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Beryllium Exposure Control Program at the Cardiff Atomic Weapons Establishment in the United Kingdom

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The Cardiff Atomic Weapons Establishment (AWE) plant, located in Cardiff, Wales, United Kingdom, used metallic beryllium in their beryllium facility during the years of operation 1961–1997. The beryllium production processes included melting and casting, powder production, pressing, machining, and heat and surface treatments. As part of Cardiff's industrial hygiene program, extensive area measurements and personal lapel measurements of airborne beryllium concentrations were collected for Cardiff workers over the 36-year period of operation. In addition to extensive air monitoring, the beryllium control program also utilized surface contamination controls, building design, engineering controls, worker controls, material controls, and medical surveillance. The electronic database includes 367,757 area sampling records at 101 locations and 217,681 personal lapel sampling records collected from 194 employees over the period 1981–1997. Similar workplace samples were collected from 1961 to 1980, but they were not analyzed because they were not available electronically. Annual personal mean sampling concentrations for all workers ranged from 0.11 to 0.72 micrograms per cubic meter (μg/m^3) with 95th percentiles ranging from 0.22 to 1.89 μg/m^3; foundry workers worked in the highest concentration areas with a mean of 0.87 μg/m^3 and a 95th percentile of 2.9 μg/m^3. Area sampling concentrations, as expected, were lower than personal sampling concentrations. Mean annual area sample concentrations for all locations ranged from 0.02 to 0.32 μg/m^3. The area sample 95th percentile concentrations for all years were below 0.5 μg/m^3. For the overwhelming majority of samples, airborne beryllium concentrations were below the 2.0 μg/m^3 standard. Although blood lymphocyte testing for beryllium sensitization has not been routinely conducted among these workers, this metal beryllium processing facility is the only large scale beryllium facility of its kind to have experienced only one unique a case of clinical chronic beryllium disease (CBD) ascertained by traditional medical monitoring procedures. The treating physician determined that this lung disease was likely caused by a systems reaction resulting from a mound contaminated with beryllium. However, he could not rule out the potential for inhalation exposure. Over the 17 years of measurement data analyzed, on occasion, airborne beryllium concentrations have exceeded 2.0 μg/m^3; however, the Cardiff experience demonstrates that strict and consistent adherence to exposure control measures that emphasized airborne and surface levels and appropriate engineering controls, work practices, and use of personal protective equipment appears to have successfully prevented the incidence of clinical CBD with the exception of one unique case.

Keywords Beryllium, Industrial Hygiene, Chronic Beryllium Disease, Engineering Controls, Atomic Weapons

Beryllium is a low-density, hard metal with multiple commercial, aerospace, and defense industry applications. Metallic beryllium is used for structural materials in the aerospace industry and has a wide use in military applications such as missile and inertial guidance systems, reflectors in nuclear reactors, and mirrors in satellite optical systems. Beryllium exposure can cause (1) acute pneumonitis, a currently rare condition, caused by inhalation of beryllium salts or low-fired beryllium oxide at concentrations greater than 100 μg/m^3; (2) contact dermatitis from dermal contact with beryllium salts; and (3) chronic beryllium disease (CBD), a potentially debilitating respiratory disease.[(1)] The occupational exposure standard (OEL) for beryllium in the United Kingdom was the same as the current 8-hour OEL, 2.0 μg/m^3 time-weighted average (TWA), for beryllium in the United States until 1994 when it was reclassified as a maximum exposure limit (MEL).[2] In this article, we describe the components of the beryllium control program at a beryllium metal facility in Cardiff, Wales, and, using available exposure monitoring data, we summarize airborne beryllium concentrations experienced by workers at this facility over the period 1981–1997.

CARDIFF PLANT

The Cardiff Atomic Weapons Establishment (AWE) plant located in Cardiff, Wales, United Kingdom, was initially a Royal Ordnance Factory where fabrication of beryllium began in 1961 and ended in 1997. Over this period, there were more than 400 employees who worked at this beryllium handling facility. A large percentage of this workforce spent a significant portion of their careers at this plant. The Cardiff plant had metallurgical capabilities for melting and casting, powder production, impact milling, ball milling, hot-pressing, isostatic-pressing, machining, and heat and surface treatment. The foundry consisted of powder preparation, hot press, casting, plasma spray, impact attrition mill, and hot and cold isostatic pressing areas. Milling and turning activities occurred in the machine shop. Other departments in the facility consisted of inspection, laboratory, safety, and services (maintenance). From the late 1970s to the mid-1980s, approximately 7000–10,000 pounds (lb) of beryllium a year were processed. Beginning in the late 1980s, production declined gradually to approximately 1000 lb per year with a continued decline until the facility closed in 1997. Beryllium oxide was handled in small quantities sporadically during the first few years of operation.

It is noteworthy that the Cardiff facility was unlike the large mining, processing, or manufacturing facilities at Brush Wellman where thousands of tons of various kinds of beryllium were handled annually. In general, Cardiff was similar to the U.S. Department of Energy (DOE) Rocky Flats facility in the United States where beryllium was handled in relatively small quantities (annual uses of no more 10,000 lb), which varied with the production of nuclear materials during the years of the Cold War. The differences in the quantity and form of beryllium materials handled should be considered when comparing exposure and epidemiology studies of other facilities including the Brush Wellman sites in Elmore (Ohio), Delta (Utah), Tucson (Arizona), Reading (Pennsylvania), and Lorain (Ohio), as well as studies of various DOE sites, facilities in Japan, and elsewhere.

Recognizing the potential health hazards of beryllium and the need for stringent exposure controls, Cardiff's beryllium control program was initiated during the design phase of the facility. A strict industrial hygiene program was implemented that incorporated the important aspects of exposure controls, medical monitoring, and routine program evaluation. The Cardiff beryllium control program consisted of four key components: engineering controls, worker controls, material controls, and medical surveillance. Respirators were used to minimize potential exposures when other workplace control methods did not sufficiently reduce the airborne concentrations of beryllium to levels well below 2.0 $\mu g/m^3$. The control program was designed to maintain airborne beryllium levels below 2 $\mu g/m^3$ TWA from 1961 to the end of production in 1997 and to maintain surface levels (using the dry swipe method) below 25 micrograms per square foot ($\mu g/ft^2$) from 1961 to 1990 and below 10 $\mu g/ft^2$ from 1990 to the end of production. To evaluate program effectiveness, an extensive workplace monitoring program, relying on both area and personal lapel industrial hygiene measurements and routine medical surveillance, was conducted at the facility by health and safety personnel. Before describing the methods and results of the workplace measurement data, we briefly summarize the key components of the beryllium control program.

ENGINEERING CONTROLS

The facility consisted of offices, change rooms, beryllium process and handling areas, machine shops, laboratories, and mechanical equipment rooms. Local ventilation systems were designed so that air flowed from the office area to the change rooms, down a central hallway, and through various process and laboratory areas. This technique of directing airflow from clean areas to contaminated areas before passing through an air-cleaning device is a recognized control method in building design for toxic and radioactive materials. Air entering the facility passed through a roughing filter and a high efficiency particulate air (HEPA) filter. Each beryllium processing machine was either partially or completely enclosed and exhausted through the local ventilation systems, which were equipped with single- or double-stage HEPA filters. The velocity through the "open areas" that provided access to the machines was kept at 50 feet per minute (ft/min) (Figure 1). In 1976, a new machine shop, mechanical equipment room, and a high-velocity, low-volume exhaust system with flexible exhausts (depending on the application) were added to the facility (Figure 2). The flexible exhausts had a face velocity capture rate ranging from 6000–8000 ft/min. These additions improved the control of airborne beryllium levels from fabrication activities.

WORKER CONTROLS

Worker controls complemented engineering controls. Personnel access control zones were designated throughout the facility and strictly enforced. Personal hygiene was emphasized as part of the industrial hygiene program. A complete daily change of clothes was provided and the laundry area for contaminated clothing and respirators was located next to the change room. Decontamination was required before eating and drinking, smoking, and bathroom breaks and involved at least changing coveralls and shoes and washing hands. Shower facilities were available but not mandatory. Workers routinely wore half-mask or full-face respirators equipped with HEPA filters for work activities that required additional levels of protection. A qualitative respirator fit test program was implemented in 1985.

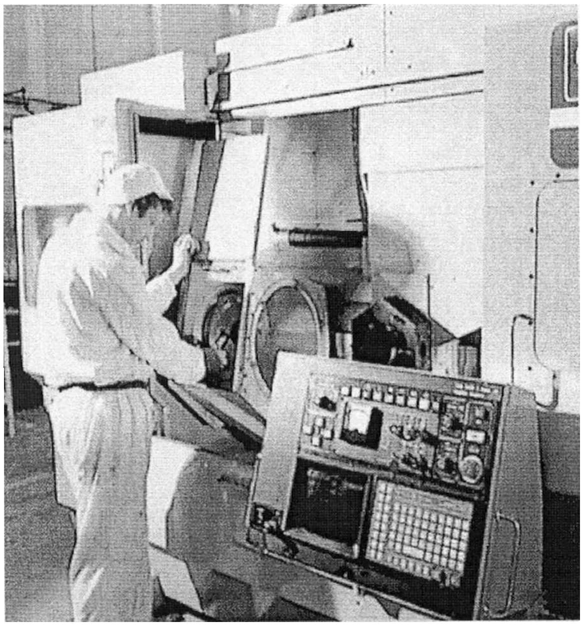

FIGURE 1
Cardiff machinist setting up a job on an enclosed C.N.C. lathe where the 50 ft/min capture velocity requirement was applied.

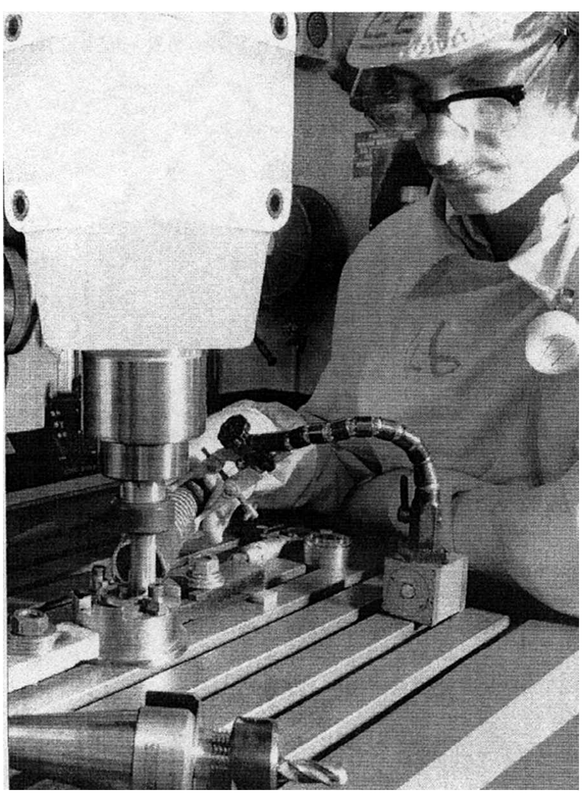

FIGURE 2
Cardiff machinist using a high-velocity close-capture ventilation duct operating at 6000–8000 fpm to remove beryllium fines during a precision milling operation.

Housekeeping was conducted daily and included the use of HEPA-filtered vacuums or wet techniques such as mopping of floors. Dry sweeping of the floor was prohibited. To evaluate housekeeping procedures, dry swipe samples were collected routinely and any areas detected with high levels were subject to immediate cleanup.

MATERIAL CONTROLS

Any materials or items removed from the beryllium control areas were carefully cleaned until a surface level of less than 1 μg/ft^2 was measured. Laundry wastewater was collected before being discharged to the sanitary sewer. An onsite beryllium flocculation plant was set in operation in the mid-1980s to remove beryllium from the wastewater.

MEDICAL SURVEILLANCE

Medical surveillance was an integral part of the beryllium control program since the facility's inception in 1961. The surveillance program included monthly spirometry, an annual physical, and annual x-rays until the mid 1980s, after which they were provided when requested. This program was managed by experienced AWE occupational health staff. It is noteworthy that at the AWE Aldermaston facility near London, one case of CBD was identified in 1978 in a machinist by traditional medical monitoring procedures. All of the evidence indicates that AWE medical staff were familiar with the symptoms of CBD and would have diagnosed any symptomatic cases among Cardiff workers if they were present.

In the mid-1980s, the Cardiff facility medical staff evaluated the beryllium-induced lymphocyte proliferation test (BLPT) to test for beryllium sensitization. This testing was discontinued because of the inability to define positive test results and concerns with reliability. A small number of unconfirmed positive BLPTs were identified in this trial, but routine health surveillance did not identify any cases of chemical CBD in this population. As part of the facility shutdown procedures in 1997, the family physicians of all beryllium workers were informed of their prior work history with beryllium.

METHODS AND DATA SOURCES

Personal and static (area) air sampling were conducted to monitor potential workplace exposures. Initially, each assigned worker who entered the beryllium work area was issued a Casella personal sampling pump that operated at a sampling rate of 2 liters per minute (L/min) and used a 37-millimeter (mm) diameter open-face cassette with Whatman 41 filter paper. This requirement was later expanded to include everyone entering the beryllium work area. Static area samples were collected with a Negretti Automation air sampler that operated at approximate sampling rates of either 30 or 60 L/min using a 60-mm-diameter Whatman 41 paper. Individual air samplers were used for the static area sampling measurements.

Sixty-one permanent locations were selected for static sampling, 13 of which were identified in 1983 as core samples. Core samples were changed at 11:30 a.m. and at the end of each day. The morning core samples were analyzed over the lunch period and reported back to the facility prior to the workers restarting their work. The afternoon core samples were analyzed and reported back to the facility prior to the beginning of the next morning's shift. Static samples were routinely collected at 61 permanent locations. Over the course of data collection, static measurements were taken at 101 different locations. The static area samples were changed by the safety technician at the end of the day and analyzed by mid-morning of the following day. Pump calibration was carried out on a routine basis by an electronics technician using equipment recommended by the manufacturers of the personal and static pumps. Total beryllium deposited on the filters was analyzed using atomic absorption spectrometry since 1976. The analytical detection limit was 0.05 $\mu g/m^3$.

The AWE Cardiff Database Analysis Project was initiated in 1994 and covers 1981–1997, years for which electronic files were available. Similar workplace samples were collected from 1961 to 1980, but they were not analyzed because they were not available electronically. Electronic copies of these data, consisting of many edited text files, were provided to the research team. The numerous text files were consolidated into two separate databases: a personal-sampling database containing 219,812 samples and an area-sampling database containing 367,825 samples. A number of steps were taken to clean up the text files and refine the electronic databases. Several information fields were added or expanded, duplicate records were identified and removed, employees with fewer than 50 records were removed, damaged records were removed, and data entry errors were corrected. In addition, the sampling duration and start times were checked for consistency, and static airflows were checked for errors.

The original personal database contained sampling data for 257 employees over the period 1981–1997. However, individuals with fewer than 50 samples were eliminated, resulting in a personal database of 194 employees. Individuals with fewer than 50 samples were eliminated under the assumption that these records represented individuals visiting the facility or very short-term employees, and not full-time employees. Results summarizing the levels of airborne beryllium for these individuals do not differ from the results of the 194 full-time employees. The current personal database after reformatting contains 217,681 records and the area database contains 367,757 records.

The original personal sampling data did not contain information on duration or flow rate. Personal daily average concentrations were calculated using calibration information and facility records regarding shift duration. Mass values (in μg) were converted to a concentration ($\mu g/m^3$) using weekday-specific exposure times (in minutes), a flow rate of 2 L/min, and a conversion factor of 0.001 m^3/L. Samples collected on Monday, Wednesday, or Friday were converted using an exposure time of 360 minutes (6 hours, adjusted from an 8-hour workday to reflect actual work time). Samples collected on Tuesday or Thursday were converted using an exposure time of 450 minutes (7.5 hours, adjusted from a 10-hour workday). Saturday data were converted using exposure times of 210 minutes (3.5 hours, adjusted down from a 4-hour workday). Sunday data were converted using exposure times of 270 minutes (4.5 hours, adjusted from a 5-hour workday). As of 1993, Friday schedules changed from an 8-hour workday to a 7-hour workday; therefore, the exposure time was changed from 360 minutes (6 hours) to 300 minutes (5 hours) for Fridays during the years 1993 through 1997. These conservative estimates provide a reasonable representation of the actual workshift times within the controlled areas of the facility. Exposure times for the personal sampling data were not adjusted to calculate an 8-hour TWA.

One uncertainty that exists in these conversions is that Saturday and Sunday hours apparently varied over time for foundry workers. It has been reported that weekend hours periodically increased to 6 hours on Saturday and 7 hours on Sunday. Because we were unable to obtain more specific information, we used the exposure times of 210 (Saturday) and 270 minutes (Sunday) for all workers on all weekend days. In the absence of more accurate information, the shorter exposure time yields more conservative (i.e., higher) concentration estimates for foundry workers on weekend shifts.

The original area sampling (static) data included information for duration and flow rates at the beginning and end of shifts. Therefore, we calculated the daily average concentration by using duration (in minutes), an average of the two flow rates (L/min), and a conversion factor of 0.001 m^3/L. Both databases (static and personal) contain measurement data as originally recorded. In a separate data field, we converted all zero values to one-half of the minimum observed level for the period when the data were collected for the personal measurement data. This value was 0.11 μg, which was converted to 0.055 μg in the Cardiff workplace measurement databases. For the area measurement data, the zero data were converted using one-half of the minimum observed levels data before calculating average concentrations, using duration and flow rate data, which resulted in a corresponding value of 0.006 $\mu g/m^3$. This substitution method for handling nondetectable data and using a fixed substituted value is commonly accepted as a practical approach when data variability is high.[3,4] All data and analysis results presented in this article reflect zero corrected data.

Static and personal sampling concentrations were analyzed using standard descriptive statistics: median, arithmetic mean, percentiles (5th, 25th, 75th, and 95th), and maximums. Box-Whisker plots were used to summarize the measurement data. The exceedance fraction point estimate was calculated for selected exposure levels. The 95 percent upper confidence limits (tolerance limits) were also calculated for the 95th percentiles of the exposure distributions.

RESULTS

Workplace and personal sampling was conducted throughout the Cardiff facility at the change room, old machine shop, new machine shop, foundry, and mechanical equipment room. The old machine shop consisted of the lathe, wet grinder, roughing/coarse machining, boring/drilling, and three different milling areas, all of which were enclosed operations. The foundry locations consisted of the hot press shop, powder preparation shop, casting furnace, glove box plasma spraying, prep/isostatic pressing, and green bar lathe. Workers routinely wore respirators to reduce exposures in the foundry, especially during specific operations known to produce workplace levels above the occupational workplace standard. The new machine shop consisted of all unenclosed operations (assembly/fitting area, metallography, turning, and milling) and utilized high-velocity close-capture ventilation (Figure 2). Janitorial workers worked in all these areas.

Area Sampling Results

Of the 367,757 area samples available in the database, 132,021 were collected in the foundry, 87,732 and 69,042 were collected in the old and new machine shops and adjacent areas, respectively, and the remaining data were collected from other sites. Annual mean concentrations for all measurement locations ranged from 0.02 μg/m^3 in 1997 to 0.32 μg/m^3 in 1985 (Table I). The only other year for which the mean concentration was 0.30 μg/m^3 or higher was 1986. At least 16,000 area samples were collected each year, with 24,000 to 25,000 collected in the mid- and late-1980s. The 95th percentile concentrations were all below 0.50 μg/m^3 over the period 1981–1997 (Table I). The percentage of measurements greater than 2.00 μg/m^3 was always less than 1 percent for each year. Over all years combined, less than one-tenth of 1 percent of all area measurements were above 2.00 μg/m^3.

Considering specific departments and operations within these departments, the foundry area, particularly the hot press shop, and the plasma spraying area, had higher concentrations than other areas (Table II). The mean and 95th percentile concentrations from the old machine shop for all years were 0.02 and 0.05 μg/m^3, respectively. The foundry had the highest mean (0.23 μg/m^3) and 95th percentile (0.59 μg/m^3). Within the foundry, the hot press shop, and plasma spraying areas had mean concentrations of 0.30 and 0.39 μg/m^3, respectively. The new machine shop, opened in 1976, had lower concentrations than the foundry and old machine shop with mean and 95th percentile concentrations of 0.02 and 0.04 μg/m^3, respectively (Table II).

Annual mean airborne beryllium concentrations in the old machine shop ranged from 0.008 μg/m^3 in 1996 to 0.04 μg/m^3 in 1982. Foundry annual mean concentrations ranged from 0.02 μg/m^3 in 1997 to 0.95 μg/m^3 in 1986. The annual mean concentrations in the new machine shop ranged from 0.007 μg/m^3 in 1994 to 0.03 μg/m^3 in 1985.

TABLE I

Cardiff facility area sample measurement data (μg/m^3), all departments, 1981–1997

Year	N	Mean	Median	95th percentile	Maximum
1981	16,504	0.08	0.004	0.39	23.20
1982	17,905	0.11	0.004	0.48	59.20
1983	19,423	0.11	0.02	0.42	88.70
1984	21,402	0.09	0.02	0.30	46.30
1985	23,788	0.32	0.02	0.35	1,128.00
1986	24,578	0.31	0.01	0.22	1,026.00
1987	25,252	0.12	0.01	0.32	403.00
1988	24,557	0.09	0.01	0.35	39.70
1989	23,835	0.09	0.01	0.37	38.90
1990	23,199	0.07	0.01	0.16	365.00
1991	20,041	0.04	0.01	0.08	73.40
1992	19,585	0.04	0.01	0.09	9.44
1993	21,332	0.02	0.01	0.06	5.71
1994	23,693	0.02	0.01	0.04	5.21
1995	23,406	0.02	0.01	0.04	23.80
1996	23,196	0.02	0.01	0.09	13.50
1997	16,061	0.02	0.01	0.04	7.02

Personal Sampling Results

Of the 217,681 personal samples, a total of 35,063 (16.1%) were from foundry workers, 34,215 (15.7%) were from inspection workers, 8,363 (3.8%) were from laboratory workers, 104,359 (47.9%) were from machine shop workers, 2688 (1.2%) were from safety workers, 12,269 (5.6%) were from services/maintenance workers, and 20,724 (9.5%) were from "undefined" workers. Although workers are labeled as belonging to a specific department, their samples can represent measurements from all areas; however, we assume the measurements represent various work activities in their department location. Among those participating in the workplace measurement program for which electronic data are available (i.e., all employees working at some point during the period 1981–1997), 34 percent of employees worked in the machine shop, 17 percent in the foundry, 11 percent in inspection, 9 percent in service/maintenance, 6 percent in the laboratory, and 4 percent in safety. For approximately 20 percent of the employees, we did not have department information. Inspectors and service staff tended to work in all different areas of the facility. Inspectors, in general, did not wear respiratory protection.

The Cardiff workforce was also quite stable, experiencing low turnover. It was not uncommon to find fathers and their sons working at the facility. Employment at the Cardiff facility was considered highly desirable and a high percentage of Cardiff workers stayed at the facility until retirement.

Trends for Entire Workforce

As expected and consistent with other studies, personal measurement concentrations were higher than static area

TABLE II
Static area airborne beryllium concentrations (μg/m^3) by department and locations (1981–1997)

Department	Location	N	Mean	Median	95th percentile	Maximum
Foundry		132,021	0.23	0.02	0.59	1,128
	Hot press shop	33,900	0.30	0.06	1.25	73.4
	Powder preparation shop	21,499	0.14	0.02	0.36	403
	Casting furnace	8,520	0.09	0.03	0.28	36.6
	Glove box plasma spraying	19,833	0.39	0.01	0.41	1128
	Prep/isostatic pressing	4,987	0.05	0.01	0.17	10.8
	Green bar lathe	3,335	0.06	0.01	0.09	42.3
Old machine shop		87,732	0.02	0.01	0.05	14.4
	Lathe	7,056	0.02	0.01	0.06	2.21
	Wet grind	4,871	0.01	0.01	0.03	3.28
	Rough/coarse machining	4,900	0.02	0.01	0.06	2.40
	Boring/drilling	2,282	0.02	0.01	0.05	0.86
	Roughing	8,079	0.01	0.01	0.04	3.70
	Milling (170)	2,183	0.05	0.01	0.17	5.19
	Milling (180)	4,784	0.02	0.01	0.07	2.56
	Milling (190)	4,968	0.01	0.008	0.04	2.01
New machine shop		69,042	0.02	0.01	0.04	20.7
	Assembly	4,999	0.02	0.01	0.06	1.02
	Metrology	9,745	0.01	0.01	0.04	4.20
	Medium turning >6″<15′ (shrouded)	15,181	0.02	0.01	0.04	5.46
	Small turning <6″ (450)	10,882	0.01	0.01	0.03	3.93
	Small turning <6″ (460)	3,973	0.02	0.01	0.04	6.19
	Milling (470)	4,570	0.01	0.01	0.03	5.37
	Turning <6″ diameter	3,702	0.02	0.01	0.03	20.70

measurements. The fixed location sites where measurement data were collected attempted to sample the breathing zone area, but were often higher off the ground and further from the specific breathing zone than the typical location of the personal lapel sample cassette (see Figure 2). Annual mean personal concentrations for all employees in the sample database over all years ranged from 0.09 to 0.72 μg/m^3. Median annual concentrations ranged from one-half the detection limit to 0.28 μg/m^3 (Table III). On an annual basis, the percentage of measurements exceeding 2.00 μg/m^3 ranged from zero (1993–1997) to 2.1 percent (1989) (Table III). Over all years, 99.5 percent of all samples in all departments combined were below 2.00 μg/m^3. By year, the 95th percentile concentration ranged from 0.22 μg/m^3 (1997) to 1.89 μg/m^3 (1989). The upper 95 percent confidence limit for the 95th percentile (the tolerance limit) ranged from 0.24 to 2.0 μg/m^3 (Table III).

Trends by Departments Within the Cardiff Facility

Personal measurements for foundry workers were the highest. For all years, the overall mean was 0.87 μg/m^3, the median was 0.22 μg/m^3, and an overall 95th percentile concentration was 2.92 μg/m^3 (Table IV). For individual workers, the mean personal sampling concentrations for foundry workers, averaged over all years, ranged from 0.1 to 1.2 μg/m^3. The maximum mean and 95th percentile (3.7 μg/m^3) for a single year occurred in 1989 (data not shown). Workers in the foundry area were required to wear respiratory protection for higher risk operations because of the greater potential for elevated exposures. Mean personal sampling concentrations in the machine shops ranged from 0.12 to 0.46 μg/m^3 from 1981 to 1997 (Table IV).

For all foundry workers, annual average concentrations ranged from a low of 0.13 to 0.17 μg/m^3 for the period 1994–1997, to a high of 2.0 μg/m^3 in 1989. During the period 1986–1990, higher concentrations were recorded (e.g., 95th percentiles ranging from 3.2 to 8.6 μg/m^3 and 95% tolerance limits ranging from 3.8 to 9.4 μg/m^3, Table III). This reflects increased production activity in the foundry area during that time period. Except for one year in the undefined group, all annual average concentrations for machine shop, service/maintenance, laboratory, inspection, and safety departments were less than 0.7 μg/m^3. With a few exceptions, most 95th percentile concentrations for all non-foundry departments were below 1.0 μg/m^3 (Table III).

TABLE III
Cardiff facility personal samples measurement data ($\mu g/m^3$), all departments, 1981–1997

Year	Count	Mean	Median	95th percentile	95% tolerance limit	Exceedance fraction (>2 $\mu g/m^3$)
1981	14,529	0.34	0.08	0.97	1.00	0.52
1982	13,870	0.33	0.08	0.89	0.95	0.08
1983	13,930	0.37	0.22	1.11	1.11	1.74
1984	13,524	0.40	0.28	0.97	0.97	0.84
1985	13,456	0.35	0.22	0.71	0.71	0.20
1986	19,415	0.35	0.14	0.97	1.11	0.45
1987	20,810	0.56	0.14	1.53	1.67	1.45
1988	19,747	0.60	0.14	1.56	1.67	1.70
1989	16,012	0.72	0.14	1.89	2.00	2.08
1990	13,053	0.42	0.14	1.11	1.25	0.66
1991	10,893	0.24	0.14	0.56	0.67	0.04
1992	9,630	0.19	0.13	0.56	0.56	0.02
1993	9,153	0.16	0.09	0.42	0.44	0.00
1994	9,667	0.13	0.09	0.33	0.33	0.00
1995	8,902	0.11	0.08	0.24	0.24	0.00
1996	7,655	0.11	0.09	0.24	0.28	0.00
1997	3,435	0.12	0.08	0.22	0.28	0.00

Examination of the Upper Tail of the Beryllium Concentrations

Several measures of exposure distributions are often used to evaluate workplace exposure control programs. The 95 percent upper confidence limit of the 95th percentile (i.e., the tolerance limit) and the exceedance fraction above a pre-specified level (in the case of beryllium, 2.0 $\mu g/m^3$) are two quantitative measures considered appropriate for compliance evaluation purposes.[4] The tolerance limits and 95th percentiles for all Cardiff workers (1981–1997) are summarized in Figure 3. At the Cardiff facility, compliance to an OEL of 2.0 $\mu g/m^3$ was achieved for the period 1981–1997. In 1989, the tolerance limit was 2.0 $\mu g/m^3$ (Figure 3). However, within a subset of Cardiff workers (the foundry workers), we see that 100 percent compliance was not achieved for all years. For the period 1986–1990, tolerance limits for the group were exceeded, as reflected by measurement concentrations from personal lapels. These concentrations, however, are not adjusted for respirator use, which if accounted for would be expected to put this group in compliance.

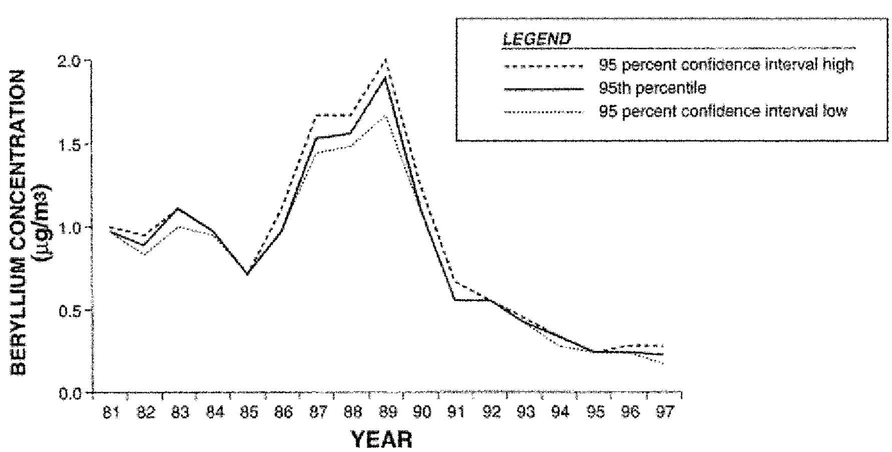

FIGURE 3
Cardiff Facility: Personal measurement data for all departments, 1981–1997.

TABLE IV
Cardiff facility personal measurement data (μg/m^3) by department and year: summary statistics

Department	Year	Count	Mean	Median	95th percentile	95% tolerance limit	Exceedance fraction (>2 μg/m^3)
Foundry	1981	2,962	0.50	0.33	1.33	1.44	2.22
	1982	2,423	0.60	0.08	0.93	0.97	0.17
	1983	2,115	0.39	0.22	1.11	1.19	1.88
	1984	1,768	0.34	0.22	0.93	0.97	0.57
	1985	1,372	0.29	0.14	0.71	0.83	0.17
	1986	3,102	0.87	0.28	3.19	3.75	7.39
	1987	3,976	1.51	0.33	5.97	6.44	14.16
	1988	4,004	1.42	0.42	5.28	5.97	12.81
	1989	3,144	2.04	0.42	8.61	9.44	18.49
	1990	2,388	1.25	0.28	4.58	5.24	10.26
	1991	2,134	0.38	0.14	1.11	1.25	0.66
	1992	1,350	0.29	0.14	1.00	1.25	0.41
	1993	1,011	0.20	0.11	0.56	0.67	0.030
	1994	918	0.15	0.09	0.37	0.42	0.0005
	1995	932	0.13	0.09	0.28	0.33	0
	1996	1,078	0.17	0.11	0.48	0.56	0.0072
	1997	386	0.14	0.08	0.42	0.56	0.0004
	All years	35,063	0.87	0.22	2.92		5.40
Inspection	1981	2,047	0.13	0.08	0.56	0.56	0
	1982	2,234	0.13	0.08	0.42	0.56	0
	1983	2,414	0.16	0.08	0.48	0.56	0.031
	1984	2,290	0.19	0.14	0.48	0.48	0.014
	1985	2,323	0.22	0.14	0.42	0.48	0.0035
	1986	3,222	0.18	0.14	0.33	0.42	0.0012
	1987	3,479	0.17	0.14	0.42	0.42	0.0017
	1988	3,256	0.43	0.14	0.44	0.48	0.0079
	1989	2,682	0.71	0.14	0.42	0.48	0.0053
	1990	2,004	0.17	0.14	0.42	0.42	0.0014
	1991	1,429	0.15	0.11	0.33	0.33	0.002
	1992	1,397	0.12	0.11	0.28	0.28	0
	1993	1,349	0.10	0.08	0.17	0.22	0
	1994	1,218	0.10	0.08	0.17	0.19	0
	1995	1,229	0.09	0.08	0.14	0.14	0
	1996	1,220	0.09	0.08	0.14	0.17	0
	1997	422	0.15	0.08	0.44	0.56	0.0008
	All years	34,215	0.22	0.11	0.42		0.0016
Laboratory	1984	197	0.26	0.19	0.56	0.97	0.062
	1985	274	0.24	0.22	0.48	0.67	0.0075
	1986	832	0.26	0.14	0.69	0.83	0.11
	1987	1,200	0.25	0.14	0.69	0.78	0.12
	1988	1,154	0.29	0.14	0.83	0.97	0.22
	1989	1,008	0.31	0.14	0.69	0.83	0.13
	1990	923	0.20	0.14	0.48	0.56	0.012
	1991	800	0.16	0.14	0.38	0.42	0.0003
	1992	411	0.15	0.11	0.42	0.42	0.00088
	1993	448	0.13	0.09	0.28	0.42	0.00003

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TABLE IV
Cardiff facility personal measurement data ($\mu g/m^3$) by department and year: summary statistics *(Continued)*

Department	Year	Count	Mean	Median	95th percentile	95% tolerance limit	Exceedance fraction ($>2\ \mu g/m^3$)
	1994	430	0.15	0.09	0.37	0.56	0.0011
	1995	432	0.13	0.09	0.33	0.48	0.00004
	1996	209	0.10	0.08	0.22	0.28	0
	1997	45	0.08	0.08	0.14	0.17	0
	All years	8,363	0.22	0.14	0.56		0.043
Machine Shop	1981	9,520	0.33	0.08	0.97	1.00	0.49
	1982	9,213	0.31	0.08	0.97	1.11	0.17
	1983	9,401	0.42	0.28	1.19	1.25	2.52
	1984	9,269	0.46	0.28	1.11	1.11	1.16
	1985	9,487	0.39	0.24	0.78	0.83	0.29
	1986	10,855	0.27	0.14	0.69	0.69	0.11
	1987	9,737	0.29	0.14	0.71	0.78	0.17
	1988	8,675	0.36	0.14	0.97	1.11	0.50
	1989	6,417	0.33	0.22	0.97	0.97	0.38
	1990	4,469	0.28	0.14	0.89	0.97	0.25
	1991	3,530	0.25	0.14	0.69	0.78	0.097
	1992	2,770	0.23	0.14	0.67	0.69	0.081
	1993	2,598	0.19	0.11	0.67	0.67	0.033
	1994	3,201	0.16	0.10	0.44	0.48	0.0026
	1995	3,043	0.12	0.09	0.28	0.28	0.00001
	1996	1,827	0.13	0.10	0.28	0.33	0.00002
	1997	347	0.18	0.09	0.42	0.50	0.0023
	All years	104,359	0.32	0.14	0.89		0.43
Safety	1986	69	0.14	0.11	0.28	0.42	0.00004
	1989	70	0.17	0.14	0.42	0.83	0.00088
	1990	467	0.16	0.14	0.42	0.42	0.00061
	1991	343	0.14	0.11	0.28	0.42	0.00003
	1992	520	0.27	0.14	1.06	1.25	0.35
	1993	367	0.30	0.14	1.00	1.22	0.66
	1994	410	0.16	0.09	0.50	0.56	0.0045
	1995	338	0.13	0.09	0.37	0.50	0.0003
	1996	86	0.12	0.08	0.28	0.42	0.00001
	1997	18	0.08	0.08	0.14	0.14	0
	All years	2,688	0.19	0.11	0.56		0.027
Services	1986	859	0.34	0.14	0.89	1.11	0.39
	1987	1,441	0.58	0.14	1.22	1.67	1.095
	1988	1,315	0.60	0.14	0.95	1.11	0.56
	1989	1,295	0.37	0.14	0.95	1.39	0.45
	1990	1,129	0.31	0.14	0.67	0.78	0.15
	1991	1,092	0.19	0.14	0.44	0.56	0.0081
	1992	1,092	0.16	0.11	0.33	0.42	0.011
	1993	1,066	0.15	0.08	0.24	0.28	0
	1994	1,107	0.10	0.08	0.17	0.22	0
	1995	906	0.09	0.08	0.17	0.17	0
	1996	585	0.09	0.08	0.14	0.14	0

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TABLE IV
Cardiff facility personal measurement data (μg/m^3) by department and year: summary statistics *(Continued)*

Department	Year	Count	Mean	Median	95th percentile	95% tolerance limit	Exceedance fraction (>2 μg/m^3)
	1997	382	0.09	0.08	0.14	0.17	0
	All years	12,269	0.29	0.11	0.56		0.069
Undefined	1986	476	0.31	0.14	0.83	1.11	0.33
	1987	977	1.25	0.14	1.43	1.89	1.73
	1988	1,343	0.45	0.14	0.83	1.11	0.45
	1989	1,396	0.23	0.14	0.56	0.56	0.031
	1990	1,673	0.16	0.13	0.42	0.42	0.0012
	1991	1,565	0.17	0.14	0.28	0.33	0.00012
	1992	2,090	0.14	0.11	0.28	0.33	0.00013
	1993	2,314	0.11	0.08	0.22	0.24	0
	1994	2,383	0.11	0.08	0.19	0.24	0
	1995	2,022	0.10	0.08	0.17	0.17	0
	1996	2,650	0.10	0.08	0.17	0.17	0
	1997	1,835	0.10	0.08	0.17	0.17	0
	All years	20,724	0.21	0.09	0.33		0.0012

The higher concentrations for foundry workers are also evident by consideration of the percentages exceeding 2.0 μg/m^3. For the same five-year period, a higher percentage of measurements greater than 2.0 μg/m^3 was observed in the foundry (Figure 4). Figure 4 also shows the large difference between area and personal measurements. The percentage of area measurements greater than 2.0 μg/m^3 for the five-year period is below 0.5 percent, whereas the percentage of personal measurements ranges from 7 percent to 19 percent.

DISCUSSION

The Cardiff facility maintained a state-of-the-art industrial hygiene program from 1961 to 1997, which consisted of engineering, worker, and material controls, as well as a medical surveillance program. Beryllium work was performed in a specially designed, separate stand-alone facility where various processes were compartmentalized. Strict access control was enforced. Regular personal air samples were collected and the data were then used to encourage behavioral change and

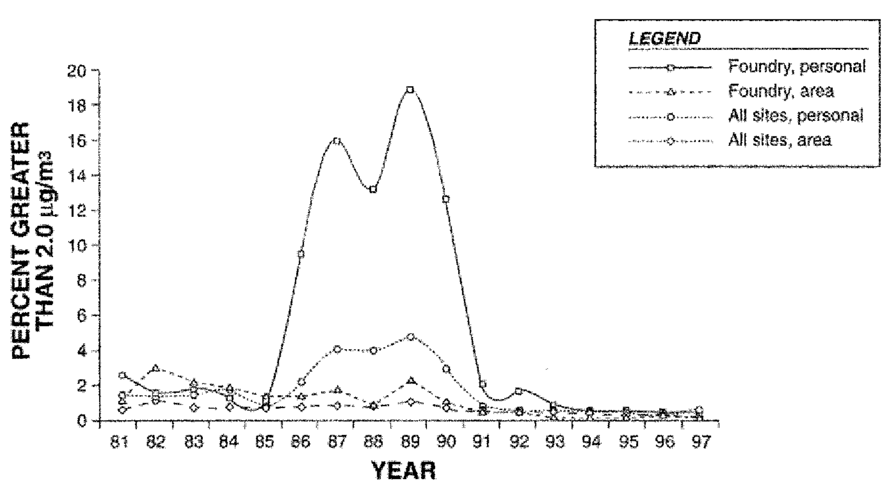

FIGURE 4
Cardiff Facility: Exceedance fractions greater than 2.0 μg/m^3 for area and personal measurements, all sites and foundry department, by year, 1981–1997.

accountability. Respiratory protection was also routinely used to control beryllium exposures in all areas except inspection. This program resulted in excellent compliance with the requirements of the current beryllium OEL of 2.0 $\mu g/m^3$ from 1961 to 1997. Because the same workplace control activities were in place for the period 1961–1980, we assume a similar achievement in exposure compliance although these beryllium measurement data have not been analyzed. It is important to emphasize that although the Cardiff site has the most extensive workplace measurement database of all beryllium facilities in existence, these measurements do not necessarily reflect actual worker exposures. For example, respiratory protection was commonly used by Cardiff workers while personal sampling was conducted, and we have not adjusted the air sampling results to account for this factor. Specific individual, job-specific, or respiratory protection use data were not available.

In the Cardiff workforce of more than 400 employees during the entire 1961–1997 time period, only one unique case of clinical CBD has been diagnosed. This unique beryllium-related health effects case occurred in 1963, when a systemic beryllium reaction was identified in a worker who sustained a minor cut to a finger on a beryllium oxide-contaminated grinding wheel. W. Jones-Williams, M.D., concluded that the resulting ulceration was progressive and necessitated the amputation of the finger. The systemic action continued into the forearm and eventually the lung. The condition was treated with corticosteroids in 1970, which resulted in the disappearance of the granulomas (on the forearm that appeared when treatment stopped) and improvement of the lungs.[5,6] For a workforce of this size (400+), we would expect to observe 4 to 20 cases of clinical CBD based on CBD prevalence rates of 1–5 percent as reported by Merril Eisenbud prior to the use of medical bronchoscopy and sensitization surveillance in the late 1980s, which allowed for the detection of subclinical cases of CBD.[7]

The Cardiff experience is in contrast to workers at U.S. DOE facilities, their contractors, and commercial beryllium manufacturing facilities,[8–11] which have observed clinical CBD in workers during the same time period using very similar medical surveillance methods. In addition, ongoing medical surveillance research continues with a mortality study of the workers employed during the period 1981–1997. Although the surveillance is ongoing, no deaths due to respiratory disease have been identified, as reported by one of the authors (G. Cogbill). The Cardiff experience suggests that a stringent beryllium control program can be successful at controlling workers' exposures to the level of the current standard and preventing clinical CBD.

The Cardiff experience in relation to CBD has differed from that of the U.S. DOE experience at facilities such as the Rocky Flats plant. At Rocky Flats, separate, specially designed and constructed facilities for the handling of beryllium were never built. Workplace controls were not as stringent as those at Cardiff. Static area measurements were used as the primary workplace monitoring system at Rocky Flats until a case of CBD was identified in 1984.[12] Prior to 1984, significant beryllium exposures to workers above the 2.0 $\mu g/m^3$ were possible. Over the next several years, DOE beryllium control programs became similar to Cardiff's, using personal samples as the primary means to measure the airborne concentration of beryllium. Based on the observations from Cardiff data, which show personal measurements are nearly always higher than static measurements, as well as Seiler's[13] analysis of exposure based on personal breathing zone versus area measurements, analyses of CBD occurrence in DOE facilities based on static area data have probably underestimated workers' actual beryllium exposures.

Cardiff's static area sampling results show that there was background airborne concentration of beryllium in the workplace and that production rates affected this background concentration as evidenced by the trend that there were higher levels in the mid- and late-1980s when higher production occurred (Figure 3). Concentrations in the foundry, both personal and area, were higher than concentrations measured elsewhere in the plant. This result is due to the fact that powder preparation and casting are more difficult to control on a consistent basis because of the nature of the material and particle size. Although Cardiff implemented and consistently enforced superior and appropriate work practices, the control program could not meet the 2.0 $\mu g/m^3$ standard 100 percent of the time. However, 95 percent of the area measurements on an annual basis varied from a low of 0.04 to 0.48 $\mu g/m^3$. Likewise, 95 percent of the area-sampling concentrations were lower than personal sampling concentrations.

The personal and area data from the Cardiff facility are quite robust because of the large number of samples that were collected. Because personal air sampling was mandatory for workers there were no significant data gaps in the database. The facility also provided comprehensive medical surveillance. The BLPT was not used routinely because of reliability concerns and therefore some number of workers could have been sensitized, and have not been detected by the historical and existing medical surveillance procedures.

Although respirators were regularly used, particularly by foundry workers, there is minimal documentation about the respirator program at the facility. The results regarding beryllium exposures and CBD occurrence observed from the Cardiff experience probably reflect only considerations about an appropriate OEL for the toxicity of beryllium metal, the predominant form of beryllium used at the facility. To the degree that form (e.g., beryllium alloy, beryllium salts, beryllium oxides, beryllium hydroxide, metallic beryllium) may determine toxicity, this study can address only one form of beryllium. By the same token, the workplace exposures, the extensive measurements, and the health experience of this workforce offer an excellent opportunity to demonstrate the effectiveness of a 2.0-$\mu g/m^3$ OEL for the metallic form of beryllium when used in conjunction with the described industrial hygiene program.

In addition, particle size may play an important role in causing CBD. The beryllium air concentrations data set did not allow us to evaluate particle size distributions. Due to the wide variety of operations and routine handling of beryllium powder, the particle size distribution can be expected to range from very fine to coarse. Better estimates of the particle size distribution for specific operations are possible using particle characterization data from similar operations.

CONCLUSION

In summary, the majority of measurements for both personal and area sampling were below 2.0 μg/m^3. These results can be attributed to the comprehensive, strictly enforced, and consistent beryllium workplace industrial hygiene control program that was implemented. Cardiff is the only facility of its kind known to consistently maintain airborne beryllium concentrations below 2 μg/m^3 (based on published data), but even with all its control measures, exceedances were observed. Although this study suggests that 2 μg/m^3, the current OEL for beryllium, is sufficient to prevent chemical CBD, this study addresses only exposures to beryllium metal, which may not act in a similar manner to other forms of beryllium. As a result of the success of the industrial hygiene program, Cardiff is the only large metallic beryllium facility in operation for over 35 years with only one unique case of chemical CBD.

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