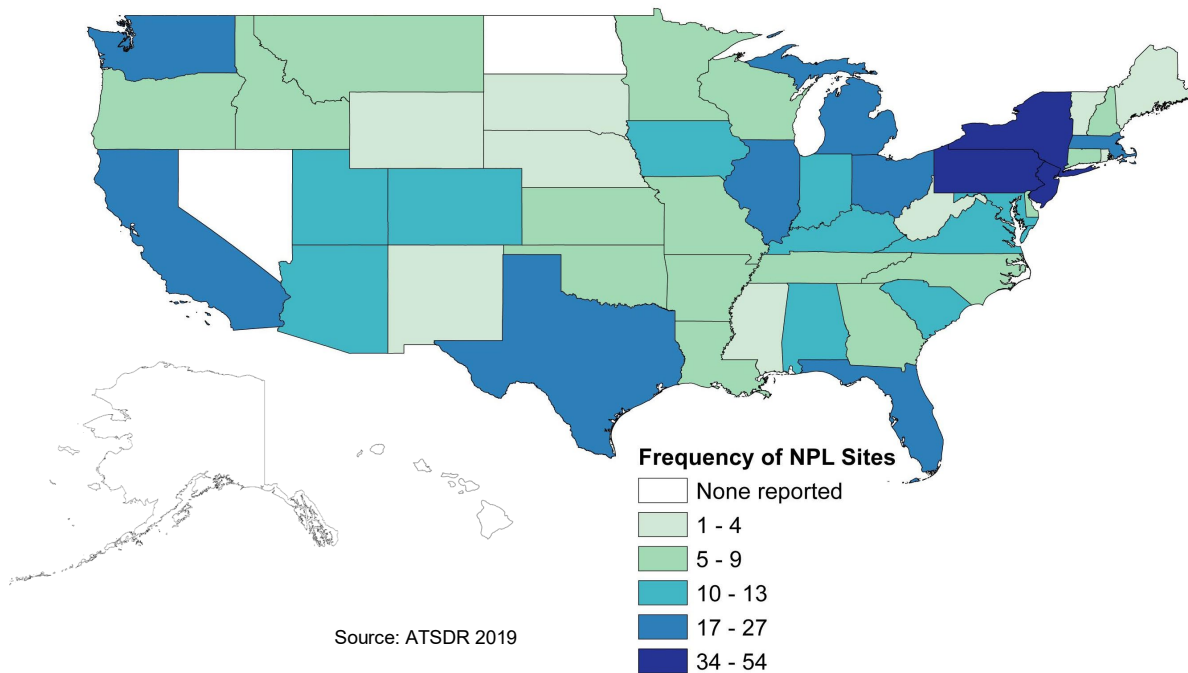


CHAPTER 5. POTENTIAL FOR HUMAN EXPOSURE

5.1 OVERVIEW

Beryllium has been identified in at least 540 of the 1,867 hazardous waste sites that have been proposed for inclusion on the EPA National Priorities List (NPL) (ATSDR 2019). However, the number of sites evaluated for Beryllium is not known. The number of sites in each state is shown in Figure 5-1. Of these sites, 530 are located within the United States, 2 are located in the Virgin Islands, one is located in Guam, and 7 are located in Puerto Rico (not shown).

Figure 5-1. Number of NPL Sites with Beryllium Contamination



- Beryllium is an element that occurs naturally in the earth's rocks. It is estimated that more than half of the world's resources of beryllium are located in the United States. Beryllium is a critical mineral with many uses in industrial components, consumer electronics, automotive electronics, defense applications, telecommunications infrastructure, energy applications, and medical applications.
- Beryllium is released to air, water, and soil from natural and anthropogenic sources. Natural sources include windblown dust, volcanic particles, and atmospheric deposition. An estimated 29,231 pounds (13,258.8 kg) of beryllium and 487,939 pounds (221,325.6 kg) of beryllium compounds were released to the environment in 2017 from U.S. manufacturing and processing facilities.
- Beryllium cannot be degraded in the environment, but it can change form.

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- Beryllium has been detected in air at levels up to 8.9 ng/m³, but most concentrations are below 0.2 ng/m³.
- The primary route of exposure to beryllium and beryllium compounds is inhalation. The general population may also be exposed to beryllium through dermal contact or through drinking water and food.
- People who work in beryllium manufacturing, fabricating, and reclaiming industries are potentially exposed to higher levels of beryllium than the general population. Beryllium carried home on shoes, clothing, and skin of occupationally exposed individuals from the workplace may increase the risk of beryllium exposure to their family members.

The major anthropogenic emission source to the environment is the combustion of coal and fuel oil, which releases particulates and fly ash that contain beryllium into the atmosphere (DOE 1996). Other anthropogenic processes, such as ore processing, metal fabrication, beryllium oxide production and use, and municipal waste combustion, release only a fraction of the amounts emitted from coal and oil combustion (Cleverly et al. 1989; EPA 1987; Fishbein 1981). Approximately 50 beryllium minerals occur in nature (Taylor et al. 2003). Beryllium is naturally emitted to the atmosphere by windblown dusts and volcanic particles (EPA 1987). The median concentration of beryllium in air in the United States is 0.15 ng/m³ (EPA 2018a).

Beryllium naturally enters waterways through the weathering of rocks and soils (EPA 1980). The sources of anthropogenic release of beryllium to surface waters include treated wastewater effluents from beryllium or related industries and the runoff from beryllium-containing waste sites (EPA 1980, 1981). Deposition of atmospheric beryllium aerosols from both natural and anthropogenic sources is also a source of beryllium in surface waters. In 2019, dissolved beryllium was detected in 692 of 2,533 surface water samples in the United States (27.3%) with an average concentration of 0.18 µg/L (WQP 2020). Dissolved beryllium was detected in 222 of 1,065 groundwater samples in the United States (20.8% of samples) with an average concentration of 0.27 µg/L (WQP 2020).

Some beryllium compounds are naturally present in soil, but the concentration of beryllium in localized soils may increase because of the disposal of coal ash, municipal combustor ash, industrial wastes that contain beryllium, and deposition of atmospheric aerosols. The average concentration of beryllium in U.S. soils is 1.8 mg/kg (n=93,090) (USGS 2016).

Beryllium released to the atmosphere from combustion processes and ore processing will probably be present as beryllium oxide. Atmospheric beryllium particulates will eventually settle to the earth's surface by dry deposition or may be removed from the atmosphere by wet deposition (i.e., precipitation).

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Upon reaching water and soil, beryllium will probably be retained in an insoluble form in sediment and soil and will be generally immobile. Although chemical reactions may transform one beryllium compound into another, beryllium cannot be degraded by environmental reactions. However, the data regarding transformation reactions of beryllium in water and soil are limited.

Bioconcentration of beryllium in plants and animals is low. In plants, uptake of beryllium appears to be restricted to the root system; no significant translocation of beryllium to the above ground parts of the plant has been observed. Beryllium is not expected to bioconcentrate in aquatic animals (EPA 1980). The beryllium concentrations in both raw carrots and field corn grown in the United States were $<25 \mu\text{g}/\text{kg}$, fresh weight (Wolnik et al. 1984).

The general population is exposed to beryllium through inhalation of air and consumption of food and drinking water. The total beryllium intake by the general U.S. population cannot be estimated due to the lack of data regarding beryllium content in food. People who work in beryllium manufacturing, fabricating, and reclaiming industries are potentially exposed to higher levels of beryllium than the general population. Smokers may also be exposed to higher levels of beryllium than nonsmokers because cigarette smoke contains beryllium.

5.2 PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

5.2.1 Production

Beryllium is an element that is present in the earth's rocks in amounts ranging from $<1\text{--}15 \text{ mg}/\text{kg}$. About 60% of the more than 100,000 tons of the world's identified resources of beryllium are in the United States; the Spor Mountain area in Utah, the McCullough Butte area in Nevada, the Black Hills area in South Dakota, the Sierra Blanca area in Texas, the Seward Peninsula in Alaska, and the Gold Hill area in Utah contain most of these resources (USGS 2019). The beryllium minerals of commercial interest are beryl (i.e., $\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$) and bertrandite (i.e., $\text{Be}_4\text{Si}_2\text{O}_7(\text{OH})_2$).

In the United States, bertrandite, which contains $<1\%$ beryllium, is the principal mineral mined. In 2018, 170 metric tons of beryllium were mined in the United States (USGS 2019). The U.S Geological Survey (USGS) in 2019 estimated that United States resources of bertrandite reserves in Utah contained 21,000 tons of beryllium. Outside of the United States, beryl is the principal beryllium mineral mined. At its operations in Utah, Materion converted bertrandite ore (from open pit mines) and beryl (which was imported) into beryllium hydroxide that was then either sold to NGK Insulators, Ltd. in Japan or shipped to the company's plant in Ohio to be converted into metal, oxide, and downstream beryllium-copper master alloy (USGS 2019, 2020).

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Beryllium hydroxide is the basic raw material to produce beryllium metal, alloys, and compounds. Bertrandite ore is wet milled, leached with sulfuric acid, and then extracted from the acid leachate with di(2-diethylhexyl) phosphate in kerosene at elevated temperature. The beryllium is then treated with aqueous ammonium carbonate to form an aqueous ammonium beryllium carbonate complex, which is then heated to precipitate beryllium as carbonate. Continued heating liberates carbon dioxide and beryllium hydroxide (i.e., $\text{Be}(\text{OH})_2$). Beryllium hydroxide is then recovered by filtration and is used to produce products such as beryllium metal, beryllium alloys, and beryllium oxide (Ballance et al. 1978; Drury et al. 1978).

Information on beryllium process production is from Balance et al. (1978). Through 1977, beryllium metal was produced by a couple of U.S. companies using the Schenzfeier-Pomelee purification process. The process starts with beryllium hydroxide and forms intermediates with the use of heat and reduction by magnesium. Water leaching or electro-refining further purifies the metal product.

Beryllium oxide was produced by dissolving technical-grade beryllium hydroxide in sulfuric acid, precipitating out hydrated beryllium sulfate, which is then calcined at 1,150–1,450 °C (Ballance et al. 1978). Copper-beryllium alloy was produced from beryllium oxide, carbon reduction in the presence of molten copper, and an arc-furnace set at 1,800–2,000 °C. Other beryllium alloys start with a copper beryllium alloy and melt in other metals (Ballance et al. 1978). It is unclear whether there are newer processes for producing beryllium metal, beryllium oxide, and beryllium alloys.

In 2017, Materion produced beryllium hydroxide, beryllium metal, metal-matrix composites, ceramics, and beryllium strip and bulk products at plants in Elmore, Ohio, Fremont, California, Tucson, Arizona, and Shoemakersville, Pennsylvania (USGS 2020). IBC Advanced Alloys Corp. produced beryllium-aluminum alloys, beryllium-copper alloys, and its own proprietary alloys at plants in Franklin, Indiana, New Madrid, Missouri, Royersford, Pennsylvania, and Wilmington, Massachusetts (USGS 2020). Beryllium alloys were also produced by Belmont Metals Inc. in Brooklyn, New York and by NGK Metals Corp. in Sweetwater, Tennessee (USGS 2020). Beryllium oxide ceramic components and compound materials were manufactured in Haskell, New Jersey by American Beryllia Inc., and beryllium metal sheets and foil were manufactured in Los Angeles, California by American Elements (USGS 2020). Recent production and mine shipments have decreased from 270 metric tons of beryllium content in 2014 to an estimated 170 metric tons of beryllium content in 2018 (USGS 2019).

Table 5-1 lists the number of facilities in each state that manufacture or process beryllium (not including beryllium compounds). Table 5-2 lists the same information for beryllium compounds only. Included in

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these tables are the activities and uses of beryllium and beryllium compounds and the range of maximum amounts of beryllium and beryllium compounds that are stored on site (TRI17 2019).

Table 5-1. Facilities that Produce, Process, or Use Beryllium

State ^a	Number of facilities	Minimum amount on site in pounds ^b	Maximum amount on site in pounds ^b	Activities and uses ^c
CA	1	0	99	9, 12, 14
GA	2	11000	109998	8, 14
IL	2	10000	99999	8
IN	1	1000	9999	8
KS	1	100	999	8
LA	1	0	99	12, 14
MO	2	20000	199998	8
NC	1	10000	99999	14
NV	1	10000	99999	12
NY	1			
OH	3	10000	100098	7
PA	1	10000	99999	1, 2, 3, 9
TN	1	10000	99999	7, 8
VA	1	10000	99999	9

Source: TRI17 2019; Data are from 2017

^a Post office abbreviations used.

^b Amounts on site reported by facilities in each state.

^c Activities/Uses;

- | | | |
|-----------------------|-----------------------------|--------------------------|
| 1. Product | 6. Reactant | 11. Manufacture Aid |
| 2. Import | 7. Formulation Component | 12. Ancillary |
| 3. Used Processing | 8. Article Component | 13. Manufacture Impurity |
| 4. Sale/ Distribution | 9. Repackaging | 14. Process Impurity |
| 5. Byproduct | 10. Chemical Processing Aid | |

Table 5-2. Facilities that Produce, Process, or Use Beryllium (and Compounds)

State ^a	Number of facilities	Minimum amount on site in pounds ^b	Maximum amount on site in pounds ^b	Activities and uses ^c
AK	1	100,000	999,999	1, 13, 14
CA	1	0	99	9, 12, 14
FL	3	11,100	110,997	1, 5, 9, 12, 14
GA	5	32,000	319,995	1, 3, 4, 5, 8, 9, 10, 13,14
IL	3	20,000	199,998	1, 5, 8
IN	6	23,000	230,193	1, 5, 7, 8, 12, 13, 14
KS	1	100	999	8
KY	3	21,000	209,997	1, 5, 9, 12, 13
LA	1	0	99	12, 14
MI	1	2,000	19,998	12
MO	3	21,000	209,997	8, 14
MT	1	10,000	99,999	1, 5, 12, 14
NC	4	31,000	309,996	1, 5, 9, 12, 14
ND	2	2,100	20,997	1, 5, 13

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Table 5-2. Facilities that Produce, Process, or Use Beryllium (and Compounds)

State ^a	Number of facilities	Minimum amount on site in pounds ^b	Maximum amount on site in pounds ^b	Activities and uses ^c
NM	3	20,100	200,997	1, 3, 4, 5, 9, 12, 13, 14
NV	1	10,000	99,999	12
NY	1			
OH	6	130,000	1,300,095	1, 3, 4, 5, 7, 9, 12, 13, 14
PA	5	22,100	220,995	1, 2, 3, 5, 7, 9, 12
TN	2	20,000	199,998	1, 5, 7, 8, 12
TX	3	12,000	119,997	1, 3, 4, 5, 9, 12, 13, 14
UT	1	100,000	999,999	1, 4, 6
VA	1	10,000	99,999	9
WI	1	10,000	99,999	11
WV	2	20,000	199,998	1, 3, 4, 5, 9, 12, 13

Source: TRI17 2019; Data are from 2017

^a Post office abbreviations used.

^b Amounts on site reported by facilities in each state.

^c Activities/Uses;

- | | | |
|-----------------------|-----------------------------|--------------------------|
| 1. Product | 6. Reactant | 11. Manufacture Aid |
| 2. Import | 7. Formulation Component | 12. Ancillary |
| 3. Used Processing | 8. Article Component | 13. Manufacture Impurity |
| 4. Sale/ Distribution | 9. Repackaging | 14. Process Impurity |
| 5. Byproduct | 10. Chemical Processing Aid | |

5.2.2 Import/Export

From 2014 to 2018, approximately 62 to 86 metric tons of beryllium were imported into the United States (USGS 2019). These imports include estimates of beryllium content of imported ores and concentrates, oxides and hydroxides, unwrought metals (including powders), beryllium articles, wastes and scrap, beryllium-copper master alloys, and beryllium-copper plates, sheets, and strip. In 2007, U.S. exports of beryllium-containing ores were 150 metric tons of beryllium metal equivalents (Welch 2012). Exports in the years 2014 to 2018 were between 26 and 38 metric tons of beryllium (USGS 2019). These exports include estimated beryllium content of exported unwrought metals (including powders), beryllium articles, and wastes and scrap.

5.2.3 Use

Beryllium is included in a list of critical minerals (83 FR 23295) published by the U.S. Department of the Interior in May 2018 (USGS 2019). As a critical mineral, beryllium is identified as a nonfuel mineral or mineral material that is essential to the economic and national security of the United States, has a supply chain that is vulnerable to disruption, and is essential in the manufacturing of products (USGS 2019). Using sales estimates to forecast apparent uses, 22% of beryllium products are used in industrial components, 21% in consumer electronics, 16% in automotive electronics, 9% in defense applications,

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8% in telecommunications infrastructure, 7% in energy applications, 1% in medical applications, and 16% in other applications (USGS 2019). U.S. consumption of beryllium-based products from 2017 to 2018 increased 20% likely due to sales of beryllium to the consumer electronics, defense, energy, and industrial components markets (USGS 2019).

The most common form of processed beryllium is beryllium alloy strip and bulk products, and it is used in all application areas. The majority of unalloyed beryllium metal and beryllium composite products are used in defense and scientific applications (USGS 2019). In the medical field, beryllium is used to produce pacemakers, lasers, high-resolution X-ray images, and dental alloys (Taylor et al. 2003). Recently, beryllium has been used in the construction of golf clubs and bicycle frames (Taylor et al. 2003).

Given its structural, mechanical, and material properties, beryllium is useful in the aerospace industry. Beryllium is used in aircraft bearings and bushings and as a component of fuel containers for solid propulsion jet and rocket fuel systems, gyros, and reentry vehicles. One beryllium alloy, Beralcast® is used to manufacture U.S. military fighter planes, helicopters, and missile systems (Taylor et al. 2003). The United States began using beryllium in weapons components during World War II, and beryllium is still used in the nuclear weapons program (Taylor et al. 2003).

Beryllium is also used in the electronics industry in the manufacture of springs, switches, relays, and connectors for computers, telecommunications, appliances, and automotive applications (Taylor et al. 2003). Beryllium oxide ceramics are used as semiconductor devices and integrated circuits (Taylor et al. 2003).

5.2.4 Disposal

The most significant amount of beryllium waste results from pollution control methods such as solid particulate scrubbers. Since beryllium is a valuable element, the most desirable method of handling beryllium waste is to recycle it to the producers. The leading beryllium producer in the United States has a comprehensive recycling program for its beryllium products and recovers approximately 40% of the beryllium content of new and old beryllium alloy scrap (USGS 2019). While detailed data on the quantities of beryllium recycled in the United States are not available, recycled beryllium may account for as much as 20 to 25% of total beryllium consumption (USGS 2019).

The EPA has classified beryllium powder as a hazardous waste material (40 CFR Section 261.33). Under the Resource Conservation and Recovery Act (RCRA), compliance with labeling and disposal procedures as well as obtaining permits for discharges into air and water are required for beryllium powder. Beryllium

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compounds (including beryllium) are classified as a Clean Air Act (CAA) hazardous air pollutant (HAP). Under the CAA, EPA has established national emission standards for stationary sources that emit, or have the potential to emit, beryllium to air. Beryllium solid waste should be placed into impermeable, sealed bags or containers (e.g., drums) that are labeled in accordance with the requirements of EPA regulations (Fishbein 1981). The EPA has also issued final regulations under the Clean Water Act for specific nonferrous metal manufacturing operations including beryllium processing facilities. These regulations limit the discharge of beryllium containing pollutants into navigable waters and into publicly-owned treatment works (POTWs). Waste waters containing beryllium may therefore require treatment to reduce the concentration of beryllium. A typical treatment method for beryllium involves steps such as chemical precipitation, settling clarification, neutralization, filtration, and sludge dewatering (EPA 1982, 1988a). Waste waters that contain permissible levels of beryllium may be discharged into streams and POTW facilities (EPA 1982, 1988a).

A significant amount of beryllium waste results from pollution control methods such as containment of solid particulates or aqueous suspensions resulting from air-scrubbing processes. According to the TRI17 (2019), a total of 29,231 and 487,939 pounds of beryllium and beryllium compound wastes, respectively, were disposed of by various industries in 2017 (Section 5.3). Land disposal accounted for 75.4% with air and surface water disposal accounting for 24.3% and 0.02%, respectively. Likewise, beryllium compounds disposal had 95.7% on land, 0.3% to air, 0.02% to surface water, and 1.3% was injected underground. An additional 405 and 33,528 pounds of beryllium and beryllium compound wastes, respectively, were transferred to off-site locations within the United States.

5.3 RELEASES TO THE ENVIRONMENT

The Toxics Release Inventory (TRI) data should be used with caution because only certain types of facilities are required to report (EPA 2005). This is not an exhaustive list. Manufacturing and processing facilities are required to report information to the TRI only if they employ ≥ 10 full-time employees; if their facility is included in Standard Industrial Classification (SIC) Codes 10 (except 1011, 1081, and 1094), 12 (except 1241), 20–39, 4911 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4931 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4939 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4953 (limited to facilities regulated under RCRA Subtitle C, 42 U.S.C. section 6921 et seq.), 5169, 5171, and 7389 (limited S.C. section 6921 et seq.), 5169, 5171, and 7389 (limited to facilities primarily engaged in solvents recovery services on a contract or fee basis); and if their facility produces, imports, or processes

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≥25,000 pounds of any TRI chemical or otherwise uses >10,000 pounds of a TRI chemical in a calendar year (EPA 2005).

Releases of beryllium and beryllium compounds are required to be reported under Superfund Amendments and Reauthorization Act Section 313; consequently, data are available for this compound in the Toxics Release Inventory (TRI) (EPA 2005). According to the TRI, a total of 29,231 pounds (13,259 kg) of beryllium and 487,939 pounds (221,326 kg) of beryllium compounds were released to the environment in 2017 (TRI17 2019).

5.3.1 Air

Estimated releases of 7,109 pounds (~3.2 metric tons) of beryllium to the atmosphere from 10 domestic manufacturing and processing facilities in 2017, accounted for about 24.3% of the estimated total environmental releases from facilities required to report to the TRI (TRI17 2019). These releases are summarized in Table 5-3. Estimated releases of 1,441 pounds (~0.65 metric tons) of beryllium compounds to the atmosphere from 40 domestic manufacturing and processing facilities in 2017, accounted for about 0.29% of the estimated total environmental releases from facilities required to report to the TRI (TRI17 2019). These releases are summarized in Table 5-4.

In addition to ore processing, beryllium is also released into the atmosphere during the production and use of beryllium alloys and chemicals. Beryllium is released into the atmosphere from anthropogenic sources including the combustion of coal and fuel oil, the incineration of municipal solid waste (MSW), the production, use, and recycling of beryllium alloys and chemicals, and, to a minor extent, the burning of solid rocket fuel.

Beryllium emissions from coal and fuel oil combustion account for a majority of the U.S. beryllium emissions from natural and anthropogenic sources (EPA 1987). The average beryllium concentration in U.S. coal is between 1.6 and 2.0 µg/g (Nalbandian 2012). A study by the Department of Energy (DOE) and the University of North Dakota examined the emissions of toxic trace elements from coal-fired power plants (DOE 1996). The data in this study show that stack concentrations are 2–3 orders of magnitude greater than the range of ambient air concentrations for beryllium (DOE 1996). The median stack concentration for beryllium was 0.8 µg Be/m³, and the average emission from the nine coal-fired power plants was 22.6 pounds/year (range 0.49–55.8 pounds/year). It is unclear whether the easing of emission standards for coal-fired powerplants (June 19, 2019) have influenced these data as no new comprehensive studies have been published.

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In 1986, there were 494 of 7,835 incinerated municipal waste streams containing beryllium in the United States (Behmanesh et al. 1992). In 2016, there were 71 power plants in the United States that generated electricity from burning municipal solid waste (EIA 2018). At a municipal WTE facility in Commerce, California, stack emissions for beryllium were measured at 0.2 $\mu\text{g}/\text{m}^3$ (Hasselriis and Licata 1996). The stack emissions from individual municipal WTE facilities are about the same order of magnitude as stack emissions from individual coal-fired power plants; however, the number of municipal WTE facilities in the United States is a factor of 20 less than the number of coal-fired power plants.

Table 5-3. Releases to the Environment from Facilities that Produce, Process, or Use Beryllium^a

State ^c	RF ^d	Air ^e	Water ^f	UI ^g	Land ^h	Other ⁱ	On-site ^j	Total Release	
								Off-site ^k	On and off-site
NV	1	1	0	0	21,712	72	21,713	72	21,785
OH	3	7,000	0	0	0	0	7,000	0	7,000
TN	1	23	0	0	318	0	23	318	341
NC	1	56	0	0	0	0	56	0	56
GA	2	29	0	0	15	0	29	15	44
PA	1	0	5	0	0	0	5	0	5
VA	1	0	0	0	0	0	0	0	0
LA	1	0	0	0	0	0	0	0	0
IL	2	0	0	0	0	0	0	0	0
IN	1	0	0	0	0	0	0	0	0
MO	2	0	0	0	0	0	0	0	0
KS	1	0	0	0	0	0	0	0	0
CA	1	0	0	0	0	0	0	0	0
NY	1	0	0	0	0	0	0	0	0
Total	19	7,109	5	0	22,045	72	28,826	405	29,231

Source: TRI17 2019; Data are from 2017

RF = Reporting Facilities; UI = Underground Injection

^a The TRI data should be used with caution since only certain types of facilities are required to report. This is not an exhaustive list. Data are rounded to nearest whole number.

^b Data in TRI are maximum amounts released by each facility.

^c Post office state abbreviations are used.

^d Number of reporting facilities.

^e The sum of fugitive and point source releases by a given facility.

^f The sum of on-site surface water discharges, and off-site transfers to waste-water treatment-(metals only), and publicly owned treatment works (POTWs) (metal and metal compounds).

^g The sum of on-site and off-site disposal to underground injection wells (Class I wells and Class II-V).

^h The sum of on-site and off-site disposal to: Resource Conservation and Recovery Act (RCRA) subtitle C landfills, other landfills, RCRA subtitle C surface impoundments, other surface impoundments, land treatment, other land disposal.

ⁱ Includes the sum of off-site transfers to: storage only, solidification/stabilization (metals only) disposal, other off-site management, waste broker for disposal, unknown.

^j Total on-site disposal or other releases of the chemical including emissions to air, surface water discharges, land, and underground injection wells.

^k Total amount of chemical transferred off-site for disposal or other releases, including to POTWs.

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From 2001 to 2004, beryllium released from emission stacks at Brush Ceramic Products facility ranged from less than 0.005 to less than 1.588 g Be/day and did not exceed National Emission Standard for Hazardous Air Pollutants (ATSDR 2005a). Emissions were measured from vents, baghouse stacks, and an exhaust duct.

Natural emission sources of beryllium include windblown dusts and volcanic particles. The beryllium amounts released to the atmosphere from these sources are comparable with anthropogenic sources.

Beryllium has been identified in air samples collected from 3 of the 540 current or former NPL hazardous waste sites where it was detected in some environmental media (ATSDR 2019).

Table 5-4. Releases to the Environment from Facilities that Produce, Process, or Use Beryllium Compounds^a

State ^c	RF ^d	Air ^e	Reported amounts released in pounds per year ^b				Total Release		
			Water ^f	UI ^g	Land ^h	Other ⁱ	On-site ^j	Off-site ^k	On and off-site
AK	1	0	0	0	110,000	0	110,000	0	110,000
IL	1	662	0	0	66,114	0	6,677	0	66,776
OH	3	322	16	6,421	48,466	4,559	48,804	10,980	59,784
TX	4	66	1	0	70,052	0	70,119	0	70,119
KY	3	38	0	0	29,762	0	29,800	0	29,800
PA	4	101	4	0	20,448	0	20,362	191	20,553
MI	1	0	0	0	11,232	0	11,232	0	11,232
UT	1	22	0	0	11,085	0	11,107	0	11,107
VA	1	22	0	0	11,000	0	11,022	0	11,022
WV	1	16	0	0	9,885	0	301	9,600	9,901
IN	5	35	37	0	14,725	20	14,257	560	14,817
NC	3	16	0	0	15,716	0	15,732	0	15,732
NM	3	8	0	0	14,461	8,220	14,470	8,220	22,690
FL	3	40	35	0	9,493	0	9,568	0	9,568
MT	1	20	0	0	7,120	76	7,140	76	7,216
TN	1	15	0	0	5,029	0	5,044	0	5,044
GA	3	33	0	0	7,500	0	7,533	0	7,533
ND	2	25	0	0	5,021	0	1,145	3,901	5,046

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Table 5-4. Releases to the Environment from Facilities that Produce, Process, or Use Beryllium Compounds^a

State ^c	RF ^d	Air ^e	Water ^f	UI ^g	Land ^h	Other ⁱ	Reported amounts released in pounds per year ^b		
							On-site ^j	Off-site ^k	Total Release On and off-site
MO	1	0	0	0	0	0	0	0	0
WI	1	0	0	0	0	0	0	0	0
Total	43	1,441	93	6,421	467,109	12,875	454,411	33,528	487,939

Source: TRI17 2019; Data are from 2017

RF = Reporting Facilities; UI = Underground Injection

^a The TRI data should be used with caution since only certain types of facilities are required to report. This is not an exhaustive list. Data are rounded to nearest whole number.

^b Data in TRI are maximum amounts released by each facility.

^c Post office state abbreviations are used.

^d Number of reporting facilities.

^e The sum of fugitive and point source releases by a given facility.

^f The sum of on-site surface water discharges, and off-site transfers to wastewater treatment-(metals only), and publicly owned treatment works (POTWs) (metal and metal compounds).

^g The sum of on-site and off-site disposal to underground injection wells (Class I wells and Class II-V).

^h The sum of on-site and off-site disposal to: Resource Conservation and Recovery Act (RCRA) subtitle C landfills, other landfills, RCRA subtitle C surface impoundments, other surface impoundments, land treatment, other land disposal.

ⁱ Includes the sum of off-site transfers to: storage only, solidification/stabilization (metals only) disposal, other off-site management, waste broker for disposal, unknown.

^j Total on-site disposal or other releases of the chemical including emissions to air, surface water discharges, land, and underground injection wells.

^k Total amount of chemical transferred off-site for disposal or other releases, including to POTWs.

5.3.2 Water

Estimated releases of 5 pounds (~0.002 metric tons) of beryllium to surface water from 19 domestic manufacturing and processing facilities in 2017, accounted for about 0.02% of the estimated total environmental releases from facilities required to report to the TRI (TRI17 2019). An additional < 1 pound (~0.00004 metric tons) was released to publicly owned treatment works (POTWs) (TRI17 2019). Beryllium releases (not including beryllium compounds) are summarized in Table 5-3. Beryllium compounds releases only are summarized in Table 5-4. Estimated releases of 93 pounds (~0.04 metric tons) of beryllium compounds to surface water from 43 domestic manufacturing and processing facilities in 2017, accounted for about 0.02% of the estimated total environmental releases from facilities required to report to the TRI (TRI17 2019). While beryllium compounds were released to surface water, none were reportedly released to POTWs (TRI17 2019).

Anthropogenic sources of beryllium released to water include industrial wastewater effluents. Deposition of atmospheric beryllium is also a source in surface waters; however, the relative significance of the contribution from this source, compared to industrial discharge to surface water, cannot be assessed.

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One study measured beryllium concentrations in rime (frosted objects in clouds or fogs) and snow at 10 remote mountain-top locations in the Czech Republic. Mean concentrations were reported as follows: soluble beryllium in rime 12.2 ng/L, soluble beryllium in snow 2.8 ng/L, insoluble beryllium in rime 13.0 ng/L, insoluble beryllium in snow 9.3 ng/L (Bohdalkova et al. 2012). Bohdalkova et al. (2012) also calculated that the total winter-time beryllium deposition rate, depending on the site, was up to ~15 µg/m².

Beryllium also enters the waterways from the weathering of rocks and soils (EPA 1980). Since coal contains beryllium, it is also likely that beryllium will enter surface water via leaching of coal piles. Beryllium has been identified in water samples collected from 104 of 540 NPL hazardous waste sites, where it was detected in some environmental media (ATSDR 2019).

5.3.3 Soil

Estimated releases of 22,045 pounds (~10 metric tons) of beryllium to soils from 19 domestic manufacturing and processing facilities in 2017, accounted for about 75.4% of the estimated total environmental releases from facilities required to report to the TRI (TRI17 2019). Beryllium was not released via underground injection (TRI17 2019). These releases are summarized in Table 5-3. Estimated releases of 467,109 pounds (~211.9 metric tons) of beryllium compounds to soils from 43 domestic manufacturing and processing facilities in 2017, accounted for about 95.7% of the estimated total environmental releases from facilities required to report to the TRI (TRI17 2019). An additional 6,421 pounds (~2.9 metric tons) of beryllium compounds, constituting about 1.32% of the total environmental emissions, were released via underground injection (TRI17 2019). These releases are summarized in Table 5-4.

Beryllium is naturally present in soils and sediments between 0.48 and 3.52 mg/kg (Bilski et al. 2013). Coal fly ash and municipal solid waste incinerator ash are disposed of in landfills and used in building materials (Kalyoncu 1998). Coal fly ash contains beryllium at levels of 46 mg beryllium/kg ash (Stadnichenko et al. 1961). According to the American Coal Ash Association (ACAA), fly ash production has been decreasing over the last several years, and about 38 million tons of fly ash was produced in 2017 (ACAA 2017a, 2017b). This translates to about 1,585 metric tons of beryllium produced in coal fly ash, which is either used or potentially disposed of in landfills.

One study investigated the leaching of beryllium from plant growth media made of coal fly ashes, from ashes combined with the soil, and from ashes combined with the soil and sphagnum peat moss. In most cases, the concentration of beryllium in leachate didn't depend on pore volume or on the concentration in substrates (Bilski et al. 2013). Leaching of beryllium from substrates was also not affected by the presence of soil or sphagnum peat moss (Bilski et al. 2013).

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Land application of sewage sludge containing higher than background concentrations of beryllium can be a source of beryllium contamination of soil. Deposition of atmospheric aerosols on terrestrial surfaces is another source of beryllium in soil. Valberg et al. (1996) estimated the amount of time that it would take to double the ambient soil concentration of beryllium by dry deposition (at the point of maximum impact) near a municipal solid waste incinerator in Vermont. Their estimate was between 468 and 2,275 years, depending upon the ambient concentration of beryllium in the soil. Other quantitative data regarding the relative significance of these sources was not available. Beryllium has been identified in soil samples collected from 133 of 540 NPL hazardous waste sites, where it was detected in some environmental media (ATSDR 2019).

5.4 ENVIRONMENTAL FATE

5.4.1 Transport and Partitioning

Beryllium is more likely to be present in the sediment or absorbed by the suspended matter of a natural body of water, than present in solution. Beryllium is not likely to be detected above trace levels in the water due to hydrolysis of soluble beryllium salts in the sediment at neutral pH (Svilar et al. 2013).

Air. Beryllium in air is attached to particulate matter whose residence time in air is dependent upon particle size. A study of stack emissions from coal combustion reported that most beryllium is found on particles with diameters of $<2.5 \mu\text{m}$ (Gladney and Owens 1976).

The transport of beryllium from the atmosphere to terrestrial and aquatic surfaces occurs through wet and dry deposition (Bohdalkova et al. 2012; EPA 1987). By analogy to other elements, a typical dry deposition velocity may be estimated for beryllium particles over vegetative surfaces as 0.25 cm/second (EPA 1987). The dry deposition rate of aerosol particles is a function of particle size, wind speed, and surface roughness. The process of wet deposition of airborne beryllium consists of wash-out and rain-out; wash-out involves the scrubbing of particles from the air by rain and rain-out involves their attachment to aerosols in clouds. The portion of beryllium particles transported from the atmosphere by wet deposition has not been estimated. Beryllium was detected but not quantified in rainwater from Fresno, California and was quantified in snow and rime in the Czech Republic, suggesting that transport of beryllium from the atmosphere to terrestrial and aquatic surfaces may occur by wet deposition (Bohdalkova et al. 2012; Salo et al. 1986). Beryllium containing soil can be resuspended in the atmosphere as a result of wind action.

Water. Beryllium is carried to rivers, lakes, and oceans by the process of land erosion. The amount of beryllium transported to surface waters from the land by wind-blown soil is estimated to be relatively small (Merrill et al. 1960). Acid deposition has been shown to accelerate chemical weathering of soil and

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bedrock into drainage outflow, increasing the mobility of beryllium (Jagoe et al. 1993). Beryllium is highly mobile in acidic, organic-rich continental river water, but a significant scavenging effect is seen in the estuarine-ocean mixing zone (Taylor et al. 2003). The estimated residence time of beryllium in ocean water, before it is removed from the aqueous phase by sedimentation or other removal processes, is between 150 and 570 years (Merrill et al. 1960). Beryllium is more likely to be present in the sediment or absorbed by the suspended matter of a natural body of water, than present in solution. Beryllium is not likely to be detected above trace levels in water due to hydrolysis of soluble beryllium salts in the sediment at neutral pH (Svilar et al. 2013). Bhat et al. (2002) found that 80% of total beryllium in the environment is removed by rain.

Sediment and Soil. Beryllium binds strongly to soil fulvic acid; binding increases with increasing pH. Beryllium also forms complexes with marine fulvic acids at nearly neutral pH values (Esteves Da Silva et al. 1996). However, beryllium has a much stronger affinity for clay minerals than for organic matter. Beryllium is usually associated in soil at aluminum sites with clay minerals rather than iron oxides (Lum and Gammon 1985). It tends to displace divalent cations with smaller charge-to-ionic radius ratios (Fishbein 1981). For pH values <6, the distribution of beryllium between solution and solids is related to sorption at surface sites. At pH values >6, the solute concentration of beryllium is strongly controlled by the solubility of Be(OH)₂ (Aldahan et al. 1999). The sediment-water distribution coefficients (K_d) for beryllium are very high indicating a very low mobility in sediments. At pH values >6, K_d values are very high for most soils and sediments. For Lake Michigan sediments, K_d ranged between 10⁵ and 10⁶ (Hawley et al. 1986). Beryllium may accumulate in the surface organic layer of the sediment profile; however, there is no indication as to whether the organic matter content of sediment affects K_d (Lum and Gammon 1985). The presence of organic matter did not significantly affect the K_d for saline systems (You et al. 1989); in seawater, K_d is, on average, between 316,000 and 794,000 (Hawley et al. 1986).

In highly alkaline soils, the mobility of beryllium may increase as a result of the formation of soluble hydroxide complexes, such as [Be(OH)₄]²⁻ (Callahan et al. 1979; Cotton and Wilkinson 1980). In acidic soils (e.g., forest ecosystems), dissolved Be²⁺ has been found to be the prevailing beryllium species in the soil solution, and it should be relatively mobile in these environments (Krám et al. 1998). However, leaching would not be expected to occur in less acidic soils (Hayes and Traina 1998).

Other Media. The concentration of beryllium in plants is very low. Soluble forms of beryllium must be present for uptake to occur in plants. For collard seedlings, beryllium remains in the roots, and only small portions were translocated to above ground portions (Kaplan et al. 1990). Romney and Childress (1965) examined uptake of ⁷Be in beans, barley, sunflowers, and tomato plants. Over 95% of ⁷Be was found in the roots; very little was translocated to the foliage and fruits (Romney and Childress 1965). The

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enrichment ratio of beryllium in oat grain and in alfalfa grown in both microcosms and field plots amended with beryllium containing fly ash was 1.0 (Tolle et al. 1983).

Beryllium does not bioconcentrate in aquatic organisms. A measured bioconcentration factor (BCF) of 19 was reported for beryllium in bluegill fish (EPA 1980). Other investigators have reported a BCF of 100 for freshwater and marine plants, vertebrates, and fish (Callahan et al. 1979). Comparisons of the beryllium levels in bottom-feeding biota and surface sediments from Lake Pontchartrain, Louisiana, indicate similar, but somewhat lower beryllium concentrations in biota (Byrne and DeLeon 1986). Very low bioaccumulation for beryllium was observed in southern toads (*Bufo terrestris*) exposed directly to elevated levels of beryllium and other trace metals from a coal fly ash basin (Hopkins et al. 1998). No evidence of the bioaccumulation of beryllium in the food chain of humans was located in the literature (Fishbein 1981).

5.4.2 Transformation and Degradation

As an element, beryllium does not degrade in the environment; it can only change its form.

Air. The atmospheric emission of beryllium during ore processing is likely to occur as: beryllium, beryllium ore dust, beryllium hydroxide, $\text{Be}(\text{OH})_2$; beryllium oxide, BeO ; sodium fluoroberyllate, $(\text{NH}_4)_2\text{BeF}_4$; and beryllium fluoride, BeF_2 (Fishbein 1981); from ceramic plants, atmospheric emissions are typically beryllium or beryllium oxide (Fishbein 1981). The form of beryllium emitted into the atmosphere from thermal processes is typically beryllium oxide (EPA 1998). It is unlikely that beryllium oxide in air will react with sulfur or nitrogen oxides to produce beryllium sulfates or nitrates.

Water. The common beryllium silicates, like beryl, and phenacite, are highly insoluble in aqueous solution and resist chemical weathering (Taylor et al. 2003). The reaction of beryllium in water is controlled by chemical speciation by which one species is converted to another. Beryllium is highly hydrated in acid solutions, which is a consequence of its high charge to size ratio. The speciation of beryllium in solution is: $[\text{Be}(\text{H}_2\text{O})_4]^{2+}$, $\text{Be}_2(\text{OH})_3^+$, $\text{Be}_3(\text{OH})_3^{3+}$, and possibly $\text{Be}_5(\text{OH})_7^{3+}$ in acid solution (i.e., $\text{pH} < 6$); and $[\text{Be}(\text{OH})_4]^{2-}$ in basic solution (i.e., $\text{pH} > 8$) (Cotton and Wilkinson 1980). In the pH range of 6–8, typical of most waters, the speciation of beryllium is controlled by the formation of solid beryllium hydroxide, $\text{Be}(\text{OH})_2$, which has a very low solubility (solubility product, $K_{\text{sp}} = 10^{-21}$). Table 5-5 illustrates several precipitation reactions for beryllium under a neutral environment.

Other transformations of environmental importance are the formation of insoluble basic carbonates, such as $(\text{BeCO}_3)_2\text{Be}(\text{OH})_2$, by the reaction of dissolved carbonate with beryllium solutions and the formation of beryllium sulfate (i.e., BeSO_4), by the reaction of soluble sulfates with beryllium solutions.

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Table 5-5. Precipitation of Beryllium Compounds in a Neutral (pH 6.5-9.5) Environment

Compound	Reaction	Notes
Ammonium tetrafluoroberyllate (Ammonium beryllium fluoride)	$(\text{NH}_4)_2\text{BeF}_4 \rightarrow 2[\text{NH}_4]^+_{\text{aq}} + [\text{BeF}_4]^{2-}_{\text{aq}}$ Excess H ₂ O pH 7	Remains soluble in a neutral environment
Beryllium oxide	$\text{BeO} + \text{H}_2\text{O} \rightarrow \text{Be}(\text{OH})_2$ Excess H ₂ O pH 7	Forms insoluble beryllium hydroxide in a neutral environment
Beryllium hydroxide	$\text{Be}(\text{OH})_2 \rightarrow$ no reaction Excess H ₂ O pH 7	Beryllium hydroxide is insoluble in a neutral environment
Beryllium fluoride	$\text{BeF}_2 + 2 \text{H}_2\text{O} \rightarrow [\text{BeF}_2(\text{H}_2\text{O})_2]_{\text{aq}}$ and other complexes Excess H ₂ O pH 7	Remains soluble in a neutral environment
Beryllium nitrate trihydrate	$\text{Be}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O} + 2\text{MOH}^{\text{a}} \rightarrow \text{Be}(\text{OH})_2 + 2[\text{M}]^+_{\text{aq}} + 2[\text{NO}_3]^-_{\text{aq}} + 3\text{H}_2\text{O}$ Excess H ₂ O pH 7	Forms insoluble beryllium hydroxide in a neutral environment
Beryllium sulfate tetrahydrate	$\text{BeSO}_4 \cdot 4\text{H}_2\text{O} + 2\text{MOH}^{\text{a}} \rightarrow \text{Be}(\text{OH})_2 + 2[\text{M}]^+_{\text{aq}} + [\text{SO}_4]^{2-}_{\text{aq}} + 4\text{H}_2\text{O}$ Excess H ₂ O pH 7	Forms insoluble beryllium hydroxide in a neutral environment
Beryllium oxalate trihydrate	$\text{BeC}_2\text{O}_4 \cdot 3\text{H}_2\text{O} + 2\text{MOH}^{\text{a}} \rightarrow \text{Be}(\text{OH})_2 + 2[\text{M}]^+_{\text{aq}} + [\text{C}_2\text{O}_4]^{2-}_{\text{aq}} + 3\text{H}_2\text{O}$ Excess H ₂ O pH 7	Forms insoluble beryllium hydroxide in a neutral environment
Beryllium basic acetate ^b	$\text{Be}_4\text{O}(\text{C}_2\text{H}_3\text{O}_2)_6 + 6\text{MOH}^{\text{a}} + \text{H}_2\text{O} \rightarrow 4\text{Be}(\text{OH})_2 + 6[\text{M}]^+_{\text{aq}} + 6[\text{C}_2\text{H}_3\text{O}_2]^-$ Excess H ₂ O pH 7	Forms insoluble beryllium hydroxide in a neutral environment

Source: EPA 1998

^aMOH is a base; M in MOH signifies a cation such as sodium (Na) or potassium (K).

^bBeryllium basic acetate is not a true basic salt; it is a covalent compound.

Lithogenic beryllium has a long oceanic residence time of 600-1,000 years and may be supplied from eolian dust, fluvial inputs, and successive lateral transport (Tazoe et al. 2014). Tazoe et al. (2014) observed that beryllium concentration in the ocean increases with depth, reflecting its remineralization from settling particles.

Sediment and Soil. Typical transport and distribution processes for beryllium in soil include precipitation, complexation, and anion exchange. Important factors affecting the transformation of beryllium in soils and sediments include pH, ionic strength (i.e., salinity), concentration and distribution of species, composition of the mineral matrix, organic matter, biological organisms, and temperature (Section 5.4.1). Data suggesting the biotransformation of beryllium or its compounds in soil were not located.

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5.5 LEVELS IN THE ENVIRONMENT

Reliable evaluation of the potential for human exposure to beryllium depends, in part, on the reliability of supporting analytical data from environmental samples and biological specimens. Concentrations of beryllium in unpolluted atmospheres and in pristine surface waters are often so low as to be near the limits of current analytical methods. In reviewing data on beryllium levels monitored or estimated in the environment, it should also be noted that the amount of chemical identified analytically is not necessarily equivalent to the amount that is bioavailable.

Table 5-6 shows the limits of detection typically achieved by analytical analysis in environmental media. Presented in Table 5-7 are the summary range of concentrations detected in environmental media. Table 5-8 indicates beryllium levels at NPL sites.

Table 5-6. Lowest Limit of Detection for Beryllium Based on Standards^a

Media	Detection limit	Reference
Air	0.0002 ng/m ³	EPA 2014; EPA 2020
Surface wipe	0.0001 µg per wipe	NIOSH 2007, Method 9110 Surface wipes by Fluorometry
Water	0.02 µg/L	EPA 1994
Urine	0.12 µg/L	CDC 2011
Soil, sludge, sediments, and other solid wastes	0.3 µg/L	EPA 1988c

^a Detection limits based on instrumentation and using appropriate preparation and analytics. These limits may not be possible in all situations.

Table 5-7. Summary of Environmental Levels for Beryllium

Media	Low	High	For more information
Outdoor air (ng/m ³)	0.0001	8.9	Section 5.5.1
Indoor air (ng/m ³)	NS	0.0045	Section 5.5.1
Surface water (µg/L)	0	32.6	Section 5.5.3
Groundwater (µg/L)	<1	18	Section 5.5.3
Drinking water (µg/L)	<0.005	5.2	Section 5.5.3
Food (µg/kg fresh weight)	ND	36	Section 5.5.4
Soil (mg/kg)	0.1	2.10	Section 5.5.2
Effluent (µg/L)	0	0.08	Section 5.5.4

ND = not detected, NS = not specified

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Table 5-8. Beryllium Levels in Water, Soil, and Air of National Priorities List (NPL) Sites

Medium	Median	Geometric mean	Geometric standard deviation	Number of quantitative measurements	NPL sites
Water (ppb)	5	7.26	8.83	159	104
Soil (ppb)	1,600	2,644	6.52	231	133
Air (ppbv)	6.15x10 ⁻⁷	8.04x10 ⁻⁷	2.43	4	3

^a Concentrations found in ATSDR site documents from 1981 to 2019 for 1,867 NPL sites (ATSDR 2019). Maximum concentrations were abstracted for types of environmental media for which exposure is likely. Pathways do not necessarily involve exposure or levels of concern.

5.5.1 Air

Since beryllium has been routinely manufactured, machined, and stored at the Lawrence Livermore National Laboratory (LLNL) since the 1950s, a study was conducted to determine its levels at various locations of the facility and in different environmental media (Sutton et al. 2012). Beryllium concentrations in airborne particles sampled from 1974 to 2010 at the main facility in Livermore, California ranged from 0.1 to 540 pg/m³ with a median concentration of 12.6 pg/m³. Beryllium levels at the LLNL test facility located between Livermore and Tracy, California ranged from 0.3 to 430 pg/m³ with a median concentration of 11.0 pg/m³ over the years 1981–2010 (Sutton et al. 2012). Monthly sampling at both facilities showed a clear seasonal variation in beryllium levels. Higher levels were typically observed in late summer/early fall when temperatures and wind speed are usually elevated, and precipitation is low for this part of the state. Lower levels of beryllium in particulate matter were observed in the winter months when precipitation is greater, and temperatures and wind speed are lower.

Beryllium has been monitored in ambient air at the Brush Wellman plant in Elmore, OH since 1958. From January 1997 to April 2002, maximum weekly average concentrations measured at 10 monitors ranged from 0.0012 to 0.0137 µg/m³ (ATSDR 2006). Maximum monthly average concentrations ranged from 0.0004 to 0.0029 µg/m³ (ATSDR 2006). In addition to these 10 monitors, a monitor in a parking lot north of the plant measured maximum weekly concentration of 0.0173 µg/m³ from February 1-8, 1999 and a maximum monthly concentration of 0.0077 µg/m³ from January 1999 to May 2001 (ATSDR 2006). Using air modeling at a Brush Wellman facility in Tucson, Arizona in 1999, the Arizona Department of Environmental Quality estimated that average annual ambient beryllium levels next to the plant were 0.008 µg/m³ based on an emission rate of 4.28 g/day (ATSDR 2000). The maximum one-hour level was estimated to be 0.0014 µg/m³ (ATSDR 2000). The estimated maximum levels in air were concluded to pose no apparent public health hazard to the surrounding community (ATSDR 2000). A school district located near this facility monitored ambient air from 2002 to 2005. Beryllium concentrations ranged from

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0.0000038 to 0.0003087 $\mu\text{g}/\text{m}^3$ (ATSDR 2005a). No average concentrations exceeded National Emission Standards, Arizona Ambient Air Quality Guidelines, or the ATSDR cancer risk evaluation guide (ATSDR 2005a).

The average concentration of beryllium in Japanese cities was 0.042 ng/m^3 , with a maximum concentration of 0.222 ng/m^3 . Beryllium concentrations in Germany were 0.06–0.33 ng/m^3 in urban air (Svilar et al. 2013).

Beryllium in the ambient air is collected by EPA, state, local, and tribal agencies for EPA's Air Quality System (AQS). The data are available in pre-generated data files, and data from recent years are summarized in Table 5-9 (EPA 2018a). According to these results, the mean levels over the last few years are generally less than 0.2 ng/m^3 . The detection limit for aerometric determination of beryllium by approved methods for monitoring hazardous air pollutants ranges from 0.00002 to 0.2 ng/m^3 depending on the method (EPA 2020). Averages at most of these monitoring stations are listed above the method detection limits. Measurements at 100 U.S. locations indicated an average daily beryllium concentration of <0.5 ng/m^3 (Drury et al. 1978; Fishbein 1981). Beryllium concentration in urban air is usually higher, possibly due to burning of coal and fuel oil. Most coal plants in the United States are located in Texas, Indiana, and Ohio (EIA 2019). Beryllium concentration is monitored in Ohio by AQS, and the highest mean concentrations are measured there (EPA 2018a). In populous cities where ambient concentrations of beryllium are monitored, average concentrations were 0.14 to 0.17 ng/m^3 in Minneapolis, 0.152 ng/m^3 in Los Angeles, 0.006 to 0.01 ng/m^3 in Philadelphia, and 0.152 ng/m^3 in San Francisco (EPA 2018a). In 1985, in Jacksonville, Florida, beryllium was below the limit of detection in air (Del Delumyea et al. 1997).

Table 5-9. Percentile Distribution of Annual Mean Beryllium (TSP) Concentrations (ng/m^3) Measured in Ambient Air at Locations Across the United States

Year	Number of U.S. Locations	25th	50th	75th	95th	Maximum
2015	97	0.0074	0.10	0.15	0.28	0.91
2016	93	0.012	0.085	0.15	5.4	8.9
2017	85	0.011	0.088	0.15	0.28	0.65
2018	74	0.041	0.15	0.17	0.28	0.32

TSP = total suspended particles
Source: EPA 2018a

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The ambient concentration of beryllium found in air near power stations in Castellon, Spain ranged from not detected to 1.61 ng/m³ (Boix et al. 2001). Beryllium concentrations in atmospheric particulate samples in and around a beryllium processing facility near Navi Mumbai, India were 0.48±0.43 ng/m³ (n=397). The levels of beryllium during the monsoon season were comparatively lower and often were below the detection limit (Thorat et al. 2001).

Sax et al. (2006) analyzed indoor and outdoor home air in New York City and Los Angeles. The mean concentration of beryllium in indoor home air was 0.0015 ng/m³ in New York City and 0.0018 ng/m³ in Los Angeles. The mean concentration in outdoor home air was 0.0028 ng/m³ in New York City and 0.0018 ng/m³ in Los Angeles.

Table 5-10. Outdoor Air Monitoring Data for Beryllium

Location(s)	Geographic type	Date(s)	Range	Mean concentration	Notes	Reference
Livermore, California	Outdoor air at LLNL main site	1974-2010	0.0001-0.54 ng/m ³	25.9 pg/m ³		Sutton et al. 2012
Between Livermore and Tracy, California	Outdoor air at LLNL experimental test facility	1981-2010	0.0003-0.043 ng/m ³	24.6 pg/m ³		Sutton et al. 2012
Elmore, Ohio	Outdoor air at Brush Wellman Plant	January 1997-April 2002	NS	0.0004-0.0029 µg/m ³	10 monitors; means are maximum monthly average concentrations	ATSDR 2006
Four air monitoring locations in Tucson, Arizona	Outdoor air near Brush Wellman Facility	November 19, 2002, to March 31, 2005.	0.0000038-0.0003087 µg/m ³	0.000008-0.000031 µg/m ³	Monitors were located at 3 elementary schools near the plant and the transportation building	ATSDR 2005
New York, New York	Outdoor home air	June-August 1999	NS-0.011 ng/m ³	0.0028 ng/m ³	96% of the 40 measurements were above the LOD	Sax et al. 2006
Los Angeles, California	Outdoor home air	February-March 2000; September-October 2000	NS-0.0060 ng/m ³	0.0018 ng/m ³	98% of the 41 measurements were above the LOD	Sax et al. 2006

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Table 5-10. Outdoor Air Monitoring Data for Beryllium

Location(s)	Geographic type	Date(s)	Range	Mean concentration	Notes	Reference
Navi Mumbai	Outdoor air around a beryllium processing facility	1991-1996	0.01-2.5 ng/m ³	0.48 ng/m ³	5 sites were sampled for a total of 397 samples	Thorat et al. 2001
Castellon, Spain	Outdoor air near power stations	NS	ND-1.61 ng/m ³	NS		Boix et al. 2001
Jacksonville, Florida	Outdoor air	1945-1995	<LOD	<LOD		Del Delumyea et al. 1997

LOD = limit of detection; ND = not detected; NS = not specified

Table 5-11. Indoor Air Monitoring Data for Beryllium

Location(s)	Geographic type	Date(s)	Range	Mean concentration	Notes	Reference
New York, New York	Indoor home air	June-August 1999	NS-0.0034 ng/m ³	0.0015 ng/m ³	97% of the 40 measurements were above the LOD	Sax et al. 2006
Los Angeles, California	Indoor home air	February-March 2000; September-October 2000	NS-0.0045 ng/m ³	0.0018 ng/m ³	98% of the 41 measurements were above the LOD	Sax et al. 2006

LOD = limit of detection; NS = not specified

5.5.2 Sediment and Soil

Beryllium concentrations ranged from 0.4 to 1.4 mg/kg in four background samples collected several miles from a Brush Wellman facility manufacturing ceramic beryllium products in Tucson, Arizona in 1999 (ATSDR 2000). In 30 soil samples near the facility, beryllium levels were 0.3 to 3.0 mg/kg, and it was concluded that these levels did not present a public health hazard to the community (ATSDR 2000). Average concentration in the soil adjacent to the facility was 0.69 mg/kg and in the soil up to a quarter of a mile away from the facility was 1.05 mg/kg (ATSDR 2005a). In 2000, beryllium concentrations in soils at elementary schools and an administration building near this facility ranged from 0.17 to 1.2 mg/kg with average concentrations at these locations ranging from 0.40 to 0.83 mg/kg (ATSDR 2005a). These measurements also did not present a public health hazard to the community (ATSDR 2005a).

Beryllium concentrations in the soil of the main facility of the LLNL ranged from 0.10 to 0.71 mg/kg in 1988–1994 and 2007 (Sutton et al. 2012). Beryllium levels in the test facility located between Livermore

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and Tracy, California ranged from 0.20 to 2.10 mg/kg from 1991 to 2010. Although beryllium concentrations in soils have been shown to vary considerably between different locations and geologies, the levels of beryllium in soil at the LLNL facilities appear comparable to levels found in the natural environment.

Beryllium was detected in the soil near a hazardous waste incinerator in Constanti, Catalonia, Spain; the mean concentrations were 0.40 mg/kg in 1996–1998 and 0.60 mg/kg in 2009 and 2011. In addition, mean levels of beryllium were higher in rural soils (0.62 mg/kg), than in urban areas (0.49 mg/kg) in 2011 (Vilavert et al. 2012). In Alcala de Henares, Spain, beryllium concentrations were 0.79 mg/kg in soil samples from the University of Alcala campus and 0.35 mg/kg in urban zones of the city (Granero et al. 2002). Table 5-12 provides more details on beryllium soil and sediment concentrations at discussed sites.

Beryllium is the 44th most abundant element in the Earth's crust. The average beryllium concentration in the Earth's crust is approximately 2–5.0 mg/kg (Drury et al. 1978; Griffitts and Skilleter 1990; Krám et al. 1998). Beryllium occurs in silicate minerals and feldspar minerals. The greatest known concentrations of beryllium are found in certain pegmatite bodies. Beryllium ores can contain several thousand mg beryllium per kg solid ore (Fishbein 1981).

Shacklette and Boerngen (1984) reported the average and range of beryllium concentrations in soils and other surficial materials in the conterminous United States as 0.63 and <1–15 mg/kg, respectively. Frink (1996) summarized several different studies and reported that the most likely concentration of beryllium in uncontaminated soils (in the Northeast United States) ranges from <1 to 7 mg/kg. The average concentrations of beryllium in the O or A horizons (sandy loam) and the B horizon (clay) in Maryland were 0.71 and 0.46 mg/kg, respectively (Sparling and Lowe 1996). The average concentration in Florida soils was 0.46 mg/kg with a range of 0.01–5.92 mg/kg (Chen et al. 1999). The average beryllium concentration in California soils was measured as 1.14 mg/kg (Chen et al. 1999). There are few beryllium rich soils in the United States, and these areas are in sparsely settled areas that are not important for food production (Griffitts and Skilleter 1990). The concentration of beryllium in soil around beryllium processing facilities in Navi Mumbai, India ranged from 1.42 to 2.75 mg/kg (Thorat et al. 2001). These levels were comparable to background levels reported in the literature.

In bottom sediments of the Detroit River and western Lake Erie, concentrations of beryllium ranged from 0.1 to 3.8 µg/g beryllium (Lum and Gammon 1985). The beryllium levels in the sediments of Lake Pontchartrain, Louisiana were 0.05–0.5 µg/kg dry wt (Byrne and DeLeon 1986). The concentration of beryllium in sediments from the Neosho River in southeastern Kansas ranged from 0.52 to 1.1 µg/g dry weight in 1992 (Allen et al. 2001). Beryllium concentrations in the sediment of the coastal Beaufort Sea

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ranged from 0.3 to 2.3 µg/g (Trefry et al. 2003). Beryllium levels in the sediment of the Rongjiang River and its estuary were 5.11 to 8.02 mg/kg, with an average concentration of 6.60 mg/kg. However, only a fraction was bioavailable and reported as 0.23 – 0.33 mg/kg (Gu et al. 2018).

Sediment samples were taken from 15 stormwater ponds in the Minneapolis-St. Paul, Minnesota metropolitan area, and analyzed for contaminants. Beryllium was detected in 20% of the samples at a mean concentration of 0.83 mg/kg dry weight (Crane 2019).

Table 5-12. Concentrations of Beryllium in Soil and Sediment

Location	Value	Reference
LLNL main site		
Range	0.10–0.71 mg/kg	Sutton et al. 2012
Mean	0.31 mg/kg	
Median	0.28 mg/kg	
Brush Wellman facility in Tucson, Arizona		
Background samples		ATSDR 2000
Range	0.4-1.4 mg/kg	
Surface soil samples		
Range	0.3-3.0 mg/kg	
LLNL experimental test facility		
Range	0.20–2.10 mg/kg	Sutton et al. 2012
Mean	0.79 mg/kg	
Median	0.68 mg/kg	
Hazardous waste incinerator in Catalonia, Spain		
Mean in 1998	0.40±0.23 mg/kg	Vilavert et al. 2012
Mean in 2009	0.60±0.19 mg/kg	
Mean in 2011	0.60±0.18 mg/kg	
Alcala de Henares		
Campus zone		Granero et al. 2002
Mean	0.79±0.40 mg/kg	
Urban zone		
Mean	0.79±0.40 mg/kg	
Surface sediment of Rongjiang River		Gu et al. 2018
Mean	6.60 mg/kg dry wt	

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Table 5-12. Concentrations of Beryllium in Soil and Sediment

Location	Value	Reference
Minneapolis-St. Paul, Minnesota		
Stormwater pond sediment		
Mean	0.83 mg/kg dry wt	Crane 2019
% detects	20%	

dry wt = dry weight; LNNL = Lawrence Livermore National Laboratory; kg = kilogram; mg = milligram; Other than ranges and medians, values are means± standard deviation

5.5.3 Water

The EPA's STORET database estimates that for years 1960–1988, the geometric mean concentration of total beryllium in the United States surface waters was 70 ng/L (Svilar et al. 2013). Average concentration estimates for total beryllium in U.S. surface waters from 2015 to 2020 were 0.17 µg/L with a range of 0 to 32.6 µg/L (WQP 2020). Dissolved beryllium was detected in 483 of 6,036 surface water samples analyzed for U.S. Geological Survey's National Water Information System from 2015 to 2020 with a mean concentration of 0.14 µg/L (WQP 2020). In lakes/reservoirs, dissolved beryllium was detected in 109 of 112 samples (97% of sites) with an average concentration of 0.09 µg/L (WQP 2020). In spring waters, dissolved beryllium was detected in 5 of 6 samples (83% of samples) with an average concentration of 0.09 µg/L (WQP 2020). In rivers/streams, dissolved beryllium was detected in 1,899 of 7,493 samples (25% of samples) with an average concentration of 0.23 µg/L (WQP 2020). The median total beryllium concentration of Great Lakes water samples ranged from <4 to 120 ng/L. The percentage of beryllium in suspended particulates of Great Lakes water samples ranged from 2 to 88% (Rossmann and Barres 1988). Beryllium concentrations measured in the Houston Ship Channel ranged from 8 to 24 ng/L (Saleh and Wilson 1999).

Beryllium concentrations in groundwater tend to be higher than in surface water (Taylor et al. 2003). The WQP (2020) lists the number of detections of beryllium in groundwater water at several locations around the United States. In groundwater, dissolved beryllium was detected in 10 of 118 groundwater samples (8.5% of samples) with an average concentration of 0.27 µg/L; total beryllium was detected in 1,074 of 1,239 sites (87% of samples) with an average concentration of 0.09 µg/L. Beryllium was present in 14 samples from wells in the glacial aquifer system of the Northern United States out of 847 samples analyzed, with only one of the samples containing beryllium at concentrations ≥1 µg/L (USGS 2009).

For the USGS National Water-Quality Assessment Program, a comprehensive study of trace elements in groundwater across the United States was conducted from 1992 to 2003. In this study, the USGS

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collected data from 5,183 monitoring and drinking-water wells representing more than 40 principal and other aquifers in humid and dry regions and in various land-use settings (USGS 2011). Very few detections (0.13%) exceeded the beryllium maximum contaminant level of 4 µg/L.

During a site visit to the Brush Wellman plant in Elmore, Ohio in 2001, beryllium was not found in any split well water samples taken from eight residencies near the plant (ATSDR 2006).

Leung and Jiao (2006) conducted a study to analyze the influence of urbanization on groundwater. It was found that beryllium was present in higher mean concentrations in the groundwater of a natural area (0.45 ppb), than in a developed area (0.18 ppb) in Hong Kong during the wet seasons. The natural area referred to an area without anthropogenic influence. The authors concluded that the water in the natural areas were more acidic and had a higher dissolved oxygen content and that changes in the concentrations might be due to natural processes such as water-rock interactions since the natural slopes were uphill to the developed spaces. The median concentration of beryllium in groundwater samples taken around the Denver, Colorado metropolitan area in 1993 was measured at <1 µg/L (Bruce and McMahon 1996).

Rainwater and streams also contain beryllium. In Australia, rainwater and streams had an average beryllium concentration of 0.05–0.08 µg/L (Meehan and Smythe 1967). In Great Britain rainfall had <0.06 µg beryllium/L. Streams however contained between 0.01 and 0.25 µg beryllium/L with higher concentrations in deforested areas (Neal et al. 1992).

Table 5-13. Groundwater Monitoring Data for Beryllium

Location(s)	Type	Date(s)	Range	Mean concentration	Notes	Reference
Elmore, Ohio	Split well water samples	May 31, 2001 and July 26, 2001	ND	ND	Samples were taken from 8 residencies near the Brush Wellman plant; LOD was 5 µg/L for the first set of samples; 2 µg/L for the second set of samples	ATSDR 2006
United States	Glacial aquifer system	1991-2001	0.032-1.2 µg/L	NS	847 samples analyzed; 98% of samples were below detection	USGS 2009
United States	Groundwater across the U.S.	1992-2003	<1-18 µg/L	NS	3,025 samples	USGS 2011

LOD = limit of detection; ND = not detected; NS = not specified; USGS = United States Geological Survey

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Results from EPA's Six-Year Review of national drinking water regulations from 2006 to 2011 show that beryllium was found in 2,165 of 164,392 drinking water samples in concentrations ranging from 0.002 to 2000 µg/L (EPA 2016). The average concentrations of beryllium in bottled and tap water in the United States were <0.1 and 0.013 µg/L, respectively. Table 5-14 summarizes some selected data on the beryllium content of drinking water (Vaessen and Szteke 2000). In Australia, median concentrations in drinking water were measured at 0.02 µg/L with a range of 0.02 to 0.15 µg/L (Hinwood et al. 2015).

Table 5-14. Beryllium Content of Drinking Water

Product	Number of samples	Mean (µg/kg)	Range (µg/kg)
Mineral water (bottled)			
Spain			
Lanjaron	3	NS	0.12±0.01
Ortigosa del Monte	3	<0.6	<0.6
United States			
All samples	72	<0.1	<0.1–5.2
Domestic samples ^a	18	<0.1	<0.1–0.2
European samples ^b	54	<0.1	<0.1–5.2
Poland			
Nieszawa	3	0.17	NS
Zyweic Zdroj	3	0.15	NS
Tap Water			
Spain-Granada	3	NS	0.09±0.01
Germany-Mainz	NS	0.008 ^c	<0.005±0.009
German-Weisbeden	NS	NS	0.034±0.002
Saudi-Arabia-Riyadh (schools)	59	1.24 ^c	0.4–2.17
The Netherlands	266	<0.1	<0.1–0.2
	91	<0.05	<0.05–0.21
United States	NS	0.013 ^c	0.01–0.7

Source: Vaessen and Szteke 2000

^a nine brands

^b 28 brands

^c arithmetic mean

NS = Not specified

Concentrations of beryllium in deep ocean water are fairly uniform globally, and concentrations in ocean water tend to be lower than in river water (Taylor et al. 2003). The concentration of total beryllium in seawater ranges from 0.02 to 0.9 ng/L, with an average of <0.5 ng/L (Measures and Edmond 1986; Merrill et al. 1960). Tazoe et al. (2014) reports mixed layer water from less than 200 m deep in the eastern North Pacific Ocean had a concentration of 7 pmol beryllium/kg. However, beryllium concentration increased

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with depth from 200 to 3,500 m, reaching a concentration of 29 pmol/kg. This profile is similar to that of the western North Pacific Ocean (Tazoe et al. 2014).

5.5.4 Other Media

Beryllium was detected in 8 of 39 samples of effluent in facility wastewater sewers and streams with an average concentration of 0.03 µg/L (WQP 2020). In 197 samples of wastewater treatment plant effluent, beryllium was detected with an average concentration of 0.0004 µg/L (WQP 2020).

Beryllium was found in the carpets of the LLNL site, after vacuuming, at a concentration of 0.002– 0.480 µg/100 cm². Beryllium concentrations in overhead dust were reported to range from 19.4 to 151 µg/100 cm² at an industrial facility located in Schenectady, New York. Beryllium was also detected in surface dust at the front offices and wire annealing/pickling areas of a Copper-Beryllium alloy facility at 0.05– 13.6 µg/100 cm² (Sutton et al. 2012).

Beryllium has been found in products made from aluminum, like shrapnel fragments; aluminum cans; and aluminum foil (Abraham et al. 2014). This study found that the beryllium content of shrapnel and aluminum cans were all approximately 100 ppb while the beryllium content of aluminum foil was 25 ppb (Abraham et al. 2014). While there is some concern that the beryllium in aluminum cans and plastic bottles may leach into the beverage contained inside, Abraham et al. (2014) found that the concentration of beryllium in carbonated water from aluminum cans and plastic bottles was below the detection limits (0.01 ppb). Kilinc et al. (2010) also studied beryllium levels in beverages and found mean concentrations of beryllium ranging from 0.03 to 0.94 ng/mL in 20 types of natural mineral water, flavored mineral water, energy drinks, curative mineral water, and thermal spring water purchased in Turkey. Results for Abraham et al. (2014) and Kilinc et al. (2010) are shown in Table 5-15.

Table 5-15. Concentration of Beryllium in Aluminum and Beverage Samples

Sample type	Beryllium Concentration (ppb)
Shrapnel fragments	105.3
Aluminum soda can	183.7
Aluminum beer can	120.0
Aluminum carbonated water can	110.7
Aluminum foil	25.0
Carbonated water from aluminum cans	<LOD
Carbonated water from plastic bottles	<LOD
Natural mineral water, 7 brands	0.05- 0.94
Cherry flavored mineral water, 3 brands	ND-0.05
Lemon flavored mineral water	ND
Orange flavored mineral water	0.20
Peach flavored mineral water	ND
Mixed fruit flavored mineral water, 3 brands	ND-0.16
Energy drink, 2 brands	ND-0.030

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Table 5-15. Concentration of Beryllium in Aluminum and Beverage Samples

Sample type	Beryllium Concentration (ppb)
Curative mineral water from Yurtbasi, Elazig, Turkey	0.05
Thermal spring water from Bingol, Turkey	0.51

Sources: Abraham et al. 2014; Kilinc et al. 2010

LOD = Limit of detection, ~0.01 ppb = ~0.01 ng/mL

ND = Not detected

Electronic waste often contains beryllium, and surprisingly dental materials also have minute traces of beryllium. Hibbert et al. (2014) analyzed beryllium in the ash of incinerated e-waste and measured the following mean concentrations (in mg/kg): 0.01 in batteries, 0.1 in screens, 43 in circuit boards, and 44.89 in plastics. In a study to determine chemical elements present in irreversible hydrocolloids, dental impression materials commonly used in Brazil and Europe, beryllium was found in all 8 samples at <0.125 ppb. It was one of the elements with the lowest concentrations (Borges de Olival et al. 2018).

The beryllium concentration in several foods, fruits, and fruit juices from around the world are shown in Table 5-16 and Table 5-17. The median concentration of beryllium in the 38 foods listed in Table 5-16 is 22.5 µg/kg fresh weight (excluding kidney beans) and the range of concentrations is <0.1–2,200 µg/kg fresh weight. The highest concentrations (in µg/kg fresh weight) were reported for kidney beans (2,200), crisp bread (112), garden peas (109), parsley (77), and pears (65). The average concentration of beryllium in fruit and fruit juices, listed in Table 5-17, is 13.0 µg/L, and the concentrations ranged from not detected to 74.9 µg/L.

Table 5-16. Beryllium Content of Various Fresh Foods

Product	Concentration (µg Be/kg fresh weight)			
	Number of samples	Mean	Range	Reference
Bananas, pulp	400	4.2	ND-18	Cowgill 1981
Beans	3	0.07	ND-0.07	Meehan and Smythe 1967
Beans, kidney	-	2,200 ^a	-	Awadallah et al. 1986
Cabbage	1	0.2	-	Meehan and Smythe 1967
Cabbage	95	0.091	ND-0.50	Bibak et al. 1999
Cane sugar:				
Brown	-	30	-	Hamilton and Minski 1973
Demerara	-	6	-	Hamilton and Minski 1973
Refined	-	2	-	Hamilton and Minski 1973
Granulated	-	0.2	-	Hamilton and Minski 1973
Carrots, raw	NS	<25	-	Wolnik et al. 1984
Clams, hardshell	31	2±3	-	Capar and Yess 1996
Clams, softshell	10	<2	-	Capar and Yess 1996
Crabs	6	15	10-20	Meehan and Smythe 1967
Coriander	-	34 ^a	-	Awadallah et al. 1986
Corn, field	-	<25	-	Wolnik et al. 1984
Dill	-	59 ^a	-	Awadallah et al. 1986
Eggplant (aubergine)	-	26 ^a	-	Awadallah et al. 1986

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Table 5-16. Beryllium Content of Various Fresh Foods

Product	Concentration ($\mu\text{g Be/kg}$ fresh weight)			
	Number of samples	Mean	Range	Reference
Fish, whole:				
Mullet	8	11	1.6-19	Meehan and Smythe 1967
Blackfish	4	11	3.7-18	Meehan and Smythe 1967
Garden pea	-	109 ^a	-	Awadallah et al. 1986
Green pepper	-	42 ^a	-	Awadallah et al. 1986
Hen eggs, yolk	1	0.2	-	Meehan and Smythe 1967
Hen eggs, yolk, and white	1	0.06	-	Meehan and Smythe 1967
Honey				
Eucalyptus	-	0.18±0.09	-	Bettinelli et al. 2000
Robinia	-	0.38±0.02	-	Bettinelli et al. 2000
Meat	3	4	4-5	Kaiser et al. 1972
Milk	100	0.2	ND-0.7	Meehan and Smythe 1967
Milk	21	<0.01	<0.01	Saribal 2019
Mushrooms	1	1.6	-	Meehan and Smythe 1967
Mushrooms, European wild	1,303	9	<5-36	Seeger et al. 1984
Orange juices	-	<1	-	McHard et al. 1980
Oysters	59	0.6	0.2-5.4	Meehan and Smythe 1967
Oysters, east coast United States	93	<2	-	Capar and Yess 1996
Oysters, west coast United States	40	<2	-	Capar and Yess 1996
Parsley	-	77 ^a	-	Awadallah et al. 1986
Peanuts, kernels	2	0.5	0.3-0.8	Meehan and Smythe 1967
Pears	-	65 ^a	-	Awadallah et al. 1986
Potatoes	-	59 ^a	-	Awadallah et al. 1986
Potatoes	41	0.4–0.6	0.2-1.4	Hofele et al. 1994
Rice	3	4	3-5	Kaiser et al. 1972
Tomatoes	1	0.2	-	Meehan and Smythe 1967
Vegetable marrow, pumpkin	-	20 ^a	-	Awadallah et al. 1986

^aOriginal data based on dry weight; concentrations are recalculated to fresh weight = concentration * (fresh wt *10)

ND = not detected; - = not specified

Table 5-17. Beryllium Content of Various Fruits and Fruit Juices

Product	Number of samples	Mean ($\mu\text{g/L}$)	Range
Apple juice	4	22.5	<0.1–43.6
Citrus fruit			
Ruby red grapefruit	1	1.3	—
Lime	1	<0.1	—
Tangerine	1	0.8	—
Grape cultivars	3	4.4	<0.1–7
Lemon products			
CA lemon	1	17.4	—
Bottled lemon	1	17.0	—
Lemonade	1	55.3	—
Orange juice	5	2.8	<0.1–2.8
Papaya (pulp)	3	74.9	64.5–84.1
Pear (pulp)	1	37.3	—
Red currant	1	1.1	—

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Table 5-17. Beryllium Content of Various Fruits and Fruit Juices

Product	Number of samples	Mean (µg/L)	Range
Stone fruit (pulp)			
Apricot	1	<0.1	—
Peach	1	<0.1	—
Plum	1	1.6	—
Prune	1	3.6	—
Sour cherry	1	1.5	—
Tomato sauce	2	42.4	39.8–45.0
Tropical fruit			
Banana	1	1.5	—
Kiwi	1	3	—
Mango	1	4.5	—
Pineapple	1	<0.1	—

— = not specified; CA = California
Source: Barnes 1997

More recently, Bocio et al. (2005a) investigated the concentration of beryllium and several other metals in meat, fish and seafood, pulses (edible seeds of the legumes), cereals, vegetables, fruits, tubers, whole milk, yogurt, eggs, and sugar sold in Catalonia, Spain near a hazardous waste incinerator. Beryllium was below the limit of detection (<0.05 µg/g) in all samples.

The beryllium concentration in the tissue of bottom fish (e.g., English sole or *Parophrys vetulus*) from Commencement Bay, Tacoma, Washington was 6 µg/kg (Nicola et al. 1987). Beryllium levels in oysters and clams in Lake Pontchartrain, Louisiana were 0.051 and 0.083–0.38 µg/g dry weight, respectively (Byrne and DeLeon 1986). A U.S. FDA survey of concentrations of beryllium and other elements in oysters and clams collected from U.S. coastal areas in use for shellfish production ranged from not detected to 0.002 mg/kg wet weight (Capar and Yess 1996). In 1991, the concentration of beryllium in mussels species from the Neosho River, Kansas were 0.02–0.04 in pimpleback (n=3 at Cottonwood River), not detected–0.02 in monkeyface (n=2 at Humboldt), 0.03 for monkeyface (n=1 at Leroy), and 0.02–0.04 for monkeyface (n=4 at Oswego) µg/g dry weight mussels (Allen et al. 2001).

Beryllium concentrations in three species of fish from the Clinch River in Tennessee, adjacent to the U.S. Department of Energy's Oak Ridge Reservation, were 0.63 µg/kg (striped bass), 0.92 µg/kg (white bass), and 0.72 µg/kg (crappie) (Burger and Campbell 2004). Compared to contaminant levels in fish from Poplar Creek, within the boundaries of Oak Ridge Reservation, mean beryllium concentrations are higher in Clinch River but not significantly higher; concentrations in fish from Clinch River were 0.92 µg/kg while concentrations in fish from Poplar Creek were 0.88 µg/kg (Burger and Campbell 2004).

Beryllium has been detected in orchard leaves and in various trees and shrubs in the United States at concentrations of 26 and <1 µg/kg, respectively (IARC 1980). The beryllium concentrations varied with

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the plant species and the degree of water contamination in their respective environments (Sarosiek and Kosiba 1993). Beryllium levels were below detection limits (not specified) in vegetation in the immediate vicinity of a municipal solid waste incinerator near Catalonia, Spain (Meneses et al. 1999).

A study by Fresquez et al. (2013) analyzed 50 cigarette brands available in Atlanta, Georgia and found that the mean concentration of beryllium ranged from 0.015 to 0.049 $\mu\text{g/g}$. A smoker who smokes 20 cigarettes per day is projected to be exposed to 1.5 μg of beryllium per day (Svilar et al. 2013). In a review focusing on cigarettes from the United States, yields of 0–0.0005 $\mu\text{g Be}$ per cigarette have been reported in 4 of 12 studies of smoke measurements; however, 8 of 12 studies failed to detect beryllium at any concentration (Smith et al. 1997).

The beryllium concentration in coal ash is on average 46 mg/kg in the United States (Stadnichenko et al. 1961). Beryllium concentrations in U.S. coal range from 0.18 to 3.17 mg/kg depending on the state and coal type, but concentrations typically range from 1.46 to 1.52 mg/kg (Taylor et al. 2003). In the Czech Republic, beryllium content in the ash of Czech coal ranged from 0 to 1,507 ppm (0 to 1,507 mg/kg) depending on the basin (Pesek et al. 2005). Beryllium concentrations in ammonia, nitrate, and phosphorus fertilizers used in agriculture ranged from <0.2 to 13.5 $\mu\text{g/g}$ (Raven and Loeppert 1997).

5.6 GENERAL POPULATION EXPOSURE

The general population is exposed to trace amounts of beryllium by inhalation of air and ingestion of drinking water and food. The general population may be exposed to beryllium because of coal incineration. If the average concentration of beryllium in air is assumed to be <0.03 ng Be/m^3 (Section 5.5.1), and a normal U.S. adult inhales approximately 20 m^3 of air per day, then the inhalation exposure for a U.S. adult would be approximately <0.6 ng Be/day . This value may be somewhat higher for persons living near sources of beryllium emission.

Graphite furnace atomic absorption spectrometry (GFAAS) was utilized to detect beryllium in the blood and serum of 10 individuals from the general population of Montreal, Canada. The average concentration of beryllium was $0.63 \pm 0.08 \mu\text{g/L}$ in the blood and $0.43 \pm 0.03 \mu\text{g/L}$ in serum. Slightly higher levels appeared in the blood and serum of smokers as compared to nonsmokers (Stephan et al. 2008). Three studies of general adult populations measured median beryllium concentrations in whole blood ranging from 0.01 to <0.03 $\mu\text{g/L}$ (Cesbron et al. 2013; Gouille et al. 2005; Nisse et al. 2017).

Bjorklund et al. (2012) studied beryllium and other metals in human breast milk from 60 samples. Beryllium levels ranging from below the instrumentation detection limit (0.48 ng/L ; 50% of samples) to

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22 ng/L (2 ng/L median) were reported from new mothers in Sweden from 2002 to 2009 (samples obtained 2–3 weeks postpartum). Hinwood et al. (2015) reported that median beryllium concentrations in pregnant women in Australia were <50 ng/L in blood (n=172) and urine (n=173). Ninety-two percent and 82% of blood and urine samples were below the detection limit (not specified). Concentrations ranged from less than <50 to 59 ng/L in blood and less than <50 to 91 ng/L in urine.

Because beryllium absorption mainly occurs via inhalation and leads to an accumulation of beryllium in the upper respiratory tract and lungs, Nogaj et al. (2014) measured the concentration of beryllium in the pharyngeal tonsils of 379 children (176 girls, 203 boys) between the ages of 2 and 17 years (median 6.0 years) living in southern Poland. The average concentration found in pharyngeal tonsil samples was 16 ng/g with a range of 1 to 58 ng/g. The mean concentration of beryllium was higher ($p<0.05$) in girls than in boys, and concentrations also varied significantly by location. Higher mean concentrations were also found in children living in polluted areas with industrial activity. However, Bocio et al. (2005b) determined human tissue beryllium concentrations were below detection limits (50 ng/g) for residents living near an incinerator.

The mean concentration of beryllium in urine of about 500 nonoccupationally exposed individuals in the United States according to the 3rd National Health and Nutrition Examination Survey (NHANES) was 0.22 $\mu\text{g/g}$ of creatinine (Paschal et al. 1998). Other studies reported mean urinary beryllium concentrations ranging from <0.03 to 0.4 $\mu\text{g/L}$ for persons not occupationally exposed (Apostoli and Schaller 2001). In the last cycle of NHANES that measured urinary beryllium, all values that were not missing were below the lower detection limit of 0.072 $\mu\text{g/L}$ (CDC 2011). Urinary beryllium hasn't been analyzed by NHANES in the last several cycles of the survey.

In a study of 982 adult men and 1,018 adult women in northern France, beryllium was found in 57% of blood samples and 58% of urine samples (Nisse et al. 2017). The mean concentration of beryllium in blood was 0.02 $\mu\text{g/L}$. There was no difference in mean concentration between males and females, and there was also no difference between survey participants who were smokers, former smokers, or non-smokers. The mean concentration of beryllium in urine was 0.04 $\mu\text{g/L}$.

A study on preliminary results of environmental exposure to metals in Italy measured the serum metal levels of beryllium in subjects from Umbria and Calabria. The mean concentrations in Umbria and Calabria were 0.06 and 0.05 $\mu\text{g/L}$, respectively (Bocca et al. 2010).

In a study on mothers' and neonates' exposure to metals in China, beryllium was found in maternal and umbilical cord samples at 0.03 $\mu\text{g/L}$ (Guan et al. 2010). Guan et al. (2010) also found that mothers 35 years or older had significantly higher levels of beryllium than younger mothers. Higher levels of

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beryllium were also found in mothers who had a history of stillbirth. Guan et al. (2010) also investigated the relationships between maternal beryllium levels and other factors like history of spontaneous abortion, exposure to harmful occupational factors, residence proximity to a major transportation route, residence proximity to an industrial chimney, and exposure to second-hand smoke during pregnancy, but they did not find significant positive associations between any of these factors and maternal beryllium levels.

Reliable data regarding the daily exposure rate to beryllium from food consumption are lacking. Few studies have measured levels in food abroad (Pearson and Ashmore 2020; Saribal 2020). In New Zealand, beryllium was detected in several white wine samples, and to a lesser extent in varying food products ranging from 0.001 mg/kg in soya milk to 0.022 mg/kg in salad dressing (Pearson and Ashmore 2020). In over 20 milk samples in Turkey, beryllium was below the detection limit of 0.01 ng/mL (Saribal 2020). It has been estimated that the daily intake of beryllium from U.S. food is 0.12 µg (EPA 1987). This estimate is based on a value for beryllium content of a total diet sample of 0.0001 µg/g food and a daily consumption of 1,200 g of food (EPA 1987). It is believed by Vaessen and Szteke. (2000) that the amount of beryllium in food was underestimated in the EPA (1987) health assessment. However, Bocio et al. (2005a) determined meat, seafood, cereals, seeds, vegetables, pulses (edible seeds of legumes), fruits, milk, dairy products, eggs, and sugar were below detection limits (0.05 µg/g) near an incinerator in Spain. In another study examining the trace element concentrations of food samples via hospital diets in Japan, the average daily intake of beryllium was determined to be 84.4 µg/day (Muto et al. 1994). Other investigators have reported the total daily intake of beryllium in the range of 5–100 µg/day (Vaessen and Szteke 2000).

Beryllium workers may bring home beryllium and expose the general population in this manner. Workers who do not shower or change clothing prior to leaving work could expose their family and others to beryllium. Fabrics experimentally exposed at a beryllium production worksite contained up to 2.8 mg Be/m² (NIOSH 1995). Resuspended beryllium dust concentrations in air from unwashed clothing can reach levels of 0.64 µg/m³. The shaking of contaminated clothes can administer an inhalation dose of approximately 17 µg beryllium (NIOSH 1995). In another study, beryllium concentrations in machine shop workers' personal vehicles were measured. The highest concentrations of beryllium were measured on the driver's floor of the workers' vehicles at 19 µg/Be/ft² (Sanderson 1999).

5.7 POPULATIONS WITH POTENTIALLY HIGH EXPOSURES

Several populations are at high risk for beryllium exposure. Individuals with the highest risk include people who are occupationally exposed to beryllium from manufacturing, fabricating, or reclaiming industries. A National Occupational Exposure Survey conducted by NIOSH during 1981–1983 estimated

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that 13,938 workers were potentially exposed to beryllium, 4,350 to beryllium oxide, and 1,740 to beryllium copper in the workplace (NIOSH 2002).

People who work in industries where beryllium is present have a greater probability of inhalation exposure than nonoccupational groups. The estimated time-weighted average (TWA for 8-hour day) beryllium exposure levels for some workers in a plant that extracted and produced beryllium metal were $>50 \mu\text{g}/\text{m}^3$ during the mid-1960s. Beryllium exposure levels were $>30 \mu\text{g}/\text{m}^3$ during the mid-1970s. After 1977, this plant complied with the previous OSHA maximum TWA concentration of $2 \mu\text{g}/\text{m}^3$ (Kriebel et al. 1988a), which has since been updated. The TWA personal air concentration for beryllium in a precious metal refinery in 1983 ranged from 0.22 to $42.3 \mu\text{g}/\text{m}^3$ (Cullen et al. 1987). The Rocky Flats Environmental Technology Site in Colorado reported mean concentrations of beryllium from area and breathing zone monitors as 0.16 and $1.04 \mu\text{g}/\text{m}^3$, respectively (Stange et al. 1996a). At the Cardiff Atomic Weapons Establishment in the United Kingdom, annual mean area and personal sampling concentration ranges of beryllium were from 0.02–0.32 and 0.09–0.72 $\mu\text{g}/\text{m}^3$, respectively, over the period from 1961 to 1997 (Johnson et al. 2001). OSHA changed the beryllium maximum 8-hour TWA permissible exposure limit to $0.2 \mu\text{g}/\text{m}^3$ in 2019.

Morton et al. (2011) compared levels of beryllium in urine samples of an occupationally exposed group of workers, employed in an aluminum smelter facility where beryllium exists as an impurity of the bauxite ore, to a group of non-occupationally exposed individuals. The mean and 90th percentiles of beryllium in the urine for workers at the aluminum smelter were 19.5 and 42.0 ng/L, respectively, while the mean and 90th percentile of the control group was 11.6 and 20.0 ng/L, respectively. Horng et al. (2002) compared urine concentrations of beryllium in steel production workers and steel quality control workers to a control group. The mean concentrations of beryllium in production workers and quality control workers were 1.58 and 1.39 $\mu\text{g}/\text{L}$ respectively, while the mean in controls was 0.83 $\mu\text{g}/\text{L}$. The mean concentrations in production workers and quality control workers were both significantly higher than in the controls. The beryllium concentration exceeded 2 $\mu\text{g}/\text{L}$ in 2 production workers, which is considered above normal.

Martin and Lariviere (2014) concluded after a review of the literature that although there is significant exposure to beryllium in the aluminum smelting industry, BeS is rare. From January 2004 to April 2005, blood samples of 359 former workers at American Beryllium in Tallevast, Florida, household members, and residents showed that 348 individuals were not beryllium sensitive, three were abnormal, five were borderline, one was uninterpretable, and two tests could not be analyzed (ATSDR 2005b). Skalny et al. (2018) assessed the hair metal levels in aluminum plant workers and concluded that beryllium was not one of the metals to which workers had an increased risk of exposure. However, Godderis et al. (2005)

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concluded that exposure in an aluminum cast-house appeared to be acceptable (did not exceed the TLV-TWA defined by ACGIH), but exposure to beryllium due to aluminum recycling requires more attention. Hulo et al. (2016) found that beryllium levels in exhaled breath condensate were higher in aluminum potroom workers and exposed subjects at a primary aluminum production plant than in controls.

There have been no reports of diseases attributable to beryllium exposure as a result of beryllium ore mining operations (Eisenbud and Lisson 1983; EPA 1987). People living near beryllium-emitting industries may be at a slightly increased risk of beryllium exposure due to contact with beryllium-contaminated dust within the household, as opposed to ambient air levels. Granero and Domingo (2002) estimated that adults in Alcala de Henares, Spain, an area with industrial activity and heavy traffic, are exposed to 2.7×10^{-9} mg/kg day by inhalation while children are exposed to 6.3×10^{-9} mg/kg day. No new cases of beryllium disease in people living near beryllium-processing industries have been reported in the past several years, probably because the past exposures were relatively high compared to present levels of beryllium in the ambient and workplace air (EPA 1987; NIOSH 1995). A small percentage of the population is sensitive to very low concentrations of beryllium, but there is no evidence that sensitivity develops at beryllium concentrations present in food or water, or that sensitivity is aggravated by ingestion of beryllium.

Beryllium exposures may be higher in areas with naturally high beryllium soil levels, and near beryllium processing sites, electric power plants, and waste sites containing beryllium. At waste sites, beryllium that is found in excess of natural background levels is most likely to be in soil. The National Emission Standard for Hazardous Air Pollutants (NESHAPS) restricts the amount of beryllium emitted into the environment by industries that process beryllium ores, metals, oxides, alloys, or wastes. The NESHAPS can be met by complying with either a 10 g per 24-hour emission limit or by meeting an ambient air concentration of $0.01 \mu\text{g}/\text{m}^3$ of air averaged over a 30-day period (EPA 1982). Machine shops machining alloys containing <5% beryllium by weight are excluded from regulation under the NESHAPS emission standard (40 CFR Part 61, subpart C 61.30(b) 2001).

Occupationally exposed workers who carry beryllium dust on their clothes, shoes, or skin from the workplace to their home may increase the risk of beryllium exposure to their family members and themselves (Taylor et al. 2003). In a report to Congress by NIOSH, several historical cases of home contamination by beryllium were reported (NIOSH 1995). The most recent case was in 1992. The majority of these cases were from the contamination of machinist workers' clothing with beryllium dust (NIOSH 1995). Permissible exposure limits have been significantly reduced since the 1990s so it is unclear whether today's 'take home' amounts would be considered a high beryllium exposure.

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Furthermore, beryllium industries are required to provide showers and launder employee's work clothes in an effort to reduce the potential for 'take home' beryllium exposures (29 CFR 1910.1024).

Dental technicians who work with beryllium-containing dental alloys without using appropriate handling safeguards may be exposed to higher levels of beryllium than the normal population (Stark et al. 2014) and can develop CBD (Kotloff et al. 1993; Fireman et al. 2006). Additionally, individuals may be exposed to high levels of beryllium from implanted dental prostheses (EPA 1987; Taylor et al. 2003). Not all dental alloys contain beryllium, however beryllium is still present in dental alloys in the United States (OSHA 2002). The highest concentration of beryllium released from base metal alloy used as dental crowns measured in an artificial oral environment was 8 µg/day per crown (Tai et al. 1992). The mantles of some lanterns used by campers contain approximately 600 µg of beryllium, and most of the beryllium becomes airborne during the first 15 minutes when a new mantle is used (Fishbein 1981). Therefore, people who camp outdoors and use these mantles are possibly exposed to higher than normal levels of beryllium.

The mean concentration of beryllium in cigarettes available in the U.S. ranged from 0.015 to 0.049 µg/g (Fresquez et al. 2013). It is estimated that smoking 20 cigarettes per day could expose an individual to 1.5 µg of beryllium per day (Svilar et al. 2013). In a study based in Romania, beryllium was detected more frequently in e-cigarette users (21% of those sampled) than cigarette smokers (2% of those sampled), although the median blood concentration of beryllium in non-smokers (0.75 ng/mL, detected in 5% of 58 people sampled) was higher than in cigarette smokers (0.26 ng/mL) or e-cigarette users (0.30 ng/mL) (Badea et al. 2018). Nevertheless, smokers may have a higher probability of exposure to beryllium than the nonsmoking population.