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Beryllium Sensitization, Chronic Beryllium Disease, and Exposures at a Beryllium Mining and Extraction Facility

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In this study, we examine beryllium sensitization, chronic beryllium disease (CBD), and workplace exposures at a beryllium mining (mine) and extraction facility (mill) in Delta, Utah. Historical airborne beryllium data collected between 1970–1999 included general area (GA), breathing zone (BZ), and personal lapel (LP) measurements and calculations of job-specific quarterly daily-weighted averages (DWAs). We compared GA, BZ, and DWA data to airborne beryllium data from a mixed beryllium products facility and a beryllium ceramics facility located in Elmore, Ohio and Tucson, Arizona, respectively. At the Delta facility, jobs involving beryllium hydrolysis and wet-grinding activities had the highest air concentrations; annual median GA concentrations were less than 0.3 $\mu g/m^3$ or both areas. Annual median GA sample concentrations ranged from 0.1–0.4 $\mu g/m^3$ at Delta. These levels were generally lower than Elmore (0.1–1.0 $\mu g/m^3$) and were comparable to the Tucson facility (0.1–0.4 $\mu g/m^3$). Median BZ concentrations were higher, whereas DWAs were lower at the Delta facility than at the other two facilities. Among the 87 employees at the Delta facility, 75 participated in the medical survey; there were three persons sensitized, one with CBD. The individual with CBD previously worked at the Elmore facility for 10 years. Cumulative CBD incidence rates were significantly lower at the Delta facility: 0.3 percent compared to 2.0 percent for Elmore and 2.5 percent for the Tucson facility. Sensitization and CBD prevalence rates determined from cross-sectional surveys for the Delta facility were lower than but not significantly different from rates at the other two facilities. There was no sensitization or CBD among those who worked only at the mine where the only exposure to beryllium results from working with bertrandite ore. Although these resnlts are derived from a small sample, this study suggests that the form of beryllium may affect the likelihood of developing CBD. Specifically, exposure to beryl and bertrandite ore dusts or to beryllium salts, in the absence of exposure to beryllium oxide particulates appears to pose a lower risk for developing CBD.

Keywords Beryllium, Chronic Beryllium Disease, Beryllium Sensitization, Mining, Exposure

Chronic beryllium disease (CBD) is a potentially debilitating and fatal lung disease. It is a significant occupational health concern in the manufacturing and processing of beryllium-containing materials. Previous medical and epidemiological data collected from workers at nuclear weapons facilities and beryllium manufacturing facilities have reported facility prevalence rates of beryllium sensitization as measured in the blood of 2.0–6.9 percent and facility CBD prevalence rates of 0.6–4.6 percent.[1–7] These studies have raised several key issues, including whether CBD can result from exposures of less than the occupational exposure limit (OEL) of 2 $\mu g/m^3$, whether a dose-response relationship exists between total airborne beryllium concentration and CBD, and whether the chemical form or particle size of beryllium is more predictive of CBD risk than is total air mass concentration.

Rates of CBD have been reported as 4.1 percent among beryllium manufacturing workers,[4] 2.9–3.6 percent among precious metal refinery workers,[5] and 1.8 percent among beryllium ceramics workers.[2] Other studies in which both beryllium sensitization and CBD were considered reported the following rates: (1) 2.0 percent and 1.7 percent among nuclear weapons workers;[6] (2) 1.5 percent and 0.6 percent in another study of nuclear weapons workers;[7] (3) 6.9 percent and 4.6 percent in a study of beryllium manufacturing workers;[3] and (4) 5.9 percent and 4.4 percent among all beryllium ceramics workers.[1] Within this latter group, the beryllium sensitization rate was 14.3 percent among machinists, who had the highest exposures at the facility.[1] In contrast with these studies, a facility in Cardiff, Wales, United Kingdom, has reported one case of CBD where lung involvement occurred subsequent to a hand wound contaminated with beryllium oxide and local and ascending skin and lymphatic granulomatosis in the involved arm.[8] This facility used traditional occupational health monitoring procedures including chest radiography and pulmonary function tests.[9] However, neither current nor former workers at this facility have undergone surveillance using the beryllium blood lymphocyte proliferation test (BLPT) to detect beryllium sensitization.

Mining and Milling Facility

Beryllium ore is mined and milled at the Delta facility in Utah, which currently employs 87 workers, 3 of whom worked exclusively in the mine and mill. The Delta mining and milling facility has been in operation since 1969. The industrial hygiene program was instituted in the same year and consisted of air sampling (both area and breathing zone) of beryllium, engineering controls, and a respirator program. Personal lapel sampling surveys were conducted in 1983–1985 and were instituted on a regular basis in 1999. Since its inception in 1969 there have been generally less than 100 employees, with a total of 360 employees who ever worked at the Delta facility. The types of occupations at the facility include administrative personnel, maintenance, services, and production employees (e.g., operators of the hydrolysis and other processing areas such as leaching, wet grinding, and thickening). Each of these occupational groups represents 20–30 percent of the workforce.

Employees at this beryllium mine and ore facility participated in two prior surveys, in 1979 and 1982, which used a predecessor version of the lymphocyte proliferation test. In the Rom et al. study,[10] 13 of 82 (15.9%) participants were considered positive in 1979, and 5 of 61 (8.2%) in 1982. Three persons were positive in both surveys, and no diagnosis of CBD was made. There was no relationship found between positive results on the blood test and pulmonary function or X-ray findings.

Production Techniques

Beryl ore (containing 3.6–5.0% beryllium) was the major source of beryllium until 1969, when Brush Wellman Inc. began commercial extraction from bertrandite ore (containing an average concentration of 0.23% beryllium).[9] The ore is wet milled, leached with sulfuric acid at high temperatures, and separated from solids by counter-current decantation (CCD) thickener operations (Figure 1).

A beryllium concentrate is produced when the leach solution undergoes a counter-current solvent extraction process. Aqueous ammonium carbonate is used to strip beryllium from the organic phase of the solution. The strip solution is heated producing co-extracted iron and aluminum precipitates. These precipitates are removed by filtration and the solution is heated and filtered several times to yield a beryllium hydroxide product. Beryl ore, mined in South America and collected worldwide from the tailings left from gemstone mining, is also processed at the mining and extraction facility. The extraction process involves melting the ore and reacting it with sulfuric acid to produce a water-soluble sulfate solution that is processed thereafter in the same manner as bertrandite ore.

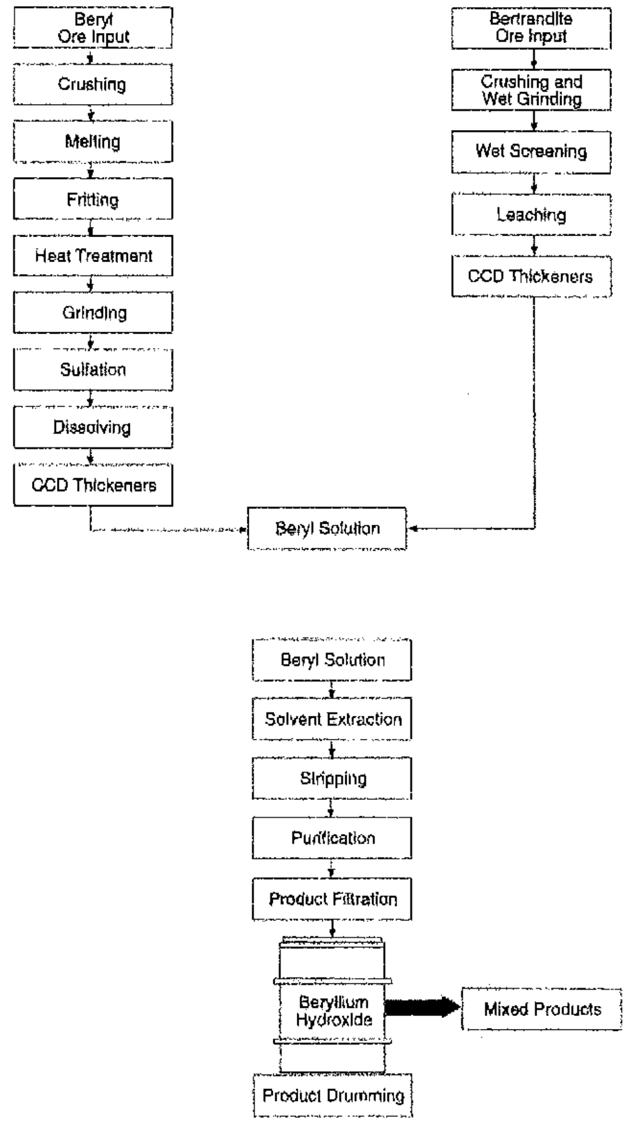

FIGURE 1
Processes at the beryllium mining and extraction facility. CCD = counter current decantation.

The beryllium hydroxide product from the extraction process is packed in barrels and sent to facilities where it is used as the input material for chemical/furnace extraction of beryllium metal and beryllium oxide, and as the input material for the formulation of copper beryllium master alloy (4% by weight).

The Elmore, Ohio, facility is a primary producer of beryllium-containing materials and products for the use in commerce. The Elmore facility manufactures the three product lines (alloys, metal, and beryllium oxide) using a combination of chemical treatment, heat driven chemical reactions, melting and casting, powder metallurgy, and hot and cold working of beryllium and alloy products. The beryllium oxide powder produced at Elmore is shipped to the facility in Tucson, Arizona, where the powder is prepared for use in processes that consolidate the powder into useful ceramic shapes. Processing operations include pressing, firing furnaces, and machiniug.

Although exposure to beryllium, as measured by airborne mass concentration, occurs at the Delta facility, the specific characteristics of the beryllium in the air at the mill, the chemical species (beryllium hydroxide, beryllium salts, and beryllium ores), and the particle size distribution have not been determined. Based on knowledge of the mining and milling processes at the Delta facility, beryllium exposure at the mine is from inhalation of dust containing bertrandite (hydrated beryllium silicate). At the mill, beryllium in the air may be in the form of dust from bertrandite, as well as beryl (beryllium aluminum silicate) ores, mists containing soluble beryllium salts (beryllium sulfate, beryllium ammonium carbonate, and beryllium carbonate), and particles escaping from the process of precipitation and packaging of the plant's end product, hydrated beryllium hydroxide. These forms of beryllium differ from the forms to which most beryllium manufacturing and U.S. Department of Energy workers are exposed: beryllium metal, alloys, and beryllium ceramics. This mining/extraction workforce at the Delta facility may provide important information regarding the relative toxicity of different forms of beryllium.

Occupational Health Surveillance at the Delta Site

The industrial hygiene program includes personal, high-volume breathing-zone sampling, and area monitoring for beryllium in air, administrative and engineering controls, work practice assessments a comprehensive respirator program and health safety education.

The Blood Lymphocyte Proliferation Test (BLPT), which measures immunological response to beryllium, was developed in the 1970s and has been modified to its current protocol.(12) It is now used in beryllium industries to identify workers sensitized to beryllium. Delta workers have participated in mandatory quarterly or annual pulmonary function tests, pulmonary diffusion tests, and chest x-rays since the mine and plant opened in 1969. From September 1996 to January 1997, a survey was conducted to evaluate employees for beryllium sensitization and CBD. Facility-wide beryllium air concentration trends and medical monitoring results for sensitization and CBD were examined at the Delta facility and compared to the Elmore and Tucson facilities.

METHODS

Historical Beryllium Exposure Data

A variety of airborne beryllium concentration monitoring data (general area [GA], breathing zone [BZ], and personal lapel [LP]) have been routinely collected at Brush Wellman facilities. The same sampling protocol was used at all three facilities. Available electronic and hard-copy air concentration data for the Delta, Utah facility (1970–1999), the Elmore, Ohio facility (1978–1999), and the Tucson, Arizona facility (1981–1999), were consolidated (Table I). Of the 34,307 beryllium air samples collected at Delta, 95 percent were general area (GA), 3 percent were high-volume breathing-zone (BZ), and 2 percent were personal lapel (LP) samples. Daily-weighted averages (DWAs) were used to estimate time-weighted-average employee exposures; 1519 DWA estimates were calculated at the Delta facility.

TABLE I
Type and number of samples collected at the beryllium mine and mill (Delta), mixed products (Elmore), and ceramics production (Tucson) facilities

	General area samples		Breathing zone samples		Daily-weighted average samples		Personal lapel samples	
Facility	Years available	No. of samples	Years available	No. of samples	Years available	No. of samples	Years available	No. of samples
Mine and mill	1970–1999	32,568	1970–1999	1,014	1985, 1990–1993	1,519	1990, 1992, 1994–1999	725
Mixed products[A]	1978–1999	187,462	1978–1999	17,920	1958–1996 (1985, 1990–1993)	6,839 (1,043)	1994–1999	1,552
Ceramics production	1981–1999	11,327	1981–1999	8,797	1981–1998	730	1982–1985,	816
					(1985, 1990–1993)	(316)	1991–1999	

[A]Additional exposure data have been collected at this facility but are not included in this summary.

Air Sampling Methodology

High-volume, continuous, and low-flow sampling methods were used at various times by the facility. High-volume samplers draw air through a 10.5-cm (diameter) Whatman 41 filter at a rate of 200 to 400 liters per minute. Continuous samplers draw air through a 25-mm Whatman 41 filter/cassette at a flow rate of 10 to 20 liters per minute. Low-flow samplers draw air through a 0.8-μm pore size mixed cellulose ester filter/cartridge at a sampling rate of approximately 2 liters per minute.

GA samples were taken in locations near certain processes or activities using the three sampling methods described above. GA samples collected by the high-volume method were usually for 30 minutes, but could range from 10 minutes to 1 hour.[13] The continuous method was used to obtain samples for a period of 8–24 hours. BZ samples were taken within a 1-foot radius of an operator's head using the high-volume method for 1–5 minutes.[12] LP samples were collected using standard 8-hour personnel sampling methods using the low-volume method by placing a filter cassette on a worker's lapel for an entire 8-hour work shift.

Using the methodology developed by the U.S. Atomic Energy Commission,[14] task- or activity-specific GA and BZ sample results were averaged over a quarter (three-month period) to arrive at an average concentration for a task. DWAs were calculated for each job title by taking the average time each task is performed in the job title and multiplying this number by the average concentration for that task. These results were summed to calculate the DWA for a specific job title.[15] Samples were analyzed by flame atomic absorption spectrophotometry.[16] The analytical detection limit for all beryllium samples was approximately 0.1 $\mu g/m^3$. For purposes of estimating exposure, samples containing less than the detection limit were assigned the value 0.05 $\mu g/m^3$.

Characterization of Historical Air Sampling Data

GA and BZ data were averaged for each year to evaluate general facility-wide and work-area specific trends over time. Descriptive statistics (mean, median, maximum, 95th percentile, its upper 95% confidence [tolerance] limit,[17] and fraction exceeding 2.0 $\mu g/m^3$) were calculated and compared across all three facilities. The fraction exceeding 2.0 $\mu g/m^3$ (the "exceedance fraction") is the simple proportion of the total measurements that are greater than 2.0. DWAs and LP samples that were available by job titles at Delta for 1985 and 1990–1993 were described similarly.

Medical Monitoring of Chronic Beryllium Disease

During the period September 1996 through January 1997, all 87 current employees at the Delta facility were invited to voluntarily participate in a survey for beryllium sensitization and CBD. Workers who initially did not agree to participate were encouraged to reconsider during the course of the survey. Before blood was drawn for the BLPT, the facility nurse administered a questionnaire that included questions on respiratory symptoms, medical history, work and exposure history, and any work history outside the mining and extraction facility that may have involved beryllium exposure.

BLPTs

Sixty milliliters of blood from each participant was collected in six 10-mL heparinized vacutainer tubes. Three sample tubes were sent via overnight courier to each of two separate laboratories for BLPT analysis: (1) Specialty Laboratories in Santa Monica, California, and (2) the Cleveland Clinic in Cleveland, Ohio. Blood test results were reported as normal (negative response to beryllium), abnormal (positive response to beryllium), or unsatisfactory. A test was considered positive if two or more of six beryllium stimulation indices were equal to or greater than 3.0.[2] The test was unsatisfactory if there was no response to either of the positive controls (phytohemagglutinin and either *Candida albicans* or tetanus toxoid antigen). Testing was repeated on participants with unsatisfactory test results.

Clinical Evaluation

Any participant with one or more abnormal BLPT result(s), or with unexplained respiratory symptoms was offered clinical evaluation, which included examination by a pulmonologist, flexible fiberoptic bronchoscopy with bronchoalveolar lavage (BAL), BAL lymphocyte proliferation testing (BALLPT), and transbronchial biopsies.

CBD diagnosis was based on (1) evidence of beryllium sensitization, as demonstrated by two abnormal BLPTs or an abnormal BALLPT, and (2) the presence of granulomas on biopsy.[12] Individuals were diagnosed with clinical CBD if they experienced respiratory symptoms and were positive on the above two criteria. Individuals with CBD who met the above criteria but were asymptomatic were considered to have subclinical CBD. Individuals who were positive for beryllium sensitization (at least two abnormal BLPTs and/or abnormal BALLPT) and who lacked granulomas on biopsy were considered to be beryllium sensitized but not positive for CBD.

Surveys at Other Brush Wellman Facilities and Incidence of Sensitization and Disease

Similar medical screening surveys have been performed at the Tucson and Elmore facilities.[1,3] Available information on these surveys included the number of employees involved in the surveys, the number of employees sensitized, and those diagnosed with CBD prior to and during each of the surveys, as well as the total number of employees ever employed at these three facilities. Using the number of employees who currently work at each of the facilities as denominators, the prevalence of sensitization and CBD was calculated for all three plants: Delta (1996–1997), Elmore (1993–1995), and Tucson (1992). Cumulative incidence rates for CBD at each facility were also calculated over the following time periods: 1969–1996 for Delta, 1960–1996 for Elmore, and 1980–1996 for Tucson.

Workplace and Work History Associations with Beryllium Sensitization and CBD

Personnel data were reviewed to ascertain all jobs held by the employee, the duration the employee worked at each position, and the area and department of each job held. An employee who worked at another work site with beryllium exposure for more than one month was classified as having beryllium exposure from another work site. Job positions were grouped into two categories: administration and production.

Potential relationships between surrogate measures of beryllium exposure (industrial hygiene qualitative evaluation, employee self-report, and accidental exposure) and beryllium sensitization or CBD were evaluated. Several cumulative exposure scores were created by multiplying exposure duration and the relative exposure levels. Relative exposures were based on the qualitative exposure scale (scale of 1–6 devised for job positions and areas of the facility) and on a review of available airborne beryllium data by consensus between a plant health and safety official and senior manager who were unaware of the medical survey results. A cumulative exposure score was created by multiplying the above scale by the time in days in any job position and summing this over an employee's entire work history.

Statistical Analyses of Health Survey Data

Questionnaire and clinical results were analyzed using the Fisher's exact test and Student's t-test, where appropriate. In cases of small numbers, only descriptive analyses are presented. One case of CBD was observed in an employee who worked at both the mill and at the Elmore facility. Cumulative incidence rates of CBD cases were evaluated using chi-square analysis. Exposure data were summarized as described previously.

RESULTS

Exposure Trends

General Area Sampling

The annual median airborne concentrations for GA samples taken at Delta ranged from 0.1 to 0.6 $\mu g/m^3$ from 1970 to 1999. GA concentrations have decreased over time at all three facilities (Figure 2). Annual median concentrations ranged from 0.1 to 1.0 $\mu g/m^3$ and from 0.1 to 0.4 $\mu g/m^3$ for the Elmore and Tucson facilities, respectively. The highest concentration for all Delta samples occurred in 1971 (234.5 $\mu g/m^3$) (Table II). In general, the annual median GA sample results for Delta were lower than those of the Elmore facility, but were comparable to those of the Tucson facility (Figure 2).

The maximum concentrations were 2,800 $\mu g/m^3$ for the Elmore facility and 296.50 $\mu g/m^3$ for the Tucson facility. Approximately 5% of the GA samples collected at Delta exceeded 2.0 $\mu g/m^3$, and 11.5% and 3.0% exceeded this level for the Elmore and Tucson facilities. The highest exposure locations/activities at Delta were generally the mill wet grind and beryllium

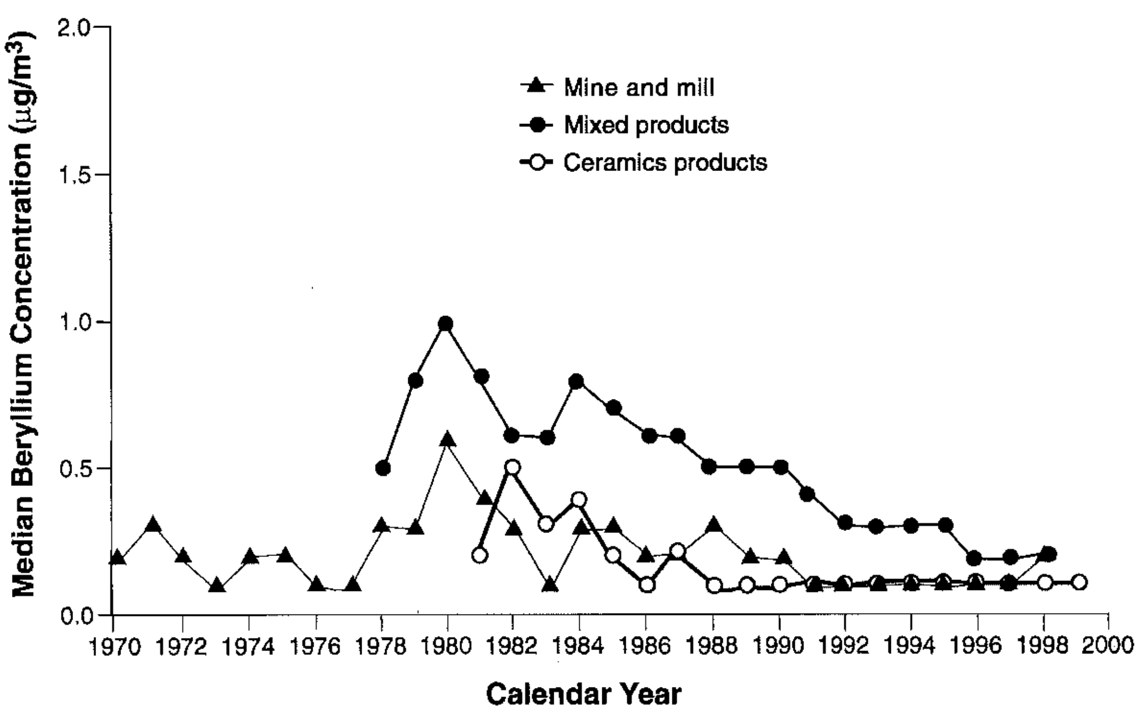

FIGURE 2
Annual median concentrations for general area samples for the mine and mill (Delta) facility, mixed products (Elmore) facility, and ceramics production (Tucson) facility, 1970–1999.

TABLE II
Summary statistics of beryllium concentrations for general area samples at the Delta facility, 1970–1999

Year	Sample size	Arithmetic mean (μg/m^3)	Median (μg/m^3)	Maximum (μg/m^3)	95th percentile (μg/m^3)	Percent >2 μg/m^3
1970	388	0.5	0.2	6.2	1.7	4.1
1971	330	1.9	0.3	234.5	2.6	8.9
1972	401	0.7	0.2	25.5	2.8	6.7
1973	512	0.9	0.1	153.3	2.0	4.9
1974	630	0.9	0.2	26.7	4.2	8.7
1975	514	0.4	0.2	9.5	1.0	1.8
1976	607	0.5	0.1	71.4	1.3	3.1
1977	609	0.4	0.1	26.8	1.4	3.1
1978	854	0.8	0.3	39.4	2.2	5.7
1979	99	1.1	0.3	17.1	5.6	14.1
1980	1,836	1.1	0.6	57.6	3.2	9.8
1981	1,945	0.9	0.4	40.9	3.1	9.7
1982	943	0.8	0.3	206.0	1.7	3.3
1983	804	0.3	0.1	15.9	0.7	1.1
1984	1,580	0.7	0.3	28.5	2.3	6.0
1985	1,754	0.6	0.3	11.4	2.2	5.6
1986	1,075	0.8	0.2	75.0	2.4	6.1
1987	1,109	0.6	0.2	36.1	2.0	4.8
1988	1,150	0.5	0.3	36.2	1.5	2.8
1989	1,035	0.4	0.2	31.1	1.3	3.1
1990	1,332	0.4	0.2	21.0	1.4	2.0
1991	1,182	0.3	0.1	5.6	1.0	2.1
1992	1,410	0.4	0.1	24.3	1.0	3.3
1993	1,516	0.4	0.1	45.0	1.3	2.6
1994	1,225	0.3	0.1	23.1	0.7	1.6
1995	1,566	0.3	0.1	17.2	0.8	1.7
1996	1,690	0.4	0.1	70.8	1.6	3.5
1997	1,762	0.4	0.1	23.9	1.5	3.5
1998	1,823	1.5	0.2	140.0	7.0	11.6
1999	887	0.3	0.1	44.3	0.8	0.5

hydrolysis areas (Tables III and IV). The beryl plant, counter current decantation (CCD) area, and solvent extraction (SX) areas were intermediate, with concentrations generally higher than the low areas, which included the maintenance, leach, services, centrifuge building, administrative building, laboratory, and mine (Tables III and IV).

Breathing Zone Sampling

The individual Delta BZ samples for all measurements, with or without duration information, ranged from below the detection limit to 806.3 μg/m^3. The annual medians for BZ samples for the Elmore facility (ranging from 0.7 to 2.1 μg/m^3) and the Tucson facility (ranging from 0.1 to 0.9 μg/m^3) were less heterogeneous than those from Delta (0.3 to 15.9 μg/m^3) (Figure 3). The highest measured concentrations for all samples were 4,504.6 μg/m^3 for the Elmore facility and 386.30 μg/m^3 for the Tucson facility. The percentage of BZ samples that exceeded 2.0 μg/m^3 was 51% at Delta reflecting the emphasis on sampling higher exposure areas. The percentage of BZ samples that exceeded 2.0 μg/m^3 was 35% at the Elmore facility and 9% at the Tucson facility. BZ levels have decreased over time (1970–1999) at all three facilities (Figure 3). By specific work areas, BZ samples were the highest at beryllium hydrolysis locations at the mill (Table IV). BZ values were not adjusted to account for the wearing of respiratory protection.

Daily-Weighted Averages

The median DWA concentrations for 10 different job titles at Delta ranged from 0.08 to 0.2 μg/m^3 (Table V). The beryllium hydrolysis operator had the highest DWA values; the maximum

TABLE III

Summary statistics of beryllium concentrations of general area (GA) samples for different areas of the Delta facility

Area	Type of sample	Duration of sampling (minutes)[A]	Number of samples	Sampling period	Arithmetic mean ($\mu g/m^3$)	Median ($\mu g/m^3$)	Maximum ($\mu g/m^3$)	95th percentile	95% tolerance limit	Percent $>2.0\ \mu g/m^3$
Wet grind	GA	≤60	2,492	1970–1996	0.9	0.3	75.0	2.7	3.0	7.4
	GA	60+	271	1978–1999	0.7	0.4	19.2	2.3	3.0	2.9
Beryllium hydrolysis	GA	≤60	4,002	1970–1996	0.9	0.4	57.6	2.9	3.3	8.1
	GA	60+	4,017	1974–1999	0.6	0.2	70.8	1.9	2.1	4.2
SX	GA	≤60	155	1980–1996	0.3	0.1	8.0	1.1	1.8	1.3
	GA	60+	1,102	1976–1999	0.2	0.1	3.9	0.6	0.8	0.7
CCD	GA	≤60	700	1975–1998	0.3	0.1	5.8	1.1	1.4	1.4
	GA	60+	66	1991–1999	0.16	0.1	3.3	0.2	3.3	1.5
Beryl plant	GA	≤60	3,520	1978–1999	0.7	0.2	45.0	2.5	2.7	6.5
	GA	60+	6,789	1978–1999	0.8	0.2	140.0	2.8	3.1	7.3
Maintenance	GA	≤60	550	1970–1996	0.2	0.1	2.9	0.5	0.6	0.2
	GA	60+	100	1996–1999	0.1	0.1	2.1	0.2	2.1	1.0
Leach	GA	≤60	1,594	1970–1996	0.2	0.1	8.5	0.6	0.7	0.7
	GA	60+	197	1984–1999	0.2	0.1	3.0	0.4	0.9	0.5
Services	GA	≤60	445	1970–1996	0.2	0.1	3.3	0.6	1.0	0.2
	GA	60+	74	1984–1999	0.1	0.1	0.2	0.1	0.2	—
Centrifuge building	GA	≤60	853	1981–1996	0.4	0.1	206.0	0.4	0.5	0.4
	GA	60+	150	1996–1999	0.1	0.1	0.7	0.2	0.4	—
Administrative building	GA	≤60	1,779	1970–1994	0.2	0.1	71.4	0.4	0.5	0.3
	GA	60+	296	1971–1999	0.1	0.1	1.6	0.2	0.3	—
Laboratory	GA	≤60	1,310	1970–1997	0.2	0.1	6.7	0.4	0.4	0.2
	GA	60+	198	1972–1999	0.1	0.1	2.0	0.2	0.6	—
Mine	GA	≤60	433	1992–1999	0.2	0.1	5.3	0.5	0.7	1.4
	GA	60+	33	1994–1999	0.5	0.1	5.3	3.9	5.3	11.5
AIS	GA	≤60	128	1990–1998	0.2	0.1	3.8	0.4	1.1	0.8
	GA	60+	60	1995–1999	0.1	0.1	0.5	0.4	0.5	—

[A]Samples without duration of sampling information are not included. Less than 1 percent of samples in each area were missing information on sampling duration. SX = solvent extraction, CCD = counter current decantation, AIS =

TABLE IV
Summary statistics of beryllium concentrations for breathing zone (BZ) and personal lapel (LP) samples for different areas of the Delta mine and mill, 1971–1999

Area	Type of sample	Number of samples	Sampling period	Arithmetic mean ($\mu g/m^3$)	Median ($\mu g/m^3$)	Maximum ($\mu g/m^3$)	95% percentile	95% tolerance limit	Percent >2.0 $\mu g/m^3$
Beryllium hydrolysis	BZ	719[A]	1971–1999	8.1	2.5	271.2	34.8	43.3	55.5
Beryl plant	BZ	10	1988–1997	1.6	1.2	4.3	4.3	4.3	37.5
Mine	BZ	10	1995–1997	1.5	0.8	6.3	6.3	6.3	22.2
Laboratory	BZ	149[B]	1976–1999	1.1	0.3	40.3	2.7	8.1	8.1
Wet grind	LP	20	1995–1999	4.4	0.8	73.3	37.6	73.3	5.0
Beryllium hydrolysis	LP	38	1992–1999	6.9	0.5	165.7	72.0	165.7	10.5
SX	LP	25	1992–1999	0.7	0.1	13.3	1.2	13.3	4.0
CCD	LP	23	1995–1999	0.1	0.1	0.4	0.3	0.4	—
Beryl plant	LP	17	1992–1999	0.9	0.3	8.1	8.1	8.1	5.9
Maintenance	LP	108	1992–1999	1.6	0.1	122.6	2.7	12.4	5.7
Leach	LP	57	1995–1999	0.18	0.1	1.1	0.7	1.1	—
Services	LP	253[C]	1996–1999	0.3	0.1	15.5	1.6	2.2	2.8
Centrifuge building	LP	1	1998	0.05	0.05	0.05	0.05	—	—
Administrative building	LP	31	1992–1999	0.09	0.1	0.2	0.1	0.2	—
Laboratory	LP	4	1995–1999	0.1	0.1	0.5	0.2	0.5	—
Mine	LP	88	1992–1999	0.3	0.1	1.6	1.1	1.6	—

Note: For breathing zone and lapel data, there is no accounting or reduction in levels for when respiratory protection is worn. In general, sampling duration was for 1–5 minutes for BZ samples and 8 hours for LP samples, unless otherwise indicated. SX = solvent extraction, CCD = counter current decantation.

[A]Sampling duration for 3 percent of samples was 60+ minutes; 5 percent of samples are missing information on sampling duration. Samples without sampling duration are not shown.

[B]The percentage of samples with missing information on sampling duration is 0.7 percent. The highest BZ value was 806.3 $\mu g/m^3$.

[C]Duration of sampling for 89 percent of these LP samples was ≤60 minutes.

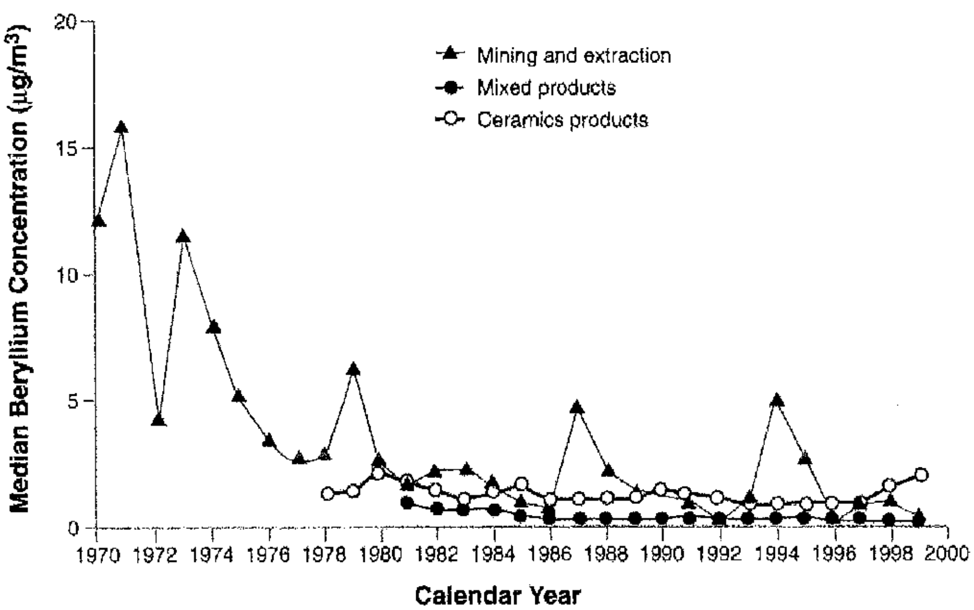

FIGURE 3
Annual median concentrations for breathing zone samples for the mining and extraction (Delta) facility, mixed products (Elmore) facility, and ceramics production (Tucson) facility, 1970–1999.

TABLE V
Quarterly daily-weighted average (DWA) concentrations by job title at the mine and mill, 1985, 1990–1993

Job title	No. of quarters	Arithmetic mean ($\mu g/m^3$)	Median ($\mu g/m^3$)	Maximum ($\mu g/m^3$)	No. of DWA >2.0 $\mu g/m^3$	% DWA >2.0 $\mu g/m^3$
Wet grind operator	19	0.2	0.2	0.3	0	0.0
Leach operator	19	0.2	0.2	0.3	0	0.0
Beryllium hydrolysis operator	19	0.4	0.2	2.5	1	5.3
Beryllium control lab technician	19	0.1	0.1	0.3	0	0.0
Beryllium instrument lab technician	19	0.1	0.1	0.3	0	0.0
SX operator	19	0.2	0.2	0.3	0	0.0
Thickener operator	19	0.2	0.1	0.3	0	0.0
Beryllium furnace operator	15	0.2	0.2	0.7	0	0.0
Sulfate mill operator	15	0.1	0.08	0.2	0	0.0
Ore processor	15	0.2	0.1	0.7	0	0.0

Note: Values are adjusted for the wearing of respiratory protection. SX = solvent extraction.

DWA value was 2.5 $\mu g/m^3$ at the beryllium hydrolysis area, which is consistent with the higher GA and BZ concentrations in this area. For the time periods when samples are available from all three locations (1985, 1990–1993), DWA concentrations calculated for 60 job titles were higher at the Elmore facility (medians ranged from 0.1 to 2.5 $\mu g/m^3$; data not shown). At the Tucson facility, DWAs (medians ranging from 0.1 to 0.5 $\mu g/m^3$; data not shown) were comparable to those of Delta. The above DWA values accounting for respiratory protection by assuming the concentration was zero when respiratory protection was worn. Though not reported here, DWAs were also calculated without adjusting for the wearing of respiratory protection.

Personal Lapel Sample Results

LP sample results (Table IV) indicate that wet grind and beryllium hydrolysis area workers had the highest air levels, with median concentrations of 0.8 and 0.5 $\mu g/m^3$, respectively. Median beryllium concentrations for 12 different areas of the plant ranged from 0.05 to 0.8 $\mu g/m^3$. The maximum concentration for a single sample was 165.7 $\mu g/m^3$ for a worker in the beryllium hydrolysis area. LP air concentrations were intermediate in the SX, CCD, beryl plant, and leach areas and were lowest in the services, centrifuge building, administrative building, laboratory, and mine areas. Three percent of individual LP sample air concentrations exceeded 2.0 $\mu g/m^3$.

Medical Monitoring Results

Seventy-five of 87 (86%) of the Delta facility employees participated in the survey and underwent BLPTs. Based on the BLPTs, two participants were confirmed to be beryllium-sensitized but did not have CBD. One individual had a single abnormal BLPT, but on additional testing, all tests were normal. This person was not considered to be sensitized but was offered pulmonary evaluation. Two additional participants had significant respiratory symptoms; one had a borderline BLPT and a previous biopsy indicating granulomatous lung disease (Table VI). Of these five individuals, three accepted a clinical evaluation. Of the three, two had no indication of CBD, and the third, the person previously known to have granulomatous disease, was diagnosed with CBD because of evidence of sensitization from the BALLPT.

Based on these counts, the prevalence of beryllium sensitization and CBD was 4.0 percent and 1.3 percent, respectively (Table VII). This beryllium sensitization prevalence was lower but not significantly different from that found at the mixed products facility (6.9%) and ceramics facility (5.9%) using comparable survey methods and definitions (Table VII). The CBD prevalence rates were 1.3 percent, 4.0 percent, and 4.4 percent for the mining and mill, mixed products, and ceramics facilities, respectively. However, these differences were also not significant ($P > 0.05$). Cumulative CBD rates, which incorporate past and present cases and all employees who have worked at the facilities, were 0.3 percent, 2.0 percent, and 2.4 percent for the mine and mill, mixed products, and ceramic facilities, respectively. The cumulative incidence rate for Delta was significantly ($P < 0.05$) lower than the other two sites (Table VII).

Demographics, Beryllium Sensitization, and CBD

The three beryllium-sensitized persons were all long-term male employees who held a variety of production jobs. None had ever worked at the mine. We compared the demographic

TABLE VI
Summary of clinical and survey findings in persons offered clinical evaluation who worked at the Delta facility

	Person				
Survey/test	A	B	C	D	E
BLPT	Confirmed positive	Confirmed positive	Unconfirmed positive	Negative, borderline	Negative
Symptoms	None	None	None	Cough, phlegm in AM, dyspnea on exertion	Dyspnea on exertion, AM cough
X-ray	Normal	Normal	Normal	1/1 small opacities	Normal
Pulmonary function test	Normal	Normal	Normal	FVC 97% FEV1 81% FEV1/FVC 73% DLCO 94%	FVC 110% FEV1 91% FEV1/FVC 66% DLCO 143%
Medical history	No significant history	No significant history	No significant history	"Sarcoidosis" treated with prednisone preceded by "asthma"	No diagnosis
Biopsy	Normal	Declined	Declined	Granulomata	Bronchial mucosa with chronic inflammation, basement membrane thickening
BAL % lymphocytes	12% lymphs	Declined	Declined	12% polys 30% lymphs	31% polys 9% lymphs
BALLPT	Not done	Declined	Declined	Abnormal (positive beryllium response)	Not done
Final status	Sensitized (blood)	Sensitized (blood)	"Unconfirmed blood positive"	CBD	Other

TABLE VII
Comparison of point prevalence of beryllium sensitization and CBD and the cumulative incidence of CBD for the Delta, Elmore, and Tucson facilities[A]

	Beryllium sensitization prevalence	CBD prevalence	CBD cumulative incidence
Delta	3/75 (4.0%)	1/75 (1.3%)[B]	1/360 (0.3%)[B]
Mine and mill			
Elmore	43/627 (6.9%)	25/627 (4.0%)	46/2, 253 (2.0%)
Mixed products			
Tucson	8/136 (5.9%)	6/136 (4.4%)	17/709 (2.4%)
Ceramics manufacturing			
Fisher's exact test	$p = 0.25$ (A,B) $p = 0.23$ (A,C)	$p = 0.34$ (A,B) $p = 0.56$ (A,C)	$p = 0.02$ (A,B) $p = 0.01$ (A,C)

[A]Prevalence calculated over (1) 1996–1997 for the Delta facility, (2) 1993–1995 for Elmore facility, and (3) 1992 at the Tucson facility.
Cumulative incidence calculated over the period of (1) 1969–1996 for the Delta facility, (2) 1960–1996 for the Elmore facility, and (3) 1980–1996 for the Tucson facility.
[B]Single individual with CBD who worked at Delta facility also worked 10 years at Elmore facility.

characteristics between those beryllium sensitized ($n = 3$), which includes the person who had CBD, and the 72 employees with normal blood test results. There was no significant difference observed between the mean age of the sensitized workers and the other employees (Table VIII). The one employee with CBD was older than the average age of the sensitized and other employees. No significant association was found between beryllium sensitization and gender or smoking history (Table VIII).

Workplace and Work History Associations with Beryllium Sensitization and CBD

The mean duration of employment at the mining and extraction facility among beryllium-sensitized cases was 21.3 years compared to 14.9 years for other employees (Table VIII). The person with CBD worked at the Delta facility for 27.7 years and prior to that worked at the Elmore facility for 10 years. While at the mixed products facility, this person was involved with beryllium metal and beryllium oxide production and briefly worked with beryllium oxide ceramics operations. All of these processes are known to be associated with increased rates of CBD.[1,3] Because of this association with previous work, the case could not be attributed solely to exposures at the mixed products facility or mill. However, for the purposes of the study analyses, he was classified as a mill employee.

There were only three employees with beryllium sensitization who worked exclusively at the Delta facility. The employee with CBD had worked in both administration and production at the mill; the other two sensitized employees had worked only in the mill.

A recognized accident or incident that produced an unusually high exposure to beryllium was commonly reported (52% of all employees). However, there was no relationship between history of accident and beryllium sensitization (TableVIII). Based on self-report of beryllium exposure at work, none of the individuals with beryllium sensitization or CBD classified their work exposure as "high." Most reported moderate or minimum exposure (Table VIII). It should be noted, however, that beryllium in air concentrations at the occupational exposure limit (OEL) is not detectable by sight, taste, or smell.

The mean cumulative exposure based on the qualitative exposure score assignments ranged from 216 to 37,931 beryllium exposure days. The mean for this score among the beryllium-sensitized employees was higher than that noted for the non-cases (26,215 beryllium exposure days versus 15,582 beryllium exposure days) with a P value of 0.09 (Table VIII).

DISCUSSION

Average annual GA and BZ concentrations have decreased over time from 1970 to the present at the mining and extraction facility. For all four methods of exposure assessment (GA, BZ, LP, and DWA), we observed the same ranking of job areas or job titles by exposure levels. That is, the beryllium hydrolysis and wet grind areas/job titles had consistently higher exposures.

Annual median GA and LP sample concentrations at the mining and extraction facility were generally below the 2.0 $\mu g/m^3$ OSHA occupational exposure limit (OEL) for an 8-hour work shift, with exceedance fractions of 5 percent and 3 percent, respectively. Although BZ results at the mining and extraction facility indicate common exceedance above 2.0 $\mu g/m^3$, these BZ samples were usually taken for short periods of time (1–5 minutes) and were often taken to capture high levels of personal exposure. These BZ sample results are useful for identifying high-exposure tasks, but these concentrations do not represent the average air concentration over an entire work shift.

The DWA attempts to estimate the daily average concentration over the entire work shift by accounting for the level and duration of exposure for each task. The DWAs are generally lower than 2.0 $\mu g/m^3$ for all job titles at the mining and extraction facility.

Limitations of the Exposure Assessment Using Historical Data

To summarize the thousands of measurements that had accumulated over three decades of sampling, for facility-wide comparisons, GA and BZ results were expressed as medians and means regardless of the type of sampling method, location, or duration of sampling. For the most part, GA samples consisted of short-term samples in earlier years (1971–1983) and long-term samples in later years (1984+). The data were summarized to arrive at a single median and mean result to represent all GA or BZ sample results for a facility for a given year. Although general comparisons could be made of exposure levels at each of the three facilities, the different processes at each plant precluded us from comparing similar areas, processes, or worker exposures.

Although the total number of LP samples collected at Delta was moderately large, when stratified by specific job titles or year of sampling, the sample sizes were limited. Therefore, exposure estimates based on LP measures should be considered preliminary.

Beryllium Sensitization and CBD

The employee participation rate at the Delta facility was acceptable but lower than in two previous surveys.[1,3] Eleven of the 87 Delta facility workers (14%) declined to participate in the BLPT survey. Of the five workers offered pulmonary evaluation with bronchoscopy, two declined evaluation. With regard to respiratory symptoms or levels of beryllium exposure, there was no apparent difference between the individuals who did and did not participate, although complete information was not available on these employees. The small numbers of employees and health events provided very limited statistical power to detect associations between any variables and sensitization or CBD, particularly for specific job titles, work process or work area-related risks that had been found in other beryllium screening programs.[1–3,6] No relationship was found between work

TABLE VIII

Demographics and work history factors of beryllium-sensitized and CBD persons and other employees at the mine and mill

Demographics	Mean age (years)	Male (n = 64) (%)	Never smoker (n = 42) (%)	Former smoker (n = 25) (%)	Current smoker (n = 8) (%)	History of rash possibly attributed to beryllium
Beryllium-sensitized employees[A] (n = 3)	48.4	100	66.7	33.3	0	100
Employee with CBD (n = 1)	60.1	100	0	100	0	100
Other employees (n = 72)	44.8	84.7	55.6	33.3	11.1	31.9

Work history	Mean duration of employment (years)	Ever worked in mine (%)	Ever worked iu productiou (%)	Beryllium exposure >1 mo. at mixed products facility (n = 3) (%)	Beryllium exposure >3 mo. at mixed products facility (n = 1) (%)	History accident or incident with unusual beryllium exposure (n = 39) (%)	Self-assessment of high exposure at work (%)	Ever en in a position classified as "high exposure" (%)
Beryllium-sensitized employees[A] (n = 3)	21.3	0	100	33.3 (n = 1)	33.3 (n = 1)	100.0 (n = 3)	0	33
Employee with CBD (n = 1)	27.7	0	100	100.0 (n = 1)	100.0 (n = 1)	100.0 (n = 1)	0	0
Other employees (n = 72)	14.9	13.3	75	2.8 (n = 2)	0	50.0 (n = 36)	16.7	30

[A]Includes CBD case.
[B]Single individual with CBD who worked at Delta facility also worked 10 years at Elmore facility.

assignments in the mine, mill, or administration and production areas and beryllium sensitization or CBD.

With low statistical power, it was difficult to observe a dose-response relationship between exposure to beryllium and beryllium sensitization or CBD. However, there is an indication that longer employment duratiou at the facility was associated with sensitization. The surrogate exposure markers used in this study were not iudividual measures of personal exposure; rather, they reflected an individual's perceived exposure, the opinion of safety staff, or assignments made by linking job title data to iudividual workers. Lack of a statistically significant dose-response relationship between exposure and sensitization or CBD may be a result of low statistical power, exposure misclassification, or the absence of an exposure-risk response.

Two persons with abnormal BLPTs declined clinical evaluation. Therefore, CBD could not be diagnosed nor excluded in these individuals. Former workers were not included in the BLPT survey. Since its inception, the plant has conducted regular medical surveillance of active workers using pulmonary function tests, x-ray, and respiratory questionuaires. No other cases of CBD have been detected by these less sensitive methods. However, the similar medical surveillance performed at the other two facilities had resulted in identification of many CBD cases prior to the use of BLPT-based survey surveillance. In addition, our contact letter to former employees at the time of the BLPT survey did not yield any CBD cases, whereas contact letters sent at the other two facilities have resulted in self-identified CBD cases.

Although two additional persons who worked solely at Delta were confirmed to be sensitized to beryllium, the low cumulative incidence of CBD and the special circumstances of the one person diagnosed with CBD (with previous experience at the Elmore facility) could suggest that the ore and mining exposures have a lower potential for inducing CBD. The lower potential may not be due to lower overall beryllium exposure, because total particulate levels (i.e., the levels of airborne beryllium concentrations as currently measured) at the Delta and the Tucson facility are comparable.

At the ore-processing mill, there was widespread potential exposure to bertrandite, beryl, and to soluble beryllium salts (beryllium sulfate, beryllium ammonium carbonate, and beryllium carbonate) and limited potential for exposure to beryllium hydroxide. Beryllium hydroxide is spatially limited to a small area, and extensive procedural and personal protection are incorporated when handling this material. In contrast, the movement of bertrandite and beryl ore supplies, the ore crushing and milling operations, and the large area of the mill devoted to chemical processes involving the soluble salts create a variety of opportunities for exposure to these materials. For the most part, production work in these areas has not required respiratory protection. Respiratory protection is more commonly used during maintenance activities.

Bertrandite and beryl ore have not been considered to be sources of potential beryllium sensitization. Hamilton reports that naturally occurring beryl ores have not caused any reported illness,[18] and illness was not detected in a study of beryl gem workers.[19] Extraction of beryllium from bertrandite requires leaching with hot sulfuric acid, and extraction from beryl requires an additional preparation step of melting and refreezing the ore as a glass. Therefore, the main suspect for beryllium sensitization is the soluble salt form of the substance. These salts have the potential for sensitization via respiratory, dermal, and oral routes. In other manufacturiug processes involving beryllium, the use of soluble salts is relatively restricted to intermediary steps in the production of beryllium oxide and beryllium metal, although they may be produced in acid leaching or pickling processes. Beryllium oxide particulate appears to be most consistently associated with risk of CBD, although it is not clear whether this association is primarily a function of its chemistry or its tendency to form very small particles (less than 1 μm) during manufacturing processes. Beryllium metal appears to have the second highest potential for disease, and again, it is unclear whether it is the metal itself, the surface beryllium oxide, or the particle size that increases the risk.

Absence of potential for concomitant respiratory exposure to beryllium oxide or metallic beryllium particulate may be a factor that has limited the risk of CBD among the mining/extraction workers at the Delta facility. The one person diagnosed with CBD had this additional exposure component. Kreiss et al. have previously suggested that the combination of soluble salt exposure and beryllium oxide or beryllium metal particulate may create the highest risk level for CBD.[3]

Beryllium ore and salts appear to pose a lesser health hazard when compared to beryllium metal and beryllium hydroxide, but a firm conclusion cannot be made from this medical survey at the Delta facility due to the following: (1) the relatively small number of people at risk, (2) lack of direct information on what proportion of air sample mass is composed of bertrandite, beryl, or beryllium salt, (3) lack of information on the particle size distribution of particulate at the facility, and (4) the possibility that cases of CBD may have occurred in former employees of the facility but remain undetected.

This article is based on a preliminary evaluation of CBD and sensitization cases at the Delta facility. Continued medical surveillance and exposure monitoring that assess uot only total particulates but also small particle size fractions will provide more information on whether the risk of CBD from exposures at this facility was previously undetected, is low, or is negligible. Continued surveillance and monitoring will also help to clarify the potential roles of particle size and chemical form in predicting beryllium sensitization or CBD.

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