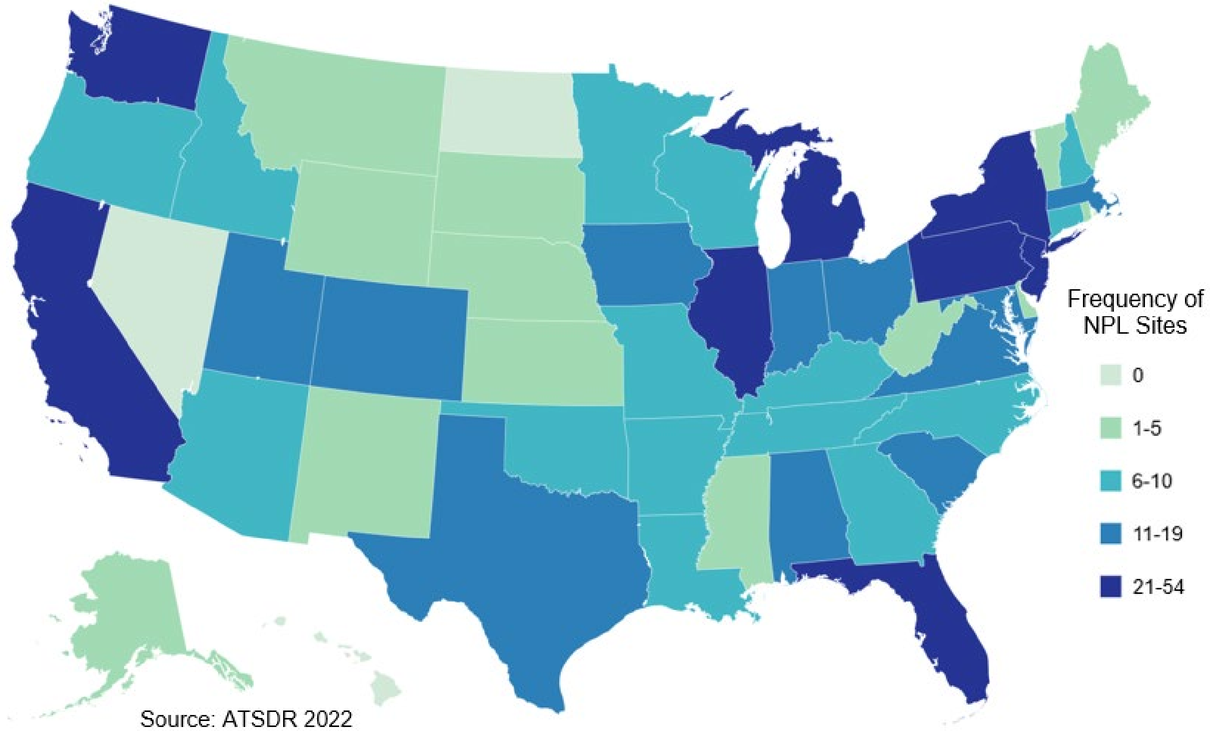
CHAPTER 5. POTENTIAL FOR HUMAN EXPOSURE

5.1 OVERVIEW

Beryllium has been identified in at least 548 of the 1,868 hazardous waste sites that have been proposed for inclusion on the EPA National Priorities List (NPL) (ATSDR 2022). However, the number of sites in which beryllium has been evaluated is not known. The number of sites in each state is shown in Figure 5-1. Of these sites, 538 are located within the United States, 2 are located in the Virgin Islands, 1 is located in Guam, and 7 are located in Puerto Rico (not shown). Data are not available to determine whether beryllium detections at NPL sites are from anthropogenic activity or are naturally occurring levels.

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



Source: ATSDR 2022

- 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.
- Beryllium cannot be degraded in the environment, but it can change form.
- Beryllium has been detected in air at levels up to 20 ng/m^3, but most concentrations are <0.2 ng/m^3.
- 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 average concentration of beryllium in air in the United States is 0.081 ng/m^3 (EPA 2022a).

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, 1983). Deposition of atmospheric beryllium aerosols from both natural and anthropogenic sources is also a source of beryllium in surface waters. In 2021, beryllium was detected in 27% of 4,559 surface water samples in the United States, with an average concentration of 0.140 µg/L, and in 36.7% of 392 groundwater samples, with an average concentration of 0.343 µg/L (WQP 2022). Beryllium is generally not detected in drinking water (EPA 2016; USGS 2011, 2015).

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 (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).

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 μg/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 naturally present in the earth's crust at <1–15 mg/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, McCullough Butte area in Nevada, Black Hills area in South Dakota, Sierra Blanca area in Texas, Seward Peninsula in Alaska, and Gold Hill area in Utah contain most of these resources (USGS 2022). The beryllium minerals of commercial interest are beryl (i.e., $Be_3Al_2Si_6O_{18}$) and bertrandite (i.e., $Be_4Si_2O_7(OH)_2$).

In the United States, bertrandite, which contains <0.5 weight percent beryllium, is the principal mineral mined (USGS 2016). In 2021, 170 metric tons of beryllium were mined in the United States (USGS 2022). The U.S Geological Survey (USGS) estimated that U.S. resources of bertrandite reserves in Utah contained 20,000 tons of beryllium in 2022. 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 or shipped to the company's plant in Ohio to be converted into metal, oxide, and downstream beryllium-copper master alloy (USGS 2022).

Beryllium hydroxide is produced through the SX-carbonate process in which 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., $Be(OH)_2$). Beryllium hydroxide is then recovered by filtration and used to produce products such as beryllium metal, beryllium oxide, and beryllium alloys (EPA 1978; Svilar et al. 2013).

Beryllium metal is produced from beryllium hydroxide through conversion to a halide salt and then reduction to the metallic form (Svilar et al. 2013). The only commercially relevant process involves beryllium fluoride formation and magnesium reduction; beryllium hydroxide is dissolved in an ammonium hydrogen fluoride solution producing ammonium tetrafluoroberyllate, which dissociates into ammonium fluoride and beryllium fluoride at ≥130°C, and into gaseous ammonium fluoride and beryllium fluoride between 900 and 1,100°C. The gaseous beryllium fluoride is cooled, forming solid grains, and is then reduced with pure magnesium at 1,300°C to give beryllium metal (Svilar et al. 2013).

Beryllium oxide is produced from beryllium hydroxide through calcination or from the basic carbonate, acetate, or sulfate salts by ignition (Svilar et al. 2013). The calcination process proceeds through dissolution of bertrandite or beryllium hydroxide in sulfuric acid and treatment with saturated ammonium carbonate to precipitate out heavy metal impurities. The solution containing beryllium hydroxide is concentrated by boiling, and basic beryllium carbonate is precipitated out. The beryllium carbonate is then converted to beryllium oxide through heating at high temperatures (Svilar et al. 2013).

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).

Materion Corporation and Materion Natural Resources reported to EPA's Chemical Data Reporting Rule manufacture of beryllium, beryllium fluoride (BeF_2), beryllium hydroxide, beryllium oxide, and sulfuric acid, beryllium salt (1:1) in 2019 at sites in Elmore, Ohio, and Delta, Utah (EPA 2022b). IBC Advanced Alloys Corporation 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 between 2017 and 2021 have remained relatively constant at between 150 and 170 metric tons of beryllium content but are decreased from 270 metric tons of beryllium content produced in 2014 (USGS 2019, 2022).

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 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 (TRI21 2022).

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]
AL	1	10,000	99,999	12
GA	1	10,000	99,999	14
IL	1	100	999	8
IN	1	1,000	9,999	14
MO	2	10,000	99,999	8
NC	1	0	99	14
NV	1	10,000	99,999	12
NY	1	0	99	12
OH	1	10,000	99,999	8

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]
PA	1	10,000	99,999	1, 2, 3, 4, 8, 9
TN	1	1,000	9,999	2, 3, 6
VA	1	100,000	999,999	9
WI	1	10,000	99,999	8

[a] Post office state abbreviations used.
[b] Amounts on site reported by facilities in each state.
[c] Activities/uses:

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

Source: TRI21 2022 (Data are from 2021)

Table 5-2. Facilities that Produce, Process, or Use Beryllium 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	2	10,000	99,999	1, 5, 12, 13, 14
AZ	1	100,000	999,999	8
FL	3	1,000	9,999	1, 5, 9, 14
ID	1	10,000	99,999	1, 5, 12, 13, 14
IL	2	1,000	9,999	1, 5, 7
IN	6	0	99,999	1, 5, 7, 12, 13, 14
KY	4	10,000	99,999	1, 3, 4, 5, 10, 12, 13
MI	2	1,000	999,999	12
MT	1	10,000	99,999	1, 5, 12, 14
NC	2	10,000	99,999	1, 5, 9, 12, 14
ND	4	100	99,999	1, 5, 13, 14
NM	1	10,000	99,999	1, 3, 4, 5, 13, 14
NV	2	100	9,999	1, 5, 12, 13, 14
OH	2	10,000	999,999	1, 3, 4, 5, 7, 12, 13
PA	2	100	9,999	1, 5, 7, 12
SC	1	10,000	99,999	1, 5, 12, 13, 14

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

State[a]	Number of facilities	Minimum amount on site in pounds[b]	Maximum amount on site in pounds[b]	Activities and uses[c]
TN	1	10,000	99,999	1, 5
TX	2	1,000	99,999	1, 3, 4, 5, 9, 12, 13, 14
UT	3	1,000	999,999	1, 4, 5, 7, 9, 12
WV	3	10,000	99,999	1, 3, 4, 5, 9, 12, 13

[a] Post office state abbreviations used.
[b] Amounts on site reported by facilities in each state.
[c] Activities/uses:

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

Source: TRI21 2022 (Data are from 2021)

5.2.2 Import/Export

From 2017 to 2021, approximately 49–67 metric tons of beryllium were imported into the United States (USGS 2022). 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. Imports originated from Kazakhstan (41%), Japan (16%), Brazil (11%), Latvia (10%), and other unspecified countries (22%). Two companies reported importing beryllium in 2019 to the EPA Chemical Data Reporting rule: TMS International, LLC, at a site in Horsham, Pennsylvania, and Nucor Corporation at a site in Cincinnati, Ohio (EPA 2022b). Exports during this time period were between 25 and 38 metric tons of beryllium (USGS 2022). 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 published by the U.S. Department of the Interior in 2018 (DOI 2018). 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, 23% of beryllium products were used in industrial components, 17%

in aerospace and defense applications, 17% in automotive electronics, 12% in consumer electronics, 11% in telecommunications infrastructure, 5% in energy applications, 1% in semiconductor applications, and 14% in other applications (USGS 2022). Reported consumption of beryllium ore was relatively stable between 2017 to 2021 in the United States, at 160–170 metric tons. Apparent consumption of beryllium (based on production, imports, exports, and adjustments for government and industry stock changes) varied between 167 and 202 metric tons for the same time period (USGS 2022).

The three main forms of beryllium used commercially are 0.2–2.0% beryllium alloys (especially copper-beryllium alloys), pure beryllium metal and >50% beryllium alloys, and beryllium oxide ceramics (Svilar et al. 2013). Beryllium alloy strip and bulk products are used in all sectors reporting usage of beryllium products (USGS 2022). The majority of unalloyed beryllium metal and beryllium composite products are used in defense and scientific applications (USGS 2022). In the medical field, beryllium is used to produce pacemakers, lasers, high-resolution x-ray images, and dental alloys (Taylor et al. 2003). Beryllium has also 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 containing alloys are used in aircraft bearings and bushings, gyros, and reentry vehicles. One beryllium aluminum metal matrix composite containing 60–70% beryllium is used to manufacture components for 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-containing alloys are 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 beryllium alloy scrap (USGS 2022). While detailed data on the quantities of beryllium recycled in the United States are not available, recycled beryllium may account for as much as 20–25% of total beryllium consumption (USGS 2022).

The EPA has classified beryllium powder as a hazardous waste material (EPA 1980). Compliance with labeling and disposal procedures, as well as obtaining permits for discharges into air and water, are required for beryllium powder. Beryllium 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-containing 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). 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). Wastewaters 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). Wastewaters 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.

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

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

5.3.1 Air

Estimated releases of 32 pounds (~0.01 metric tons) of beryllium to the atmosphere from 16 domestic manufacturing and processing facilities in 2021, accounted for about <1% of the estimated total environmental releases from facilities required to report to the TRI (TRI21 2022). These releases are summarized in Table 5-3. Estimated releases of 737 pounds (~0.334 metric tons) of beryllium compounds to the atmosphere from 43 domestic manufacturing and processing facilities in 2021, accounted for about <1% of the estimated total environmental releases from facilities required to report to the TRI (TRI21 2022). These releases are summarized in Table 5-4.

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

		Reported amounts released in pounds per year[b]							
							Total release		
State[c]	RF[d]	Air[e]	Water[f]	UI[g]	Land[h]	Other[i]	On-site[j]	Off-site[k]	On- and off-site
AL	1	0	0	0	11,000	0	11,000	0	11,000
CA	1	0	0	0	0	0	0	0	0
GA	1	1	0	0	0	0	1	0	1
IL	1	0	0	0	0	0	0	0	0
IN	1	10	0	0	250	0	10	250	260
MO	2	0	0	0	0	0	0	0	0
NV	1	0	0	0	23,390	0	23,390	0	23,390
NY	2	0	0	0	0	0	0	0	0
NC	1	0	0	0	0	0	0	0	0
OH	1	0	0	0	0	0	0	0	0
PA	1	0	6	0	0	2,274	6	2,274	2,280
TN	1	1	3	0	98	7	1	108	109
VA	1	0	0	0	0	0	0	0	0

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

		Reported amounts released in pounds per year[b]							
							Total release		
State[c]	RF[d]	Air[e]	Water[f]	UI[g]	Land[h]	Other[i]	On-site[j]	Off-site[k]	On- and off-site
WI	1	19	0	0	0	0	19	0	19
Total	16	32	9	0	34,738	2,281	34,428	2,632	37,060

[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 are included in releases to air by a given facility.
[f] Surface water discharges, wastewater treatment (metals only), and publicly owned treatment works (POTWs) (metal and metal compounds).
[g] Class I wells, Class II-V wells, and underground injection.
[h] Resource Conservation and Recovery Act (RCRA) subtitle C landfills; other onsite landfills, land treatment, surface impoundments, other land disposal, other landfills.
[i] Storage only, solidification/stabilization (metals only), other off-site management, transfers to waste broker for disposal, unknown.
[j] The sum of all releases of the chemical to air, land, water, and underground injection wells.
[k] Total amount of chemical transferred off-site, including to POTWs.

RF = reporting facilities; UI = underground injection

Source: TRI21 2022 (Data are from 2021)

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

		Reported amounts released in pounds per year[b]							
							Total release		
State[c]	RF[d]	Air[e]	Water[f]	UI[g]	Land[h]	Other[i]	On-site[j]	Off-site[k]	On- and off-site
AK	2	10	31	0	75,546	0	75,587	0	75,587
AZ	1	0	0	0	0	0	0	0	0
FL	3	66	8	0	5,217	1	5,291	1	5,292
ID	1	0	0	0	39	0	39	0	39
IL	2	7	23	0	18,671	0	18,701	0	18,701
IN	6	34	68	0	40,245	21	39,867	501	40,368
KY	4	39	28	0	35,443	0	35,510	0	35,510
MI	1	0	0	0	47,141	0	47,141	0	47,141
MT	1	10	0	0	5,630	0	5,640	0	5,640
NV	2	4	0	30	90	0	124	0	124
NM	1	6	1	0	12,565	0	12,572	0	12,572
NC	2	10	0	0	9,430	0	9,440	0	9,440

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

		Reported amounts released in pounds per year[b]							
							Total release		
State[c]	RF[d]	Air[e]	Water[f]	UI[g]	Land[h]	Other[i]	On-site[j]	Off-site[k]	On- and off-site
ND	3	141	0	0	16,259	0	15,116	1,284	16,400
OH	2	296	7	2,721	33,382	555	33,685	3,276	36,961
PA	2	5	2	0	163	0	7	163	170
SC	1	0	0	0	3,500	0	3,500	0	3,500
TN	1	15	0	0	8,300	0	8,315	0	8,315
TX	2	22	0	0	24,985	0	25,007	0	25,007
UT	3	22	0	0	70,618	512	70,128	1,024	71,152
WV	3	48	0	0	40,395	0	32,143	8,300	40,443
Total	43	735	168	2,751	447,619	1,089	437,813	14,549	452,362

[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 are included in releases to air by a given facility.
[f] Surface water discharges, wastewater treatment (metals only), and publicly owned treatment works (POTWs) (metal and metal compounds).
[g] Class I wells, Class II-V wells, and underground injection.
[h] Resource Conservation and Recovery Act (RCRA) subtitle C landfills; other onsite landfills, land treatment, surface impoundments, other land disposal, other landfills.
[i] Storage only, solidification/stabilization (metals only), other off-site management, transfers to waste broker for disposal, unknown.
[j] The sum of all releases of the chemical to air, land, water, and underground injection wells.
[k] Total amount of chemical transferred off-site, including to POTWs.

RF = reporting facilities; UI = underground injection

Source: TRI21 2022 (Data are from 2021)

In addition to ore processing, beryllium is 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, and the production, use, and recycling of beryllium alloys and chemicals.

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 mg/kg (Nalbandian 2012). A study by the U.S. 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 800 ng beryllium/m^3, 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.

In 2016, there were 71 power plants in the United States that generated electricity from burning municipal solid waste (EIA 2018). At a municipal Waste to Energy (WTE) facility in Commerce, California, stack emissions for beryllium were measured at 200 ng/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.

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

Natural emission sources of beryllium include windblown dusts and volcanic particles (EPA 1987). The beryllium amounts released to the atmosphere from these sources are comparable with anthropogenic sources.

EPA’s National Emission Inventory (NEI) database contains information regarding sources that emit criteria air pollutants (CAPs) and their precursors, and HAPs for the 50 United States, Washington DC, Puerto Rico, and the U.S. Virgin Islands. Emissions are estimated from multiple sources, including state and local environmental agencies; the TRI database; computer models for on- and off-road emissions; and databases related to EPA's Maximum Achievable Control Technology (MACT) programs to reduce emissions of HAPs. Beryllium emissions estimated from the 2017 inventory are summarized in Table 5-5.

Table 5-5. National Emission Inventory (NEI) Total National Emissions for Beryllium Estimated by Sector 2017

Sector	Emissions (pounds)
Fuel combustion; industrial boilers, ICEs; oil	4,960.465443
Fuel combustion; residential; oil	1,100.625465
Fuel combustion; electric generation; coal	819.7181334
Industrial processes; NEC	715.0629264
Waste disposal	712.1226555
Fuel combustion; commercial/institutional; oil	467.6194022
Industrial processes; ferrous metals	340.434015
Industrial processes; chemical manufacturing	334.9908699
Industrial processes; non-ferrous metals	308.2304331
Fuel combustion; industrial boilers, ICEs; biomass	230.5769837
Fuel combustion; industrial boilers, ICEs; other	215.3496435
Fuel combustion; industrial boilers, ICEs; coal	193.1682183
Industrial processes; petroleum refineries	152.1537728
Industrial processes; mining	94.38606246
Industrial processes; pulp and paper	71.23058617
Mobile; locomotives	69.84502661
Industrial processes; cement manufacturing	62.85708888
Fuel combustion; electric generation; natural gas	49.43143851
Fuel combustion; industrial boilers, ICEs; natural gas	44.87894611
Fuel combustion; electric generation; biomass	43.18536062
Fuel combustion; commercial/institutional; coal	35.41704347
Fuel combustion; electric generation; oil	34.17308683
Industrial processes; storage and transfer	26.78581592
Fuel combustion; commercial/institutional; biomass	12.56330221
Fuel combustion; commercial/institutional; natural gas	11.7537222
Fuel combustion; residential; natural gas	5.485452997
Fuel combustion; commercial/institutional; other	5.303044665
Industrial processes; oil and gas production	2.867526585
Fuel combustion; electric generation; other	2.217535117
Miscellaneous non-industrial NEC	2.217015546
Solvent; industrial surface coating and solvent use	0.475640686
Solvent; degreasing	0.011
Dust; construction dust	0.000018
Bulk gasoline terminals	0.000000172
Fuel combustion; residential; other	0

Source: EPA 2017

ICE = internal combustion engine; NEC = not elsewhere classified

5.3.2 Water

Estimated releases of 9 pounds (~0.004 metric tons) of beryllium to surface water from 16 domestic manufacturing and processing facilities in 2021, accounted for about <1% of the estimated total environmental releases from facilities required to report to the TRI (TRI21 2022). These releases are summarized in Table 5-3. Estimated releases of 168 pounds (~0.076 metric tons) of beryllium compounds to surface water from 43 domestic manufacturing and processing facilities in 2021, accounted for about <1% of the estimated total environmental releases from facilities required to report to the TRI (TRI21 2022). These releases are summarized in Table 5-4.

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.

In a limited sampling campaign, industrial effluent samples collected by the State of Oregon Department of Environmental Quality (DEQ), beryllium was detected in 7 of 9 samples at 0.017–4.2 μg/L (WQP 2022).

Treated municipal wastewater effluent is not likely a significant source of beryllium to aquatic environments. In 168 samples of wastewater effluent analyzed between 2000 and 2013 by the State of Oregon DEQ, beryllium was only detected in 3 samples at 0.013–0.023 μg/L (WQP 2022). Beryllium was not detected in 448 wastewater effluent samples collected by Metro Water Recovery in Colorado between 2014 and 2021, or in 49 samples collected by the Colorado Department of Public Health and Environment between 2018 and 2022 (WQP 2022).

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.

5.3.3 Soil

Estimated releases of 34,738 pounds (~15.6 metric tons) of beryllium to soil from 16 domestic manufacturing and processing facilities in 2021, accounted for about 93.7% of the estimated total environmental releases from facilities required to report to the TRI (TRI21 2022). These releases are summarized in Table 5-3. Estimated releases of 447,619 pounds (~203 metric tons) of beryllium compounds to soil from 43 domestic manufacturing and processing facilities in 2021, accounted for about

98.95% of the estimated total environmental releases from facilities required to report to the TRI (TRI21 2022). An additional 2,751 pounds (~1.2 metric tons), accounted for about <1% of the total environmental emissions, were released via underground injection (TRI21 2022). 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 (USGS 1998). Coal fly ash contains beryllium at levels of 46 mg beryllium/kg ash (USGS 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).

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 were not available.

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 dissolution 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 μm (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 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 adsorbed 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 adsorption ratio (Kd) for beryllium are very high, indicating a very low mobility in sediments. At pH values >6, Kd values are very high for most soils and sediments. For Lake Michigan sediments, Kd 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 Kd (Lum and Gammon 1985). The presence of organic matter did not significantly affect the Kd for saline systems (You et al. 1989); in seawater, Kd 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 $[Be(OH)_4]^{2-}$ (Cotton and Wilkinson 1980; EPA 1979). In acidic soils (e.g., forest ecosystems), dissolved Be^{2+} 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 ^{7}Be in beans, barley, sunflowers, and tomato plants. Over 95% of ^{7}Be was found in the roots; very little was translocated to the foliage and fruits (Romney and Childress 1965). The 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). The BCF reported for freshwater and marine plants, vertebrates, and fish was 100 (EPA 1979). Comparisons of the beryllium levels in bottom-feeding biota and surfaces 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 beryl ore dust, beryllium hydroxide, beryllium oxide, sodium fluoroberyllate, and beryllium fluoride (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: $[Be(H_2O)_4]^{2+}$, $Be_2(OH)_3^{+}$, $Be_3(OH)_3^{3+}$, and possibly $Be_5(OH)_7^{3+}$ in acid solution (i.e., pH 6); and $[Be(OH)_4]^{2-}$ in basic solution (i.e., 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, $Be(OH)_2$, which has a very low solubility (solubility product, $K_{sp}=10^{-21}$). Table 5-6 illustrates several precipitation reactions for beryllium under a neutral environment.

Table 5-6. Precipitation of Beryllium Compounds in a Neutral (pH 6.5–9.5) Environment

Compound	Reaction	Notes
Ammonium tetrafluoroberyllate (Ammonium beryllium fluoride)	$(NH_4)_2BeF_4$ —> $2[NH4]^{+}_{aq}$ + $[BeF4]^{2}_{aq}$ Excess H_2O pH 7	Remains soluble in a neutral environment
Beryllium oxide	$BeO + H_2O$ —> $Be(OH)_2$ Excess H_2O pH 7	Forms insoluble beryllium hydroxide in a neutral environment
Beryllium hydroxide	$Be(OH)_2$ —> no reaction Excess H_2O pH 7	Beryllium hydroxide is insoluble in a neutral environment
Beryllium fluoride	$BeF_2 + 2\ H_2O$ —> $[BeF_2(H_2O)_2]_{aq}$ and other complexes Excess H_2O	Remains soluble in a neutral environment

Table 5-6. Precipitation of Beryllium Compounds in a Neutral (pH 6.5–9.5) Environment

Compound	Reaction	Notes
	pH 7	
Beryllium nitrate trihydrate	$Be(NO_3)_2 \cdot 3H_2O + 2MOH^a \longrightarrow Be(OH)_2 + 2[M]^+_{aq} + 2[NO3]^-_{aq} + 3H_2O$ Excess H_2O pH 7	Forms insoluble beryllium hydroxide in a neutral environment
Beryllium sulfate tetrahydrate	$BeSO_4 \cdot 4H_2O + 2MOH^a \longrightarrow Be(OH)_2 + 2[M]^+_{aq} + [SO4]2^-_{aq} + 4H_2O$ Excess H_2O pH 7	Forms insoluble beryllium hydroxide in a neutral environment
Beryllium oxalate trihydrate	$BeC_2O_4 \cdot 3H_2O + 2MOH^a \longrightarrow Be(OH)_2 + 2[M]^+_{aq} + [C_2O_4]2^-_{aq} + 3H_2O$ Excess H_2O pH 7	Forms insoluble beryllium hydroxide in a neutral environment
Beryllium basic acetate[b]	$Be_4O(C_2H_3O_2)_6 + 6MOH^a + H_2O \longrightarrow 4Be(OH)_2 + 6[M]^+_{aq} + 6[C_2H_3O_2]^-$ Excess H_2O pH 7	Forms insoluble beryllium hydroxide in a neutral environment

[a] MOH is a base; M in MOH signifies a cation such as sodium (Na) or potassium (K).
[b] Beryllium basic acetate is not a true basic salt; it is a covalent compound.

Source: EPA 1998

Other transformations of environmental importance are the formation of insoluble basic carbonates, such as $(BeCO_3)_2Be(OH)_2$, by the reaction of dissolved carbonate with beryllium solutions and the formation of beryllium sulfate, by the reaction of soluble sulfates with beryllium solutions.

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 (see Section 5.4.1). Data suggesting the biotransformation of beryllium or its compounds in soil were not located.

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 5-7 shows the limits of detection typically achieved by analytical analysis in environmental media. Presented in Table 5-8 are the summary range of concentrations detected in environmental media. Table 5-9 indicates beryllium levels at NPL sites. Levels in soil and air at NPL sites are comparable to background concentrations expected from naturally occurring beryllium (see Sections 5.5.3 and 5.5.1). The mean concentration detected in water appears to be higher than ambient means reported elsewhere (see Section 5.5.2) but is still within the range of observed ambient concentrations.

Table 5-7. Lowest Limit of Detection for Beryllium Based on Standards[a]

Media	Detection limit	Reference
Air	0.0002 ng/m^3	EPA 2014, 2020
Surface wipe	0.0001 μg per wipe	NIOSH 2007a, 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 1988b

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

Table 5-8. Summary of Environmental Levels for Beryllium

Media	Low	High	For more information
Outdoor air (ng/m^3)	0.241	0.293	Section 5.5.1
Indoor air (ng/m^3)	NS	0.0045	Section 5.5.1
Surface water (μg/L)	ND	55	Section 5.5.2
Groundwater (μg/L)	ND	20	Section 5.5.2
Drinking water (μg/L)	0.002	2,000	Section 5.5.2
Biota (μg/kg)	ND	5,300	Section 5.5.4
Food (μg/kg fresh weight)	ND	36	Section 5.5.4

Table 5-8. Summary of Environmental Levels for Beryllium

Media	Low	High	For more information
Soil (mg/kg)	ND	1,000	Section 5.5.3
Sediment (mg/kg)	ND	8.80	Section 5.5.3

ND = not detected, NS = not specified

Table 5-9. Beryllium Levels in Water, Soil, and Air of National Priorities List (NPL) Sites[a]

Medium	Median	Geometric mean	Geometric standard deviation	Number of quantitative measurements	NPL sites
Water (ppb)	5	7.13	8.87	160	105
Soil (ppb)	1,530	2,590	6.48	235	137[b]
Air (ppbv)	0.00217	0.00245	2.25	5	4

[a] Concentrations found in ATSDR site documents from 1981 to 2022 for 1,868 NPL sites (ATSDR 2022). Maximum concentrations were abstracted for types of environmental media for which exposure is likely. Pathways do not necessarily involve exposure or levels of concern.

[b] Beryllium is a natural component of soil and would be expected to be detected at all NPL sites. However, ATSDR site documents often don’t include background concentrations which are not of public health concern.

5.5.1 Air

Beryllium is a pollutant monitored in air samples aggregated in the national Air Quality System (AQS) database, which contains ambient air pollution data collected by EPA, state, local, and tribal air pollution control agencies from monitors throughout the country. Table 5-10 provides the yearly mean 24-hour concentrations of beryllium (as total suspended particulate) at ambient air monitoring stations across the United States. These results show that the mean levels of beryllium over the last few years are generally <0.2 ng/m^3.

Table 5-10. Summary of Annual Beryllium (Total Suspended Particulate) Concentrations (ng/m^3) Measured in Ambient Air at Locations Across the United States[a]

Year	Number of monitoring locations	Number of samples	Range of the arithmetic mean at all locations	Maximum concentration
2015	27	1,610	ND–0.276	1.07
2016	26	1,738	ND–0.269	0.72

Table 5-10. Summary of Annual Beryllium (Total Suspended Particulate) Concentrations (ng/m^3) Measured in Ambient Air at Locations Across the United States[a]

Year	Number of monitoring locations	Number of samples	Range of the arithmetic mean at all locations	Maximum concentration
2017	23	1,622	ND–0.649	20
2018	22	1,551	ND–0.279	2.12
2019	21	540	ND–0.278	0.89
2020	20	1,313	0.030-0.278	0.286
2021	20	1,667	0.022–0.279	0.286
2022[b]	2	38	0.241–0.283	0.293

[a] 24-hour sampling period, at local conditions.
[b] As of October 14, 2022.

ND = not detected

Source: EPA 2022a

Beryllium concentrations in urban and industrial air are usually higher, possibly due to burning of coal and fuel oil, and other industrial activities. Most coal plants in the United States are located in Texas, Indiana, and Ohio (EIA 2017), and beryllium mining or processing sites are located in Delta, Utah, and Elmore, Ohio (EPA 2022b). Maximum concentrations reported by AQS were recorded at monitors in industrial land use areas, in Cuyahoga and Columbiana Counties, Ohio, and St. Louis and Washington Counties, Minnesota.

In a limited monitoring study, beryllium was commonly detected in trace amounts in urban residential air. Sax et al. (2006) analyzed indoor (Table 5-11) and outdoor (Table 5-12) home air in New York City, New York and Los Angeles, California. The mean concentrations of beryllium in indoor home air were 0.0015 ng/m^3 in New York City and 0.0018 ng/m^3 in Los Angeles. The mean concentrations in outdoor home air were 0.0028 ng/m^3 in New York City and 0.0018 ng/m^3 in Los Angeles.

Table 5-11. Ambient Indoor Air Monitoring Studies for Beryllium

Location(s); geographic type	Date(s)	Maximum concentration	Mean concentration	Percent detected
New York, New York; indoor home air	June–August 1999	0.0034 ng/m^3	0.0015 ng/m^3	97% of the 40 measurements
Los Angeles, California; indoor home air	February–March 2000; September–October 2000	0.0045 ng/m^3	0.0018 ng/m^3	98% of the 41 measurements

Source: Sax et al. 2006

Table 5-12. Ambient Outdoor Air Monitoring Studies for Beryllium

Location(s); geographic type	Date(s)	Max concentration	Mean concentration	Percent detected	Reference
New York, New York; outdoor home air	June–August 1999	0.011 ng/m^3	0.0028 ng/m^3	96% of the 40 measurements	
Los Angeles, California; outdoor home air	February–March 2000; September–October 2000	0.0060 ng/m^3	0.0018 ng/m^3	98% of the 41 measurements	

Source: Sax et al. 2006

Beryllium has been monitored in air at Brush Wellman (now Materion Corporation) beryllium refining plant, in Elmore, Ohio since 1958. From January 1997 to April 2002, maximum weekly average concentrations measured at 10 monitors were 1.2–13.7 ng/m^3 (ATSDR 2006). Maximum monthly average concentrations were 0.4–2.9 ng/m^3 (ATSDR 2006). In addition to these 10 monitors, a monitor in a parking lot north of the plant measured maximum weekly concentration of 17.3 ng/m^3 on February 1–8, 1999, and a maximum monthly concentration of 0.0077 μg/m^3 from January 1999 to May 2001 (ATSDR 2006). Using air modeling at a Brush Wellman facility, which manufactures beryllium oxide ceramics in Tucson, Arizona, the Arizona Department of Environmental Quality estimated in 1991 that average annual ambient beryllium levels next to the plant were 8 ng/m^3 based on an emission rate of 4.28 g/day (ATSDR 2000). The maximum 1-hour level was estimated to be 1.4 ng/m^3 (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 were 0.0038–0.3087 ng/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).

A longitudinal monitoring program was conducted at the Lawrence Livermore National Laboratory (LLNL), which has been routinely machined, used, and stored beryllium since the 1950s (Sutton et al. 2012). Beryllium concentrations in airborne particles sampled from 1974 to 2010 at the main facility in Livermore, California ranged from 0.0001 to 0.54 ng/m^3, with a median concentration of 0.0126 ng/m^3. Beryllium levels at the LLNL test facility located between Livermore and Tracy, California ranged from 0.0003 to 0.43 ng/m^3, with a median concentration of 0.011 ng/m^3 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. A summary of these studies is provided in Table 5-13.

Table 5-13. Industrial Site Outdoor Air Monitoring Studies for Beryllium

Location(s)	Geographic type	Date(s)	Range	Mean concentration	Notes	Reference
Elmore, Ohio	Outdoor air at Brush Wellman Plant	January 1997–April 2002	NS	0.4–2.9 ng/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	0.0038–0.3087 ng/m^3	0.008–0.031 ng/m^3	Monitors were located at three elementary schools near the plant and the transportation building	ATSDR 2005a
Livermore, California	Outdoor air at LLNL main site	1974–2010	0.0001–0.54 ng/m^3	0.0259 ng/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	0.0246 ng/m^3		Sutton et al. 2012

LLNL = Lawrence Livermore National Laboratory; NS = not specified

5.5.2 Water

Beryllium is a natural component of the earth's crust and may therefore be detected at trace amounts in water as part of the geochemical cycle. Rainwater may also contain beryllium, through washout of atmospheric sources of beryllium; however, monitoring data for the United States were not available. In Great Britain, rainfall had <0.06 µg beryllium/L (Neal et al. 1992).

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 ranged from 0.00002 to 0.0009 µg/L, with an average of <0.0005 µg/L (Measures and Edmond 1986; Merrill et al. 1960). Tazoe et al. (2014) reported that mixed layer water from <200 m deep in the eastern North Pacific Ocean had a concentration of 7 pmol beryllium/kg. However, beryllium concentration increased 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).

The EPA maintains a Water Quality Portal (WQP) database, which aggregates water monitoring data from the National Water Information System (NWIS) and STORage and RETrieval (STORET) system. A summary of the data for ambient surface and groundwater from recent years is provided in Table 5-14 (WQP 2022).

Table 5-14. Summary of Concentrations of Beryllium (µg/L) Measured in Surface Water and Groundwater Across the United States

Surface water				
Year	Mean	Maximum	Number of samples	Percent detected
2015	0.433	32.6	1,599	53.7
2016	0.315	20.8	2,564	31.0
2017	0.400	52	6,183	19.1
2018	0.329	39	7,675	20.4
2019	0.630	55	8,091	14.6
2020	0.105	5	6,669	13.9
2021	0.140	25.8	4,559	27.0
2022[a]	0.0669	0.75	172	51.7

Table 5-14. Summary of Concentrations of Beryllium (µg/L) Measured in Surface Water and Groundwater Across the United States

	Groundwater			
Year	Mean	Maximum	Number of samples	Percent detected
2015	1.36	10	461	80.5
2016	0.541	20	474	66.0
2017	0.182	11.8	790	39.4
2018	0.153	3.79	763	32.0
2019	0.122	1.89	843	32.6
2020	0.292	15.1	715	31.0
2021	0.343	15.9	392	36.7
2022[a]	0.124	0.948	55	83.6

[a] As of October 7, 2022.

Source: WQP 2022

Generally, mean and maximum beryllium concentrations in surface water were higher than in groundwater, possibly due to increased anthropogenic influence (EPA 2002), although beryllium from natural sources tends to lead to higher concentrations in groundwater, especially near beryllium mineral sources (Taylor et al. 2003). Between 2020 and 2022, beryllium was detected at annual averages of 0.067–0.445 µg/L in surface water, and at annual averages of 0.124–0.343 µg/L in groundwater (WQP 2022). In another study, 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).

A summary of other groundwater monitoring studies is provided in Table 5-15. 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 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. In another, more recent study as part of the National Water-Quality Assessment Program, samples were collected between 1991 and 2010 from >60 regionally extensive principal aquifers that supply most of the drinking and irrigation water across the United States (USGS 2015). Less than 1% of samples collected from parts of aquifers used for drinking water (3,669 samples), shallow groundwater beneath agricultural land (1,793 samples), or beneath urban land (1,793 samples) exceeded the maximum contaminant level of 4 µg/L.

Table 5-15. Summary of Groundwater Monitoring Data for Beryllium (μg/L)

Location(s)	Type	Date(s)	Range	Mean	Notes	Reference
Elmore, Ohio	Split well water samples	May 31, 2001 and July 26, 2001	ND	ND	Samples were taken from eight 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	NS	847 samples analyzed; 98% of samples were below detection	USGS 2009
United States	Groundwater across the United States	1992–2003	<1–18	NS	3,025 samples	USGS 2011
United States	Groundwater across the United States	1993–2010	<4-NS	NS	Not detected in >99% of samples	USGS 2015

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

During a site visit to the Brush Wellman beryllium refining 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).

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 5-16 summarizes available data on the detection of beryllium in drinking water.

Table 5-16. Summary of Beryllium Detections (μg/L) in Drinking Water

Product	Number of samples	Mean	Range	Notes	Reference
Public water supply	3,669	NS	<4–NS	Not detected in >99% of samples	USGS 2015
	164,392	NS	0.002–2,000	Not detected in 98.7% of samples	EPA 2016
	NS	0.013	0.01–0.7		Vaessen and Szteke 2000
Bottled water	35	NS	<0.04–NS	Not detected in 97% of samples	FDA 2022a

Table 5-16. Summary of Beryllium Detections (µg/L) in Drinking Water

Product	Number of samples	Mean	Range	Notes	Reference
Mineral water	72	<0.1	<0.1–5.2		Vaessen and Szteke 2000
Domestic mineral water (nine brands)	18	<0.1	<0.1–0.2		Vaessen and Szteke 2000
European mineral water (28 brands)	54	<0.1	<0.1–5.2		Vaessen and Szteke 2000

NS = not specified

5.5.3 Sediment and Soil

Beryllium is the 47th most abundant element in the Earth's crust (USGS 2017). The average beryllium concentration in the Earth's crust is approximately 1.9–3.1 ppm (USGS 2017) and in soils and sediments, mean concentrations are between 0.48 and 3.52 mg/kg (Bilski et al. 2013). Beryllium occurs in silicate minerals and feldspar minerals. The greatest known concentrations of beryllium are found in certain pegmatite bodies. Beryllium ores bertrandite contains approximately 0.27% beryllium and beryl contains approximately 3.85% beryllium (Svilar et al. 2013).

USGS (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, and soil concentrations around the world reportedly range from 0.1 to 40 mg/kg (Taylor et al. 2003). 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).

Sediment and soil monitoring data were available in EPA's WQP database and are reported in Table 5-17. Because it is a natural component of the earth's crust, beryllium was frequently detected, and the averages and ranges generally agree with reported background concentration ranges. The higher reported mean and maximum concentration in soil in 2020 were due to samples from South Dakota, which likely have been impacted by the natural beryllium sources there.

Table 5-17. Summary of Concentrations of Beryllium (mg/kg) Measured in Ambient Sediment and Soil Across the United States

Year	Mean	Maximum	Number of samples	Percent detected
Sediment				
2015	0.734	3.58	948	83.8
2016	0.752	7.70	784	77.7
2017	0.752	8.80	476	98.9
2018	0.631	7.50	376	79.5
2019	1.29	4.30	615	74.5
2020	0.451	3.00	391	69.6
2021	0.504	2.00	99	22.2
2022[a]	0.662	1.13	2	100
Soil				
Year	Mean	Maximum	Number of samples	Percent detected
2015	0.234	0.460	24	100
2017	1.26	1.860	13	100
2019	1.02	1.440	7	100
2020	216	1,000	21	100

[a] As of October 7, 2022.

Source: WQP 2022

Samples collected from potentially impacted sites are reported in Table 5-18. The WQP includes monitoring data from superfund sites: the Bonita Peak Mining District in San Juan County, Colorado, Midnite Mine in Spokane tribal land in Washington, and Gay Mine in Shoshone-Bannock tribal land in Idaho. These were historic gold, uranium, and phosphate mining sites, respectively (EPA 2022c, 2022d, 2022e). Based on limited sampling campaigns, Superfund sites had consistently higher average sediment concentrations of beryllium and comparable concentrations of beryllium in soil. The ranges, however, fell within the broad range that is present naturally, and it is not clear for the Bonita Peak Mining District or Midnite Mine sites whether these samples show elevated beryllium in comparison to nearby ambient samples. The samples collected at the Gay Mine site did include background samples for comparison to samples collected at the mill shale piles, overburden disposal units, and buildings at the site; based on 2015 sampling, there may be elevated beryllium in the site's soil.

Table 5-18. Summary of Concentrations of Beryllium (mg/kg) Measured at Industrial and Urban Sites Across the United States

Location	Year	Mean	Maximum	Number of samples	Percent detected	Reference
Bonita Peak Mining District Superfund Sites						
Sediment	2015	3.29	40.5	107	100	WQP 2022
	2016	1.15	7.30	167	100	
	2017	5.08	23.1	81	100	
	2018	2.35	15.6	93	96.8	
Soil	2015	0.806	2.40	94	100	
	2016	0.641	9.00	312	100	
	2017	2.15	5.21	11	100	
	2018	0.868	3.29	42	100	
Midnite Mine Superfund Site						
Sediment	2017	1.00	1.00	10	20	WQP 2022
	2018	1.75	4.00	10	40	
	2019	2.25	5.00	10	40	
	2020	1.00	1.00	10	40	
	2021	3.50	5.00	10	20	
Gay Mine Superfund Site						
Sediment	2015	0.893	1.43	48	100	WQP 2022
Soil	2015	1.08	1.98	393	100	
Background soil	2015	0.710	0.859	147	100	
Minneapolis and St. Paul, Minnesota						
Sediment from stormwater ponds	2009	0.83	NS	15	20	Crane 2019
Brush Wellman beryllium ceramic facility; Tucson, Arizona						
Background soil[a]	1999	NS	1.4	4	NS	ATSDR 2000
Soil near the facility	1999	0.77; 1.05; 0.69[a]	3.0	5; 17; 8[b]	NS	ATSDR 2000; 2005a
Schools near the Brush Wellman facility; Tucson, Arizona						
All school sites	1999	NS	0.94	NS	NS	ATSDR 2005a
	2000	NS	1.2	NS	NS	
Sunnyside High School	2000	0.40	NS	4	NS	
Los Amingo Elementary School	2000	0.44	NS	4		
Los Ranchitos Elementary School	2000	0.54	NS	4	NS	
Fred Bull Administration Building	2000	0.72	NS	4	NS	
Esperanza Elementary School	2000	0.83	NS	4	NS	

Table 5-18. Summary of Concentrations of Beryllium (mg/kg) Measured at Industrial and Urban Sites Across the United States

Location	Year	Mean	Maximum	Number of samples	Percent detected	Reference
Lawrence Livermore National Laboratory Livermore, California						
Soil at main facility	1988–1994; 2007	0.31	0.71	87	NS	Sutton et al. 2012
Soil at test site[c]	1991–2000	0.79	2.10	60	NS	

[a] Samples collected several miles from the facility.
[b] Samples collected immediately adjacent to the facility; within a 540-foot radius of the facility; and within a 0.25-mile radius of the facility, respectively.
[c] Between Livermore and Tracy, California.

NS = not specified

To study potential urban impacts, 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), slightly higher than mean sediment concentrations seen across the country (WQP 2022).

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 0.3–3.0 mg/kg, and it was concluded that these levels did not present a public health hazard to the community (ATSDR 2000). Average concentrations were 0.77 mg/kg immediately adjacent to the facility, 1.05 mg/kg up to 530 feet from the facility, and 0.69 mg/kg up to 0.25 miles from the facility (ATSDR 2005a). Sampling distances were based on air quality monitoring, which estimated the largest amount of beryllium would fall 450–510 feet from the facility emissions stack. In 2000, based on a prevailing northwest wind, which may carry beryllium from the stacks, soil samples at schools and an administration building near this facility were collected. Soil samples 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 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.

5.5.4 Other Media

Beryllium has been detected at trace levels in organisms. Biota monitoring data are available in the Water Quality Monitoring Portal. Between 2015 to 2022, beryllium was not commonly detected and generally not above trace concentrations. Several species of plants in Idaho had detectable beryllium in 2015, and two species of frogs in North Dakota and one mussel in Tennessee had detectable beryllium in 2016. The unusually high maximum seen in 2020 is from four composite tissue samples collected in Arizona; the species collected for the composites were not reported. In this same year, beryllium was detected in tissue and organ samples of several species of fish collected in Lake Koocanusa near Rexford, Montana. The results of this and other biota monitoring studies are reported in Table 5-19.

Table 5-19. Summary of Concentrations of Beryllium (μg/kg) Measured in Biota Samples Across the United States

Year	Species	Mean	Maximum	Number of samples	Percent detected	Reference
2015		30	60	288	4.17	WQP 2022
	Grindelia squarrosa	60	60	6	16.7	
	Mentzelia rusbyi	35	50	5	40	
	Plantae	26.7	30	111	5.41	
	Gutierrezia sarothrae	30	30	4	25	
	Asteraceae	20	20	2	50	
2016		213	400	250	3.20	
	Lithobates pipiens	250	400	6	100	
	Pseudacris maculata	–	100	1	100	
	Actinonaias pectorosa	–	100	1	100	
2017				173	0	
2018				112	0	
2019				68	0	
2020		202	5,300	169	48.5	
	Taxon unknown	2,080	5,300	4	100	
	Catostomus macrocheilus	274	2,230	26	38.5	
	Oncorhynchus mykiss	258	1,210	13	46.2	
	Oncorhynchus clarkii lewisi	162	492	4	100	
	Mylocheilus caurinus	60.6	121	43	65.1	
	Ptychocheilus oregonensis	54.1	88	30	100	

Table 5-19. Summary of Concentrations of Beryllium (µg/kg) Measured in Biota Samples Across the United States

Year	Species	Mean	Maximum	Number of samples	Percent detected	Reference
2021				26	0	
2022[a]				0	NA	
1985–1986						Capar and Yess 1996
	Mercenaria	0.002 mg/kg wet weight	NS	31	NS	
	Mya areneria	<LOD	NS	10	NS	
	Crassostrea virginica	<LOD	NS	93	NS	
	Crassostrea gigas	<LOD	NS	40	NS	
1991						Allen et al. 2001
	Quadrula pustulosa	NS	0.04 ug/g	3	NS	
	Quadrula metanevra	NS	0.04 ug/g	7	NS	
2001						Burger and Campbell 2004
	Morone saxatilis	0.63	NS	15	NS	
	Morone chrysops	0.92	NS	15	NS	
	Pomoxis spp.	0.72	NS	14	NS	

[a] As of October 7, 2022.

LOD = limit of detection; NS = not specified

Source: WQP 2022

Based on limited sampling of biota from areas of seafood harvesting, seafood ingestion may not be a significant exposure route for beryllium. A U.S. Food and Drug Administration (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 concentrations of beryllium in mussels species from the Neosho River, Kansas were 0.02–0.04 µg/g dry weight mussels in pimpleback (*Quadrula pustulosa*; n=3 at Cottonwood River), not detected–0.02 µg/g dry weight mussels in monkeyface (*Quadrula metanevra;* n=2 at Humboldt), 0.03 µg/g dry weight mussels for monkeyface (n=1 at Leroy), and 0.02–0.04 µg/g dry weight mussels for monkeyface (n=4 at Oswego) (Allen et al. 2001).

Beryllium concentrations in three species of fish from the Clinch River in Tennessee, adjacent to the DOE's Oak Ridge Reservation, were 0.63 µg/kg (striped bass, *Morone saxatilis*), 0.92 µg/kg (white bass, *Morone chrysops*), and 0.72 µg/kg (crappie, *Pomoxis* spp.) (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 found in products made from aluminum, such as shrapnel fragments, aluminum cans, and aluminum foil (Abraham et al. 2014). The beryllium content of shrapnel and aluminum cans was approximately 100 μg/kg, while the beryllium content of aluminum foil was 25 μg/kg (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 μg/kg). Kılınç et al. (2011) also studied beryllium levels in beverages and found mean concentrations of beryllium ranging from 0.03 to 0.94 μg/L 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 Kılınç et al. (2011) are shown in Table 5-20.

Table 5-20. Concentration of Beryllium in Aluminum and Beverage Samples

Sample type	Beryllium concentration (μg/kg)
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, seven brands	0.05–0.94
Cherry flavored mineral water, three 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, three brands	ND–0.16
Energy drink, two brands	ND–0.030
Curative mineral water from Yurtbasi, Elazig, Turkey	0.05
Thermal spring water from Bingol, Turkey	0.51

LOD = limit of detection, ~1 μg/kg = ~1 μg/L based on water density of 1 kg/L; ND = not detected

Sources: Abraham et al. 2014; Kılınç et al. 2011

Electronic waste often contains beryllium, and dental materials also have minute traces of beryllium. Hibbert and Ogunseitan (2014) analyzed beryllium in the ash of incinerated e-waste and measured the following mean concentrations (in µg/kg): 10 in batteries, 100 in screens, 43,000 in circuit boards, and 44,890 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 eight samples at <0.125 µg/kg. It was one of the elements with the lowest concentrations (Borges de Olival et al. 2018).

The beryllium concentrations in several foods, fruits, and fruit juices from around the world are shown in Tables 5-21 and 5-22. More recent data from foods in the United States were not available. The median concentration of beryllium in the 38 foods listed in Table 5-21 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 5-22, is 13.0 µg/L, and the concentrations ranged from not detected to 74.9 µg/L.

Table 5-21. Beryllium Content of Various Fresh Foods

	Concentration (µg beryllium/kg fresh weight)			
Product	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

Table 5-21. Beryllium Content of Various Fresh Foods

	Concentration (μg beryllium/kg fresh weight)			
Product	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				
Eucaliptus	–	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 2020
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

[a] Original data based on dry weight; concentrations recalculated to fresh weight = concentration x (fresh weight x 10).

– = not specified; ND = not detected

Table 5-22. Beryllium Content of Various Fruits and Fruit Juices

Product	Number of samples	Mean (μg/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			
California 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	–
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; ~1 μg/kg = ~1 μg/L based on water density of 1 kg/L

Source: Barnes 1997

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 detection limit (<50 μg/kg) in all samples.

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 15 to 49 μg/kg. A smoker who smokes 20 cigarettes/day is projected to be exposed to 1.5 μg beryllium/day (Svilar et al. 2013). In a review focusing on cigarettes from the United States, yields of 0–0.0005 µg beryllium 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).

Beryllium was found in the carpets of the LLNL site, after vacuuming, at concentrations of 0.002–0.480 µg/100 cm^2. Beryllium concentrations in overhead dust were reported to range from 19.4 to 151 µg/100 cm^2 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 cm^2 (Sutton et al. 2012).

The beryllium concentration in coal ash is, on average, 46 mg/kg (46,000 µg/kg) in the United States (USGS 1961). Beryllium concentrations in U.S. coal range from 180 to 3,170 µg/kg depending on the state and coal type, but concentrations typically range from 1,460 to 1,520 µg/kg (Taylor et al. 2003). Beryllium concentrations in ammonia, nitrate, and phosphorus fertilizers used in agriculture ranged from <0.2 to 13.5 µg/g (<200–13,500 µg/kg) (Raven and Loeppert 1997).

5.6 GENERAL POPULATION EXPOSURE

The general population may be exposed to trace amounts of beryllium by inhalation of air and ingestion of drinking water and food. The general population may also be exposed to beryllium in air from coal incineration. If the average concentration of beryllium in air is assumed to be <0.03 ng beryllium/m^3 (see Section 5.5.1), and a normal U.S. adult inhales approximately 20 m^3 air/day, then the inhalation exposure for a U.S. adult would be approximately <0.6 ng beryllium/day. This value may be somewhat higher for persons living near sources of beryllium emission. People living near beryllium-contaminated sites may be exposed through inhalation of dust blown from the sites; in an *in vitro* assay, bioaccessibility of beryllium from contaminated soil through inhalation was estimated to be 18.5% via inhalation and 20.8% via inhalation-to-injection by mucociliary transport (Islam et al. 2022).

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 concentrations of beryllium were 0.63±0.08 µg/L in the blood and 0.43±0.03 µg/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 µg/L (Cesbron et al. 2013; Goullé et al. 2005; Nisse et al. 2017).

Björklund 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 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 were <50–59 ng/L in blood and <50–91 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 years) living in southern Poland. The average concentration found in pharyngeal tonsil samples was 16 ng/gm 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 that human tissue beryllium concentrations were below detection limits (50 ng/g) for residents living near an incinerator.

Young children may have increased exposure to beryllium from contaminated soils, compared to adults, due to their tendency to put foreign substances in their mouths and pica. Although no studies on this specific route were available, it may be of concern due to increased estimated bioaccessibility via ingestion of soils contaminated with beryllium, and the previous detections of beryllium in soils at schools near sites manufacturing beryllium products (ATSDR 2005a). From *in vitro* studies, bioaccessibility of beryllium in the gastrointestinal tract was estimated to be 56–70%, notably higher than estimates through inhalation (Islam et al. 2022).

The mean concentration of beryllium in urine of about 500 nonoccupationally exposed individuals in the United States according to the 3rd NHANES was 0.22 µg/g of creatinine (Paschal et al. 1998). Other studies reported mean urinary beryllium concentrations ranging from <0.03 to 0.4 µg/L for persons not occupationally exposed (Apostoli and Schaller 2001). In the last cycle of NHANES that measured urinary beryllium (1999–2010), all values that were not missing were below the lower detection limit of 0.072 µg/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 μg/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 nonsmokers. The mean concentration of beryllium in urine was 0.04 μg/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 μg/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 μg/L (Guan et al. 2010). Guan et al. (2010) also found that mothers ≥35 years old had significantly higher levels of beryllium than younger mothers. The study also investigated the relationships between maternal beryllium levels and other factors like history of 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). Another study 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 beryllium/m^2 (NIOSH 1995). Resuspended beryllium dust concentrations in air from unwashed clothing can reach levels of 0.64 μg/m^3. 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/beryllium/feet^2 (Sanderson et al. 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 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 TWA for an 8-hour day of beryllium exposure levels for some workers in a plant that extracted and produced beryllium metal were >50 μg/m^3 during the mid-1960s. Beryllium exposure levels were >30 μg/m^3 during the mid-1970s. After 1977, this plant complied with the previous OSHA maximum TWA concentration of 2 μg/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 μg/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 μg/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 0.02–0.32 and 0.09–0.72 μg/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 μg/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 nonoccupationally 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 were 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 μg/L respectively, while the mean in controls was 0.83 μg/L. The mean concentrations in production workers and quality control workers were both significantly higher than in the controls. The beryllium concentration exceeded 2 μg/L in two 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, beryllium sensitization 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, 3 were abnormal, 5 were borderline, 1 was uninterpretable, and 2 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) concluded that exposure in an aluminum cast-house appeared to be acceptable (did not exceed the TLV-TWA defined by the American Conference of Governmental Industrial Hygienists [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 $2.7\text{x}10^{-9}$ mg/kg/day by inhalation, while children are exposed to $6.3\text{x}10^{-9}$ 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 $\mu g/m^3$ 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 (EPA 1982).

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. 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 (OSHA 2021a).

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. ranges from 0.015 to 0.049 μg/g (Fresquez et al. 2013). It is estimated that smoking 20 cigarettes/day could expose an individual to 1.5 μg beryllium/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 nonsmokers (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.