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The characterization of exposure in the beryllium processing industry included collection of samples in the breathing zone during work near emission sources and the general area when employees performed other tasks. The amount of time an average employee spent at each task or area was determined. The arithmetic average exposure at each task was calculated and weighted by multiplying by the time spent performing the activity. These time-weighted results were added, and then divided by the total work time to estimate the daily weighted average (DWA). Each breathing zone and general area exposure measurement is identified by "BZ" or "GA" on the DWA calculation form. 643 individual DWA exposure values for workers with 38 job titles employed in the beryllium industry from 1972 to 1975 have been analyzed. Sixty-seven percent of mean breathing zone values exceeded 2 $\mu g/m^3$, and 73 percent of the maximum exposures exceeded 2 $\mu g/m^3$. In contrast, only 18 percent of the general area mean exposures exceeded 2 $\mu g/m^3$. In general, breathing zone tasks were associated with shorter exposure times than general area sample tasks; for example, 83 percent of the breathing zone tasks and 42 percent of the general area tasks were of 30 minutes or less in duration. When task-specific data are available, cumulative exposure is only one of several exposure metrics which may be constructed (e.g., highest intensity, peak cumulative). This analysis of beryllium exposure data illustrates identification of several exposure excursions within the overall time-weighted exposure. These may be useful for construction of exposure metrics for occupational epidemiology studies and for targeting efforts to control exposure. SEILER, D.H.; RICE, C.; HERRICK, R.F.; HERTZBERG, V.S.: APPL. OCCUP. ENVIRON. HYG. 11(2):98–102; 1996.

Worker exposures are commonly evaluated by a variety of air sampling strategies. Calculated exposure values may be derived from a single sample or several samples, depending upon the sampling method, the contaminant being collected, and its expected concentration. Samples of less than 8 hours in duration are frequently collected in series to evaluate exposure throughout the shift; these may reflect exposure during specific tasks, or may be collected for a predetermined time period and reflect the average exposures during all tasks conducted during the sampling period. When task specific, the results of the short-term samples permit study of these individual components of exposures experienced during the workday.

The sampling strategy developed in the beryllium industry included the collection of multiple short-duration samples to characterize exposure at each task conducted by employees. Together with the results of a time–motion study, an overall, weighted average exposure was calculated for persons with a specific job title and referred to as the daily weighted average (DWA).

The work described was undertaken as part of an evaluation of data on beryllium exposures for their utility in constructing exposure estimates for an epidemiologic study. Since the mechanism by which beryllium may cause lung disease is not well understood, the goal of this analysis was to determine if parameters other than the cumulative exposure (e.g., peak exposure or the ratio of peak to average exposure) might be constructed from the data on the DWA calculation sheet. The availability of exposure information for specific tasks offers an opportunity to characterize several parameters of exposure which may be useful in the epidemiologic analysis; a single parameter (e.g., cumulative exposure) may not be the best predictor of all health outcomes. For example, Copes *et al.*(1) found an important effect of peak exposure in the development of pleural fibrosis among asbestos miners. Cumulative exposure was found to be more predictive for parenchymal fibrosis.

Materials and Methods

Data Set

The data set was restricted to exposure information from the beryllium processing industry reported on completed DWA calculation sheets by methods that have been described.(2) The DWA exposure estimates included results from general area (GA) and breathing zone (BZ) samples; most jobs included at least two BZ and two GA tasks. GA and BZ sample results were each composed of averages of several samples collected at each task. The DWA calculation sheet contained the arithmetic mean, maximum, and minimum exposure values for each task or area monitored, a "BZ" or "GA" notation, and the time-weighted DWA calculated from the mean of each of the these short-term task or area exposure measurements. The time an employee spent at each activity, not individual sample collection times, was also noted. These estimates of duration of exposure at each task or area were used to weight each exposure measurement in calculating the DWA.

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TABLE 1. Number of GA and BZ Samples for Representative Job Titles

Job Title	Number		
	DWAs	BZ Samples	GA Samples
Alloy ajax furnace operator	12	49	60
Alloy arc furnace charge man	13	65	75
Alloy arc furnace crew chief	12	12	101
Arc furnace operator	12	46	59
Attrition mill operator	11	43	78
Billet picking chip lathe	12	50	90
Wet plant treater operator	13	17	69
Ceramic machine operator	12	18	38
Ceramic press operator	12	31	33
Cold press operator	6	12	12
Evaporator operator	13	3	91
Hydroxide operator	7	18	18
Miscellaneous powder material handler	7	17	28
Material crush pebble inspector	10	43	79
Reduction furnace operator	13	61	63
Sintering furnace operator	12	51	105
Sintering machine operator	12	19	41
Vacuum cast furnace operator	11	77	54

The DWAs were from a single facility and were collected by company personnel. All DWA calculation sheets included GA exposure measures at four locations: shoe change, locker room, cafeteria, and general plant. Durations of exposure for these areas were generally 6, 12, 30, and 30 minutes, respectively. As these were common to all DWAs, and not directly related to production process, these tasks were deleted from the data set. The remaining 1152 GA samples and 719 BZ samples directly related to production process were used in the analysis.

Exposure Metrics

In this analysis, the arithmetic averages of the short-term BZ exposures and the GA exposures for each job title were calculated for each day exposure was evaluated; means were also calculated for each job title across the duration of sampling. Calculated exposures for the various tasks were categorized into one of five groups. Category 1 included exposure values less than 1 $\mu g/m^3$. Categories 2, 3, 4, and 5 had ranges of 1 to 2, >2 to 4, >4 to 8, and >8 $\mu g/m^3$, respectively. Duration of exposure was categorized as 30 minutes or less, 31 to 60 minutes, 61 to 120 minutes, 121 to 180 minutes, and greater than 180 minutes. All category ranges were chosen *a priori*.

To illustrate the relationship between job-specific BZ and GA samples and the DWA, each BZ and GA measurement was divided by the calculated DWA exposure value of which it was a component. These multiples of the DWA were then categorized by the duration of exposure for the specific task. The data set was then restricted to those DWAs which included at least one BZ or GA exposure exceeding 2 $\mu g/m^3$; this removed DWAs for which no single component exceeded 2 $\mu g/m^3$. The multiple of the DWA was calculated and categorized as described above. Finally, the relative categorization of the maximum exposure value for job titles which contained both GA and BZ tasks was compared with the ranked DWA exposures using a previously described five-category scheme.[2] Categories 1 through 5 included exposures at the limit of detection, below the current standard, approximately at the standard, above the 2 $\mu g/m^3$ standard, and substantially above the standard, respectively. This step was undertaken to determine if the category would change. All calculations were performed using SAS®.

Results

Data Description

The overall data set contained 643 individual calculated DWA exposure values for workers with 38 job titles employed in the beryllium industry from 1972 to 1975. Table 1 presents the number of these BZ and GA samples for representative job titles in this data set. BZ samples were collected during operations including opening and closing furnaces, changing drums, and other job-specific tasks. GA sample sites included monitoring positions at control panels, the general production work area, and platform areas. Thirty-five job titles included at least one production area BZ exposure measurement; 36 job titles included at least one production area GA exposure measurement.

Exposure Range

The mean of calculated DWA values and means of GA and BZ task exposure measurements for representative job titles in

TABLE 2. Descriptive Data on Exposure Values for Representative Job Titles—November 1974

Job Title	Airborne Beryllium ($\mu g/m^3$)						
	DWA	GA			BZ		
	(Mean)	Mean (n)	Min	Max	Mean (n)	Min	Max
Alloy ajax							
Furnace operator	1.1	0.7 (6)	0.1	1.2	2.5 (6)	0.9	6.0
Attrition mill	1.1	1.0 (8)	0.4	2.4	3.5 (6)	0.8	8.9
Billet chipping	1.1	0.7 (12)	0.1	1.5	3.4 (6)	0.9	8.7
Ceramic machine operator	0.3	0.3 (3)	0.1	0.4	0.4 (2)	0.3	0.4
Reduction furnace	1.4	1.6 (5)	0.1	5.2	6.1 (5)	0.5	16.3
Sinter furnace	1.1	0.9 (10)	0.2	2.4	1.4 (4)	1.0	1.9
Vacuum cast furnace	4.8	2.0 (6)	0.4	6.7	25.6 (7)	1.4	111.4

TABLE 3. Categorization by Exposure Range of Mean, Minimum, Maximum, and Difference Between Maximum and Minimum BZ Exposure Values, Calculated by Date

Exposure Range ($\mu g/m^3$)	Number of BZ Exposure Estimates Within Range			
	Mean	Minimum	Maximum	Max-Min
<1	33	99	23	78
1.1–2.0	40	59	37	18
2.1–4.0	63	44	40	29
4.1–8.0	47	13	43	33
>8.1	40	8	80	65
Total	223	223	223	223

November 1974 are shown in Table 2. Although the DWA exposure values are below 2 $\mu g/m^3$ for six of the seven job titles, five of the BZ means exceed 2 $\mu g/m^3$, the 8-hour time-weighted average exposure limit in effect since 1948.[3,4] Moreover, the maximum exposure values exceed 2 $\mu g/m^3$ in many instances for both the BZ and GA samples. The BZ mean is greater than the GA mean for each job; for only one job (sinter furnace) is the GA maximum less than the BZ mean.

Table 3 presents the number of BZ mean, minimum, and maximum values within each category of exposure. The magnitude of the difference between the maximum and minimum concentrations measured for each task has also been included; the 223 BZ exposure estimates are specific for the date of sample collection. The data show that the majority of these short-term BZ exposures exceed 2 $\mu g/m^3$. For example, 73 percent (163 of 223) of the maximum BZ values are greater than 2.0 $\mu g/m^3$, with 36 percent (80 of 223) above 8.0 $\mu g/m^3$. Twenty-nine percent (65 of 223) of the ranges between maximum and minimum values exceed 8.1 $\mu g/m^3$. The range of BZ exposures is illustrated by the fact that the maximum exceeds the minimum in 57 percent of the data.

The results of a similar analysis conducted for the GA samples are summarized in Table 4. Both the magnitude and range of the GA data are lower than the BZ data. An analysis of the data presented in Tables 3 and 4 by job for all survey dates provided generally comparable proportions to those shown for each survey date.

Time Exposure Compared with DWA

The multiples of the DWAs for the BZ samples are shown in Table 5 by duration of exposure for each task performed. The total number of BZ exposure estimates was reduced from 719 to 705 because 14 tasks lacked information on duration of exposure. Eighty-three percent (587 of 705) of the tasks sampled in the BZ were conducted for 30 minutes or less in duration, according to the time–motion study information. Seventy-eight percent (455 of 587) of the exposures at these tasks were greater than the calculated DWA exposure value. Eight percent (55 of 705) of the BZ task exposures exceeded the DWA by ten times or more.

Table 6 presents the distribution of GA samples by range of multiples of the DWA and by duration of exposure for each task performed. Nine GA samples were not included in this analysis because the DWA calculation sheet did not contain a value for duration of exposure, reducing the number of individual GA samples in this analysis from 1152 to 1143. Fifty-eight percent (668 of 1143) of all the GA samples had a duration of exposure greater than 30 minutes, with 392 GA samples representative of activities exceeding 2 hours in duration. Seventy-two percent (824 of 1143) of the GA exposures were less than the DWA.

Multiples of the DWA for tasks representing exposures in excess of 2 $\mu g/m^3$ were compared with the duration of exposure for each task (data not shown). Restricting the analysis to BZ task exposures exceeding 2 $\mu g/m^3$ reduced the data set from the 705 exposure estimates shown in Table 5 to 418; thus, 59 percent (418 of 705) of the BZ exposure estimates were greater than 2 $\mu g/m^3$. Ninety-one percent (381 of 418) of these tasks had durations of exposure less than 30 minutes. Thirty-three percent (136 of 418) of the BZ task exposures exceeded the DWA by five or more times. For similarly categorized multiples of the DWA for GA samples, only 17 percent exceeded 2 $\mu g/m^3$; 68 percent (130 of 192) had durations of exposure greater than 30 minutes.

Both GA and BZ production task exposure estimates were included in DWA calculations for 35 job titles. As shown in

TABLE 4. Categorization by Exposure Range of Mean, Minimum, Maximum, and Difference Between Maximum and Minimum GA Exposure Values, Calculated by Date

Exposure Range ($\mu g/m^3$)	Number of GA Exposure Estimates Within Range			
	Mean	Minimum	Maximum	Max-Min
<1	132	201	67	126
1.1–2.0	58	17	67	52
2.1–4.0	25	8	46	32
4.1–8.0	14	5	33	25
>8.1	3	1	19	17
Total	232	232	232	232

TABLE 5. Categorization by Range of Multiple DWA of Duration of Exposure of BZ Exposures

Range of Multiple of the DWA	Number of BZ Exposure Estimates Within Range (Minutes of Exposure)					
	0–30	31–60	61–120	121–180	>180	Total
<1.0	132	24	2	4	17	179
1.1–2.0	129	14	5	3	27	178
2.1–3.0	91	4	3	0	4	102
3.1–4.0	64	2	0	3	0	69
4.1–5.0	38	2	1	0	0	41
5.1–10.0	79	2	0	0	0	81
>10.0	54	1	0	0	0	55
Total	587	49	11	10	48	705

Table 7, five of the job titles were in the same group when categorized by DWA and maximum BZ value. All other titles (30 of 35) increased by one or more levels, however. When categorized using maximum GA exposure values, 11 titles remained at the same level, while 14 increased in level (data not shown).

Discussion

Exposure Range

It may be observed in Table 2 that the average values for the mean, minimum, and maximum BZ values exceeded the counterpart GA samples for several job titles. BZ samples typically exceeded the calculated DWA exposure value. For example, the vacuum cast furnace operator received a mean BZ exposure of 25.61 $\mu g/m^3$, while the mean GA samples had an average concentration of 1.98 $\mu g/m^3$. The lower GA samples sufficiently reduce the overall, weighted average to produce a calculated DWA value of 4.75 $\mu g/m^3$. This trend was observed for a number of job titles, including the attrition mill operator and the reduction furnace operator.

In comparison with the BZ samples, most GA samples were below 2 $\mu g/m^3$, as shown in Tables 3 and 4. BZ means and maximum values were generally higher than GA mean and maximum values. BZ samples tended to have larger differences between maximum and minimum values when compared with the GA samples. Thus, examination of the data suggests that BZ samples represent activities of higher exposure for most metrics examined. This is consistent with BZ sample collection near points of emission, and GA samples at other locations where employees spend time. The wide range of concentrations represented by the BZ samples may result from process variability and/or differences in work practices among employees.

Task Exposure Compared with DWA

The results shown in Table 5 indicate that exposure at many BZ tasks exceeded the calculated DWA but were of short duration, with most (587 of 705) being of 30 minutes or less in duration; 19 percent (136 of 705) of these exposures exceeded the calculated DWA by five times or more. In contrast to the BZ tasks, the GA samples reflected lower exposure and were of longer duration. After removing samples less than 2 $\mu g/m^3$, it was shown that the number of GA samples was reduced dramatically—from 1143 to 192. The number of BZ tasks was reduced by less than half, from 705 to 418. The trend of BZ samples being of higher concentration and shorter duration was once again observed.

Categorizing job titles by the maximum BZ or GA exposure changed the distribution of each job title in an exposure ranking scheme compared with the initial categorization by the DWA. Thirty of 35 titles categorized using BZ maximum concentration increased by at least one group, with 16 increasing by two or more groups. Therefore, the exposure metric selected for an epidemiologic analysis could alter the overall evaluation of exposure effect. For example, suppose exposure data are available for a particular toxin reflecting both short-term, high intensity exposure and lower intensity, long-dura-

TABLE 6. Categorization by Range of the Multiple of the DWA of Duration of Exposure for GA Exposures

Range of Multiple of the DWA	Number of GA Exposure Estimates Within Range (Minutes of Exposure)					
	0–30	31–60	61–120	121–180	>180	Total
<1.0	352	105	68	159	140	824
1.1–2.0	64	40	33	37	41	215
2.1–3.0	34	12	3	7	2	58
3.1–4.0	9	1	1	2	2	15
4.1–5.0	4	4	0	1	0	9
5.1–10.0	7	2	1	0	1	11
>10.0	5	5	1	0	0	11
Total	475	169	107	206	186	1143

TABLE 7. Categorization of 35 Job Titles by DWA and Maximum BZ Exposure

DWA Exposure Category	Maximum BZ Exposure Category					
	1	2	3	4	5	Total
1	0	0	0	0	0	0
2	0	1	3	2	1	7
3	0	0	3	8	13	24
4	0	0	0	1	3	4
5	0	0	0	0	0	0
Total	0	1	6	11	17	35

The ranges of exposure in categories 1 through 5 are 0.0 to 0.20, 0.21 to 0.80, 0.81 to 3.17, 3.22 to 12.34, and 13.00 to 50.01 $\mu g/m^3$, respectively.

tion exposure. An epidemiologic analysis is planned to investigate exposure response. Analysis using the two metrics will provide similar results only if the two are highly correlated. If not highly correlated, one metric could show a strong exposure response, while the other shows no association.

With the development of full-shift sampling in the early 1970s, few data sets have been retained which include task-specific exposure measures. The observations reported are derived from the only DWA data sheets available through the Industry-Wide Studies Branch, National Institute for Occupational Safety and Health (NIOSH). It is not known why these data were forwarded to NIOSH.[2] Other similarly detailed DWA information is available from other sources[2] and should be analyzed to evaluate whether consistent results are found in a larger data set and over a longer time period.

Selection of categories for the concentration and duration of exposures is necessarily arbitrary and might be more rigorously developed in subsequent analyses; for example, in a larger data set the statistical significance of differences between groups might be determined.

In the analysis presented, the short-term BZ and GA exposure measurements are compared with the DWA standard of 2 $\mu g/m^3$. This approach was taken to contrast the potential differences in exposure categorization between the DWA and its components. In subsequent analyses, comparisons could also be made with ceiling or maximum exposure limits.[3,4]

Conclusion

The work presented was undertaken as part of a project to describe available exposure data and their applicability to a mortality study currently being conducted by NIOSH. The availability of task-specific exposure measurements used in the calculation of the DWA in the beryllium industry offers opportunity to describe exposure by metrics other than the cumulative exposure. This may be particularly valuable in this data set, where the maximum exposure, being of short duration, is not the major determinant of the DWA. Thirty-six percent (80 of 223) of the maximum BZ exposure measurements exceeded 8 $\mu g/m^3$, compared with 8 percent (19 of 232) of the maximum GA measurements. Less than 10 percent (69 of 705) of the BZ tasks exceeded 60 minutes in duration, while 44 percent (499 of 1143) of the GA tasks require more than 60 minutes to complete. Thus, the highest exposures experienced by workers generally were of short duration and exceeded both the DWA and 2 $\mu g/m^3$.

Refinement of the categories presented, or use of actual exposure magnitudes and durations, would allow construction of multiple parameters for an exposure–response analysis. Specifically, the exposure of greatest magnitude and its duration are available for study; a peak cumulative exposure could be constructed by multiplying the highest exposure by the duration, either for one job or across all jobs. The magnitude of the BZ or GA exposures compared with the calculated DWA could be used as an exposure metric influenced by the variability of airborne concentrations throughout the shift. Should an association be found between exposure and response, identification of a specific parameter as most predictive of disease would aid substantially in the development of strategies to more adequately control exposures.

The approach presented may be of value in other efforts in retrospective exposure assessment where task-specific sampling data are available.

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