing of job title estimated mean exposures (M_a). The fifth method, if useful, would describe exposure more specifically than the quarter method. For each category, the mean was calculated and confidence intervals were constructed. The range of the 95 percent confidence interval about each number was studied to determine if overlap occurred between the range of adjacent categories. The second method considered was formation of groups iteratively by setting the upper bound of a group by quadrupling (quad) the lower bound,[18] with the lower bound of the first group set at 0 and an upper bound selected to allow for several other groups to be delineated, covering the entire range of the data set. As in the first approach, means for each group were calculated and confidence intervals constructed to determine if overlap occurred.

Results

Description of the DWA Data Set

The DWA exposure estimates represent 491 different job titles divided among five different plant locations: Reading, Hazelton, Luckey, Cleveland, and Elmore. The majority of the exposure measurements, 43.3 percent, were collected at the Hazelton, Pennsylvania, facility. The data represent exposures for the years 1950 to 1978. A breakdown of the data by year and plant is given in Table 1.

When calculated by plant, the resulting coefficients of skewness for the original data ranged from 5.2 to 19.4; for the logarithmic transformed data the range was −0.1 to 1.2. For the overall data set the coefficients were 29.5 and 0.02 for the original and log transformation data, respectively. The results indicated that the industry-wide data set had a very large coefficient of skewness. After transformation of the original data to log values, the skewness was found to decrease dramatically. A similar trend was seen for the individual plants. Therefore, the logarithmic transformed data were approximately normally distributed and were used for exposure estimation. No statistical tests were used to evaluate the degree of lognormality of the data.

Trends in the Data

A total of 284 plant-specific job titles contained at least two points and were available for the evaluation of changes in exposure over time. During the visual scan of the data plots, each plot was associated with one of the *a priori* categories. The majority of the data plots (239) were included in the grouped category. Eighteen plots appeared to include two levels. Scattered plots were few (25). Only one plot was found to contain either limited or line data. Examples of plots characterized as grouped, two-level, and scattered are shown in Figure 2.

The rules were condensed to characterize three plot types as shown in Table 2 (two-level, grouped, and scattered) and used to evaluate each of the 284 plots. A second, independent rater characterized 38 randomly selected plots. The two agreed on 34 plot categorizations; in three of the four disagreements, rater B was found to be incorrect in the characterization choice according to the finalized rules. This level of agreement between the raters could not be attributed to chance (Kappa =

TABLE 1. Number of Exposure Measurements in the NIOSH Records for Each Plant, by Year

Year	Cleveland	Luckey	Elmore	Hazelton	Reading	All Plants
1950	20	—	—	—	—	20
1952	101	—	—	—	—	101
1953	57	—	—	—	—	57
1955	99	12	—	—	—	111
1956	30	59	—	—	—	89
1957	44	41	—	—	—	85
1958	—	—	98	1	—	99
1959	13	—	52	60	—	125
1960	20	—	50	122	—	192
1961	—	—	40	102	16	158
1962	—	—	15	—	—	15
1966	—	—	—	88	—	88
1967	—	—	—	92	—	92
1968	—	—	—	102	—	102
1969	—	—	—	105	—	105
1970	—	—	—	153	—	153
1971	—	—	—	148	121	269
1972	—	—	38	—	—	38
1974	—	—	251	—	—	251
1975	—	—	97	—	—	97
1978	—	—	2	—	—	2
Total	384	112	643	973	137	2249

0.65, $p < 0.0001$), and indicated that the rules could be used by a second rater.

Eighteen of the 171 plots that contained two or more data points, with at least one point above 2 $\mu g/m^3$, were found to contain two distinguishable levels by plot characterization. Means of the log exposure values and 95 percent confidence intervals were calculated for each of the two levels of data. For ten job title plots the confidence intervals did not overlap, indicating potential differences in exposure over time. It is unlikely that the identified differences were related to engineering controls for three of these ten job titles (process development person, quality control technician, and research and development technician), however. These workers might be expected to go to a number of areas in the plant during the course of the work day. Efforts to control exposures for persons in these job titles would probably not be through engineering controls, although they may have experienced lower exposures as a result of implementation of controls in the manufacturing areas. Engineering controls may have influenced exposure for extrusion operator, fluoride furnace operator, hydroxide operator, pebble float operator, sinter mix help, ore conditioner, and 100 area foremen. For the other eight jobs with two-level plots, no difference was identified in estimated exposure over time; these include beryllium metal foreman, machine shop porter, sandblast billet operator, administrative technical director, cold compactor, electrical engineer, research director, and warehouse clerk.

The grouped category accounted for 82 percent of the job titles by the finalized rules. Of the job titles for which graphical evidence existed for the possible effect of engineering controls, approximately half were not statistically separable and no documentation of use of controls was included in the available

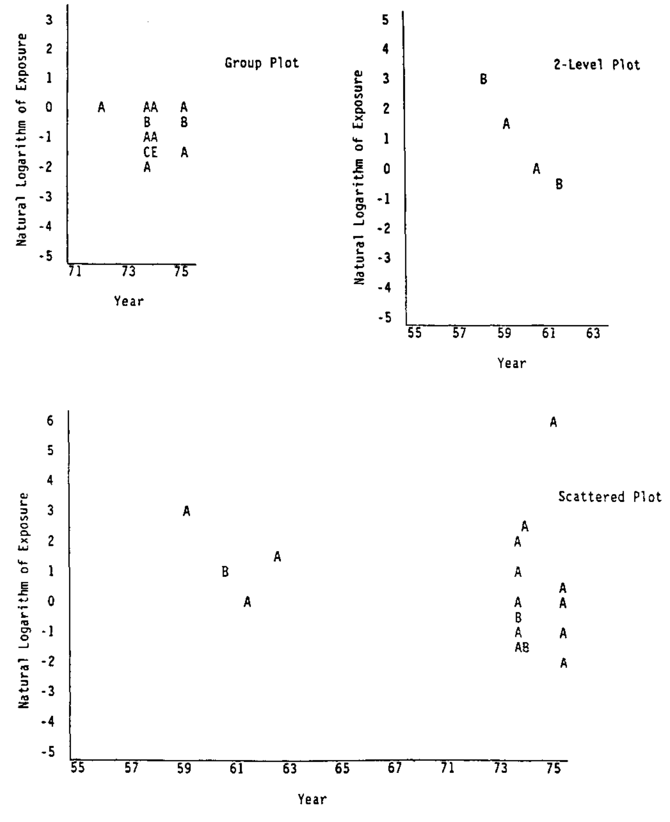

FIGURE 2. Examples of plots of exposure data categorized as "group," "2-level," and "scattered." Legend: A = 1 observation, B = 2 observations, etc.

TABLE 2. Finalized Rules for Evaluating Plots of Data on the Natural Logarithmic Scale

1. Two-level plots
   - Four quadrants are constructed by drawing perpendicular vertical and horizontal lines without intersecting data points. Two or more data points must be located above 0.693 (2 μg/m^3) and in a single quadrant. Two or more data points must be found in the opposite quadrant (e.g., quadrants 1 and 4 or quadrants 2 and 3).
2. Group plots
   - If all the data are less than 0.693 (2 μg/m^3), then the data points can be grouped.
   - If all data except one point are less than 0.693 (2 μg/m^3), and the one point does not exceed +1 (2.76 μg/m^3), then the data points can be grouped.
   - If at least 50 percent or more of the data are equal to or less than 2 (7.39 μg/m^3) and greater than or equal to 0 (1 μg/m^3), and all the rest of the data points are less than 0 (1 μg/m^3), then the data points can be grouped.
   - If all data points are within ±1 (i.e., 0.42 to 2.7 μg/m^3, 1 to 7.4 μg/m^3, etc.), they may be grouped.
3. Scattered plots (four or more values available)
   - If the plotted data are spread apart greater than +1/−1 log unit and at least one point is greater than 0.693 (2 μg/m^3), then the plot is considered to be scattered (more dispersed than grouped).

records; therefore, each exposure estimate was calculated from all of the data for that job title, without regard for date of collection.

Exposure Estimation

Because of the small number of job titles for which exposures varied across time, exposure estimates were determined for each of the job titles by plant, without regard for date. Table 3 provides a listing of selected job titles and the exposure estimates, when available, for three or more plants. The data indicate that in several instances exposure levels for a given job title differ substantially between plants. For example, the beryllium metal furnace foreman received an estimated exposure of 8.00 μg/m^3 at the Elmore facility; a person with the same job title at the Hazelton facility had an estimated exposure of 2.86 μg/m^3. Because only one measurement was available for 42 percent of the job- and plant-specific exposure estimates, statistical tests to study differences in exposure by plant were not conducted.

Categorization of Exposure Estimates

Each categorization method (quarter, fifth, quad) was applied to a frequency listing of the DWA job title mean exposures for the industry-wide data. The data set did not contain job title identifiers, thus avoiding any bias in method of selection. Table 4 shows the confidence interval, range, mean, and number of individual data values which made up each segment. All methods yielded results for which the confidence intervals did not overlap. The quad method was chosen over the quarter and fifth methods because the means of each group represent five meaningful exposure categories covering the data, with the mean of the middle exposure category approximately equal to 2.0 μg/m^3, the current beryllium standard.

A large number of the job titles had two or fewer DWA estimates for the title. The effect of these data on the overall categorization of exposures was explored by repeating the above analysis after excluding job titles for which two or fewer DWA values were available. The remaining exposure values were categorized again. Table 5 represents the calculated confidence intervals (range, mean, and number of values) using the quarter, fifth, and quad methods, respectively. The quad method resulted in large gaps between confidence intervals; for example, the upper bound of the confidence interval for group 3 is 2.06, while the lower bound of the confidence interval for group 4 is 4.17. The same observation may be made for the quarter method. Also, both provide only four categories. The fifth method resulted in five groups, one of which had a mean of 1.8 μg/m^3, or approximately 2 μg/m^3; gaps between confidence levels are also much less. Using the fifth method of exposure categorization, job titles were assigned to one of five exposure groups. Comparison of Tables 4 and 5 indicates an increase in the means for most groups at or below approximately 2 μg/m^3 when jobs with two or fewer DWAs are removed.

Discussion

Exposure Estimates

A limited number of exposure data have been published for the beryllium industry. Table 6 provides a listing of published exposure values for several job titles (References 3, 19–21). Also included are exposure estimates from the work completed in this study. Ranges are given for some job titles in the current work, as the overall job title includes several more specific titles or was conducted at more than one plant; for example, pickling includes operators, helpers, and cleaners, each with a different estimated exposure. All concentrations are listed in micrograms/cubic meter. Most of the published data reflect the range of high exposures experienced in early production of the metal and alloy. Exposure estimates generated in this work also reflect these early values, but to a lesser degree, due to the larger span of time covered by the data and the method of averaging used in each calculation. For most jobs for which a comparison was possible, considerable overlap existed between these exposure estimates and published exposure values; therefore, although these data generally covered a longer period of time, they are consistent with the results of other researchers.

When examining operators and helpers of the same job within each plant, another pattern was observed. As shown in Table 3, exposure estimates for helpers were generally higher than for the operators at the same job. This observation was made when examining the arc furnace and fluoride furnace operators and helpers at the Hazelton, Luckey, Elmore, and Reading plants. At the Elmore and Luckey plants the arc

TABLE 3. Exposure Estimates for Job Titles Conducted at Three or More Production Facilities

	Beryllium Concentration (μg/m³)				
Job Title	**Cleveland**	**Luckey**	**Elmore**	**Hazelton**	**Reading**
Air sampling operator	0.49	1.30	—	2.61	—
Arc furnace helper	—	3.60	4.19	—	2.98
Arc furnace operator	—	1.60	2.42	—	3.22
Attrition mill operator	2.95	—	2.96	3.82	—
Beryllium metal furnance foreman	0.55	0.80	8.00	2.86	—
Billet pick chip lathe	3.90	—	1.89	7.50	—
Boiler operator	—	1.38	2.75	0.84	—
Control lab technician	—	4.00	0.90	0.60	—
Decon crew	—	0.73	3.25	2.37	—
Draftsman	0.23	0.20	—	2.64	—
Electrician	0.53	0.81	7.16	—	—
Fluoride helper	—	2.73	2.64	3.17	—
Fluoride operator	—	0.50	4.41	2.70	—
Industrial hygienist	0.31	1.16	—	2.60	—
Inspector	0.72	—	—	0.54	0.52
Janitor/sweeper	0.44	1.20	—	1.29	0.62
Laundry operator	—	0.61	1.60	2.44	2.50
Leach mill operator	—	3.00	2.34	1.71	22.00
Machinist	0.40	3.62	—	0.57	—
Maintenance clerk	0.36	0.80	—	1.10	—
Maintenance foreman	0.50	0.40	6.71	2.40	0.59
Maintenance furnace rep operator	—	3.46	3.34	2.40	—
Maintenance supervisor	—	0.62	3.69	2.35	—
Maintenance welder	0.68	0.18	7.10	—	—
Material control clerk	—	0.77	7.27	0.57	—
Nurse	0.19	0.12	—	2.18	—
Ore mill process	—	—	2.14	1.69	8.50
Patterson ball mill	—	4.23	4.59	2.48	—
R & D engineer	0.23	1.40	—	2.72	—
Reduction furnace operator	—	6.16	2.83	3.33	—
Sandblast billet	—	2.70	6.80	—	—
Ship & rec/stores	0.46	0.20	—	0.97	0.25
Sintering furnace operator	1.61	—	1.38	—	15.00
Tool designer	1.87	4.60	—	1.01	—
Vacuum cast furnace	—	5.79	2.67	3.89	—

furnace helper received an estimated exposure approximately twice that of the furnace operator. The estimated exposure for fluoride helpers in the Luckey plant was five times the level estimated for the operator. At Reading the arc furnace operator exposure estimate was 3.2 μg/m³, compared with 2.98 μg/m³ for the helper; for the Elmore fluoride helper, exposure was estimated to be 1.8 μg/m³ lower than for the operator. Thus, these estimates indicate that helpers or assistants generally received higher exposures than operators or supervisors at these facilities.

During walk-through surveys at the currently operating facilities in Ohio and Pennsylvania, the existence of substantial company-collected data not included in the NIOSH files was documented. Additional AEC reports containing detailed plant layout, process, and exposure data were also identified at the Department of Energy library (formerly the AEC library) in New York City. Without additional data acquisition, it cannot be determined if the data held by NIOSH are a representative sample of the retrievable beryllium exposure measurements. No protocol for the initial NIOSH data assembly process was found in the course of this work; it is likely that the data were obtained during plant visits as examples of exposure records only.[22,23]

Differences in exposure level by source of the data (e.g., company, AEC, NIOSH) could also be investigated in a larger, better documented data set. The additional company data might also be used to distinguish among the various Cleveland facilities.

The NIOSH records include exposure information from other sampling methods. Exploration of conversion factors between the high volume DWA data and results from these other sampling methods could also expand the database. Acquisition of task-specific data from other sources would also be necessary if additional DWA formulas were needed to estimate exposures of persons.

TABLE 4. Description of Exposure Categories Formed by the Quarter, Fifth, and Quad Methods

			Beryllium Concentration (μg/m³)		
Method	**Category**	**N**	**Range**	**Mean**	**95 Percent Confidence Interval for the Mean**
Quarter	1	124	0.00–0.46	0.28	0.26–0.30
	2	121	0.47–1.10	0.74	0.71–0.77
	3	123	1.12–2.58	1.85	1.77–1.93
	4	123	2.59–50.01	6.04	4.92–7.16
Fifth	1	87	0.00–0.39	0.23	0.21–0.25
	2	108	0.40–0.77	0.54	0.52–0.56
	3	99	0.78–1.67	1.16	1.11–1.23
	4	98	1.69–2.91	2.29	2.22–2.35
	5	99	2.95–50.01	6.85	5.41–8.28
Quad	1	43	0.00–0.20	0.15	0.13–0.16
	2	161	0.21–0.80	0.49	0.47–0.52
	3	199	0.81–3.17	1.84	1.74–1.93
	4	79	3.22–12.34	5.23	4.74–5.72
	5	9	13.00–50.01	25.69	13.24–35.26

Trends in the Data

The review of the distribution of the DWA exposure estimates in this limited data set over time indicated that only a small percentage of job title exposures could be identified to be affected by engineering controls; moreover, only 58 percent of the plant-specific job titles had at least two exposure measurements. From the NIOSH records, sufficient information on individual plant processes is not available to fully characterize the potential reductions in exposure due to engineering controls over time. A more complete data set containing a larger number of measurements and covering a longer time span might be useful in identifying the effects of implementation of such controls. Historical documentation of process change and control technology implementation would also help to identify changes in level of exposure. In the larger data set, different exposure estimates could probably be computed for varying time periods.

Exposure Categories for DWAs

The ore handlers, die loaders, and leach mill and sintering furnace operators were found to have the highest exposures, especially at Reading. Furnace operations, including the alloy arc furnace charge man and fluoride furnace operators, commonly received exposures above the 2 μg/m³ standard. Also included within this group exposed on average to more than 2 μg/m³ were beryllium wet metal operators, maintenance personnel, and sulfide mill operators. The next group which was generally exposed at approximately the level of the standard included beryllium metal workers, machine shop operators, control lab workers, extraction of oxide workers, and some

TABLE 5. Description of Exposure Categories Formed for All Jobs with More Than Two DWA Measurements

			Beryllium Concentration (μg/m³)		
Method	**Category**	**N**	**Range**	**Mean**	**95 Percent Confidence Interval for the Mean**
Quarter	1	51	0.00–0.72	0.45	0.41–0.49
	2	51	0.77–1.87	1.30	1.21–1.39
	3	50	1.89–2.64	2.27	1.46–3.07
	4	54	2.66–9.50	4.11	3.69–4.53
Fifth	1	40	0.00–0.60	0.39	0.35–0.43
	2	42	0.61–1.30	0.97	0.90–1.04
	3	40	1.31–2.22	1.83	1.76–1.92
	4	41	2.24–2.91	2.50	2.44–2.56
	5	43	2.95–9.50	4.46	3.98–4.94
Quad	1	4	0.00–0.20	0.17	0.13–0.21
	2	49	0.21–0.80	0.48	0.44–0.52
	3	116	0.83–3.17	1.95	1.84–2.06
	4	37	3.22–9.50	4.69	4.17–5.21

TABLE 6. Plant Exposure Estimates and Published Data for Individual Job Titles

Job Title	Published Data	Exposure Estimates				
		Cleveland	Luckey	Elmore	Hazelton	Reading
Sinter furnace operator	2.1[19]	0.9–1.6	2.0–4.6	0.8–1.4	—	15.0
Laundry	1.0–2.5[3]	—	0.6	1.6	2.4	2.5
Pickling	0.1–0.2	—	—	—	—	0.33–0.83
Stores, shipping	2.0–3.6	0.1–0.6	0.6–0.2	1.2	1.0–1.3	0.25–0.94
Labs (R&D)	1.2–1.4	0.2–0.6	1.2–1.4	—	2.1–3.3	—
Maintenance	3.5–6.2	0.2–2.2	0.2–3.5	2.4–7.1	1.1–2.5	0.59–0.89
Melt and cast	7.6–18.0	—	5.8	2.7	3.9–4.3	0.65
Arc furnace	11.0–80.0	—	1.6–3.6	2.9–4.2	—	2.98–3.22
Melt and pour	0.4–0.8	—	—	—	3.6–3.9	—
Alloy chief operator	4.5–23.1[20]	—	1.1	2.4	—	—
Alloy helper	7.7–34.0[21]	—	—	2.0	—	—
Alloy charger	4.4–54.6	—	—	3.8	—	—
Alloy mixer	3.8–53.6	—	—	2.1	—	—

production engineers. The group exposed to levels below the standard was composed of porters, chemical engineers, tool room operators, truck drivers, and maintenance shop workers. The lowest exposure group, near the limit of detection, included the majority of administrators and their support staff. Research and development lab personnel, inspectors, supervisors, and the on-site nurse were also included in this group. The diversity of exposures across job titles and plants may be particularly useful in an epidemiologic analysis.

The formation of categories from mean exposure estimates is necessarily arbitrary. The approach taken here considers the importance of having one group with exposure at or near the allowable exposure level, and ensuring that the mean of each group is statistically separable from adjacent groups. Alternatively, actual estimates for each job title may be used without categorization. There is some indication that jobs with lower exposure were sampled less frequently than higher-exposure jobs.

Conclusions

A stepwise strategy for the development of exposure estimates from time-weighted data is described which involves describing the distribution of the data, exploring evidence for trends in the data over time, calculating estimates of exposure, and methods of categorizing the estimates. The approach is applied to DWA data from the beryllium industry. Exposure estimates determined from the available data for each job title by plant were generally consistent with previously published estimates. The results allow comparison of exposures to beryllium at five processing facilities.

Although representing exposures over more than 35 years, the data in the NIOSH records for any one year or plant are sparse, considering the quarterly monitoring requirements of the AEC. Additional data are available at existing companies and in archive sources. Acquisition of data from these sources would probably increase the number of job titles for which exposure estimates could be calculated and allow for a more comprehensive evaluation of trends in the data over time. In a larger data set for which the number of exposure measurements for each job at a plant generally exceeds unity, additional work could be conducted to describe statistical differences in exposure among job titles and facilities.

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References

1. Powers, M.: Elmore, OH, personal communication (1987).
2. National Institute for Occupational Safety and Health: Occupational Exposure to Beryllium. NIOSH, Washington, DC (1972).
3. Krieble, D.; Brain, D.; Sprince, N.L.; Kazemi, H.: The Pulmonary Toxicity of Beryllium. American Review of Respiratory Disease 137:464–473 (1988).
4. IARC Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Humans: Some Metals and Metallic Compounds, pp. 143–203. IARC, Lyon (1980).
5. Everest, D.A.: The Chemistry of Beryllium. Elsevier Publishing Company, New York (1964).
6. Okun, A.: A Protocol for the Mortality Study of Workers Exposed to Beryllium. National Institute for Occupational Safety and Health, Cincinnati, OH (1982).
7. Breslin, A.J.; Harris, W.B.: Health Protection of Beryllium Facilities Summary of Ten Years of Experience. United States Atomic Energy Commission, Department of Commerce, Washington, DC (1958).
8. Breslin, A.J.; Ong, H.; et al.: The Accuracy of Dust Exposure Estimates Obtained from Conventional Air Sampling. Am. Ind. Hyg. Assoc. J. 23:56–61 (1967).
9. Jones, A.R.; Brief, R.D.: Evaluating Benzene Exposures. Am. Ind. Hyg. Assoc. J. 32:610–613 (1971).
10. Esmen, N.A.; Hammand, Y.Y.: Log-Normality of Environmental Sampling Data. J. Environ. Sci. Hlth. 29:29–41 (1977).
11. Eisenbud, M.: Basis of the Presently Used Maximum Allowable Concentrations for Control of Be Disease. In: Workshop on Beryllium, pp. 5–7. The Kettering Laboratory, Cincinnati, OH (1961).

12. Occupational Safety and Health Administration: 29 CFR 1910.1000. Federal Register 54(12):2959 (January 19, 1989).
13. McClave, J.T.; Dietrich, II, F.H.: Statistics, 2nd ed. Dellen Publishing Company, San Francisco, CA (1982).
14. Fleiss, J.L.: Statistical Methods for Rates and Proportions. John Wiley and Sons, New York (1973).
15. Aitchison, J.; Brown, J.A.C.: The Lognormal Distribution. Cambridge University Press, Cambridge, MA (1963).
16. Dement, J.M.; Harris, Jr., R.L.; Symons, M.J.; Shy, C.M.: Exposures and Mortality Among Chrysolite Asbestos Workers. Part II: Mortality. Am. J. Ind. Med. 4:421–433 (1983).
17. Rice, C.; Harris, Jr., R.L.; Checkoway, H.; Symons, M.J.: Dose-Response Relationships for Silicosis from a Case-Control Study of North Carolina Dusty Trades Workers. In: Silica, Silicosis and Cancer. D.F. Godsmith, D.M. Winn, and C.M. Shy, Eds. Praeger Scientific, Westport, CT (1986).
18. Lynch, J.R.; Ayer, H.E.: Measurement of Dust Exposure in the Asbestos Textile Industry. Am. Ind. Hyg. Assoc. J. 27(1):431–437 (1966).
19. The American Society of Metals: The Metal Beryllium. D.W. White, Jr. and J.E. Burke, Eds. The American Society of Metals, Cleveland, OH (1955).
20. Tepper, L.; Hardy, H.; Chamberlain, R.: Toxicity of Beryllium Compounds. Elsevier Publishing Co., Amsterdam (1961).
21. Zielinski, J.F.: A Summary of Seven Years of Experience in Investigating the Dispersion of Beryllium in the Air of a Modern Foundry. In: Workshop on Beryllium. The Kettering Laboratory, Cincinnati, OH (1961).
22. Lynch, J.R.: Personal communication to C. Rice (August 1989).
23. Lainhart, W.: Personal communication to C. Rice (August 1989).