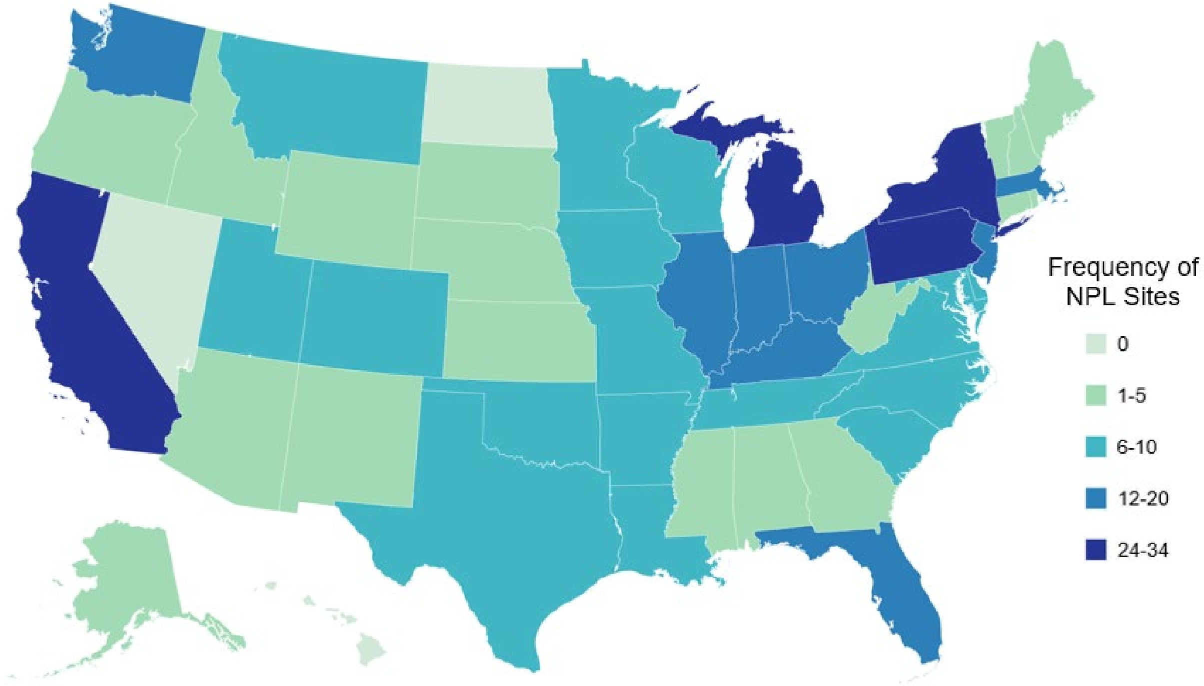
CHAPTER 5. POTENTIAL FOR HUMAN EXPOSURE

5.1 OVERVIEW

Cobalt has been identified in at least 431 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 cobalt has been evaluated is not known. The number of sites in each state is shown in Figure 5-1. Of these sites, 426 are located within the United States, 1 is located in the Virgin Islands, 1 is located in Guam, and 3 are located in Puerto Rico (not shown).

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



Source: ATSDR 2022

- In the United States, cobalt is produced from deposits as a byproduct of other metals. Cobalt is used in several commercial, industrial, and military applications. The leading use is in rechargeable batteries, followed by superalloys; other uses include magnets and tools.

- Natural sources that release cobalt include wind-blown continental dust, seawater spray, volcanoes, forest fires, and continental and marine biogenic emissions. Anthropogenic sources include the burning of fossil fuels and sewage sludge, phosphate fertilizers, mining and smelting of cobalt-containing ores, processing of cobalt-containing alloys, and industries that use or process cobalt compounds.

- Cobalt is released to the atmosphere in particulate form. It may settle to the ground by wet or dry deposition. Cobalt released into waterways may sorb to particles and settle into the sediment or be absorbed directly into the sediment.

- Cobalt levels monitored in ambient air are generally <0.002 μg/m^3 (EPA 2020). Cobalt naturally occurs in the earth's crust. Concentrations of cobalt in surface water and groundwater in the United States are generally low.

- The general population may be exposed to cobalt through inhalation of ambient air and ingestion of food and drinking water. The general population may also be exposed to cobalt transferred to users of consumer goods such as leather products and jewelry; from the wearing down of implanted medical devices and prosthetics; and by using drilling and grinding tools that contain cobalt.

- Workers in the following industries can be exposed to higher levels of cobalt via airborne dust and direct contact: hard metal production or processing (tool production, grinding, etc.); coal mining; metal mining, smelting, and refining; lithium-cobalt battery production or recycling (including electric vehicle batteries); cobalt dyes and paints; and cobalt chemical production. Populations living near these industrial sites might also be exposed to higher levels of cobalt.

Cobalt occurs naturally in the earth's crust. Due to this, it occurs naturally in seawater, in some surface water and groundwater, and in deep-sea polymetallic nodules of the Atlantic, Indian, and Pacific Oceans (Smith and Carson 1981; USGS 2023). Elevated levels of cobalt in soil and water may also result from anthropogenic activities such as the mining and processing of cobalt-bearing ores, application of cobalt-containing sludge or phosphate fertilizers to soil, and disposal of cobalt-containing wastes. Elevated levels of cobalt in the air are a combination of both natural and anthropogenic sources. Natural atmospheric sources include windblown soil, seawater spray, volcanic eruptions, and forest fires. Anthropogenic contributions include atmospheric releases and subsequent deposition from the burning of fossil fuels and waste, vehicular and aircraft exhausts, processing of cobalt and cobalt containing alloys, copper and nickel smelting and refining, and the manufacture and use of cobalt chemicals and fertilizers derived from phosphate rocks (Barceloux 1999; Lantzy and Mackenzie 1979; Nriagu 1989; Smith and Carson 1981). The emissions from natural sources are estimated to slightly exceed those from manufactured sources.

Cobalt compounds are nonvolatile, and cobalt will be emitted to the atmosphere only in particulate form. Its transport in air depends on its form, particle size and density, and meteorological conditions. Cobalt so released will return to land or surface water as wet or dry deposition. Coarse particles, those with aerodynamic diameters >2 μm (such as those obtained during ore processing), may deposit within 10 km from the point of emission; finer particles (such as are obtained from thermal processes) may travel longer distances. It is generally assumed that anthropogenic cobalt originating from combustion sources exists primarily as the oxide; arsenides or sulfides may be released during mining and ore processing (Schroeder et al. 1987). Frequently, sediment and soil are the ultimate sinks for cobalt; however, this process is dynamic, and cobalt can be released into the water depending upon conditions. Soluble cobalt compounds released into waterways will sorb to particles and may settle into the sediment or be sorbed directly by sediment. It may precipitate out as carbonates and hydroxides or with mineral oxides. It may also sorb to or complex with humic acid substances in the water. These processes are sensitive to environmental factors such as pH and the proportion of dissolved cobalt will be higher at low pH. Cobalt can also be transported in dissolved form or as suspended sediment by rivers to lakes and the sea or by ocean currents. The proportion of cobalt transported in each form is highly variable (Smith and Carson 1981). In deep sediment where water is anoxic and hydrogen sulfide is present, some mobilization of cobalt from sediment may occur, probably due to the formation of bisulfides and polysulfides (Bargagli 2000; Brugmann 1988; Finney and Huh 1989; Glooschenko et al. 1981; Knauer et al. 1982; Nriagu and Coker 1980; Shine et al. 1995; Smith and Carson 1981; Szefer et al. 1996; Windom et al. 1989). Cobalt adsorbs rapidly and strongly to soil and sediment in which it is retained by metal oxides, crystalline minerals, and natural organic matter. The mobility of cobalt-containing sediment depends on the nature of the soil or sediment; mobility increases with decreasing pH and redox potential (Eh) and in the presence of chelating/complexing agents (Brooks et al. 1998; Buchter et al. 1989; DOE 1984; King 1988; McLaren et al. 1986; Schnitzer 1969; Smith and Carson 1981) while decreasing in the presence of hydroxyl and carboxyl groups or iron and manganese oxides (Medyńska-Juraszek et al. 2020). While cobalt may be taken up from soil by plants, the translocation of cobalt from roots to above-ground parts of plants is not significant in most soils. The bioaccumulation factors (dry weight basis) for cobalt in marine fish and freshwater fish are ~100–4,000 and <10–1,000, respectively; accumulation is largely in the viscera and on the skin, as opposed to the edible parts of the fish. Cobalt does not biomagnify up the food chain (Barceloux 1999; Evans et al. 1988; Freitas et al. 1988; Smith and Carson 1981).

Atmospheric cobalt is associated with particulate matter. Mean cobalt levels in air at unpolluted sites are generally <1–2 ng/m^3. In several open-ocean environments, geometric mean concentrations ranged from 0.0004 to 0.08 ng/m^3 (Chester et al. 1991). However, in source areas, cobalt levels may exceed 10 ng/m^3; the highest average cobalt concentration recorded was 48 ng/m^3 at the site of a nickel refinery in Wales (Hamilton 1994; Smith and Carson 1981).

The concentrations of cobalt in surface and groundwater in the United States are generally low: <1 μg/L in pristine areas and 1–10 μg/L in populated areas (Hamilton 1994; Smith and Carson 1981). However, cobalt levels may be considerably higher in mining or agricultural areas. Cobalt levels in most drinking water is <1–2 µg/L, although levels as high as 107 µg/L have been recorded (Greathouse and Craun 1978; Meranger et al. 1981; Smith and Carson 1981).

The average concentrations of cobalt in the earth's crust are 20–25 mg/kg (Abbasi et al. 1989; Greathouse and Craun 1978; Merian 1985; Smith and Carson 1981). Most soils contain 1–40 mg cobalt/kg; the average cobalt concentration in U.S. soils is 7.2 mg/kg (Smith and Carson 1981). Soils near ore deposits, phosphate rocks, or ore smelting facilities, and soils contaminated by airport traffic, highway traffic, or other industrial pollution may contain high concentrations of cobalt; concentrations up to 800 mg/kg have been detected in such areas (Kloke et al. 1984; Smith and Carson 1981).

The level of cobalt in most foods is low. However, food is the largest source of exposure to cobalt in the general population. The estimated average daily dietary intake of cobalt in Canada was 11 µg/day. Food groups contributing most heavily to this intake were bakery goods and cereals (29.8%) and vegetables (21.9%) (Dabeka and McKenzie 1995). No estimates of the average dietary input of cobalt in the United States were located. People living near mining and smelting facilities or metal shops where cobalt is used in grinding tools may be exposed to higher levels of cobalt in air or soil. Similarly, people living near hazardous waste sites may be exposed to higher levels of cobalt in these media. However, much of the cobalt in soil may not be in a form that is available for uptake by the body. People who work in the hard metal industry, metal mining, smelting, and refining or other industries that produce or use cobalt and cobalt compounds may be exposed to substantially higher levels of cobalt, mainly from dusts or aerosols in air. Populations living near these sites may also be exposed to higher than background levels of cobalt. Workers in other occupations who come into contact with metal tools and devices, like dental technicians, may also be at higher risk of exposure.

5.2 PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

5.2.1 Production

Cobalt is the 33rd most abundant element in the earth's crust, averaging approximately 17.3 ppm (Dehaine et al. 2021). Pure cobalt does not exist in nature. Cobalt is found in many minerals with nickel, silver, lead, copper, and iron such as carrollite ($Cu(Co,Ni)_2S_4$), pentlandite ($(Fe,Ni,Co)_9S_8$), linnaeite (Co_3S_4), siegenite ((Co,Ni)3S4), skutterudite ($(Co,Fe,Ni)As_{2-3}$), safflorite ($(Co,Fe)As_2$), cobaltite (CoAsS), glaucodot ((Co,Fe,)AsS), erythrite ($Co_3(AsO_4)_2 \cdot 8H_2O$), heterogenite (CoO(OH)), and asbolane ($(Ni,Co)_{2-x}Mn(o,OH)_4 \cdot nH_2O$) (USGS 2017). Common cobalt ores include cobaltite, smaltite, chloranthite, and linnaeite (Clark 2023). The world's reserves of cobalt total an estimated 8.3 million tons, with the largest cobalt reserves in the D.R. Congo (Kinshasa; 4 million tons), Australia (1.5 million tons), Indonesia (0.6 million tons), Cuba (0.5 million tons), the Philippines (0.26 million tons), and Russia (0.25 million tons); all other countries combined have a total estimated reserve of 0.61 million tons (USGS 2023). In the United States, there is an estimated 0.06 million tons of cobalt resources (USGS 2023). The majority of U.S. cobalt deposits are in Minnesota, Alaska, California, Michigan, Montana, Oregon, and Pennsylvania where cobalt is produced as a byproduct of another metal. Cobalt mines were once operational in both Idaho and Missouri. Missouri produces cobalt directly from historic mine tailings (USGS 2023), while Idaho is operationally ready to mine cobalt ore (Jervois 2024). The U.S. supply of cobalt is mostly imports and secondary scrap materials (USGS 2023). In 2022, an estimated 1,900 metric tons of the U.S. cobalt supply were from scrap. Mining production increased between 2018 and 2022, with cobalt production of 480, 500, 600, 650, and 800 metric tons in 2018, 2019, 2020, 2021, and 2022, respectively (USGS 2023). Most of the world's cobalt resources are produced as a byproduct of copper mining, and cobalt is also produced as a byproduct of nickel mining (USGS 2017).

Cobalt is mined using a combination of conventional underground and open pit methods (Farjana et al. 2019) as well as by land and seabed mining of polymetallic nodules (Ou et al. 2023). The production of pure metal from these ores depends on the type of the ore, energy availability, environmental concerns, market demand, and overall project economics (USGS 2017). Sulfide ores and stratiform sediment-hosted copper-cobalt deposits are first ground and crushed, then concentrated by froth flotation and refined (De Cuyper 1988). The concentrate is then processed by leaching, roasting and then leaching, or smelting and then leaching (USGS 2017). Individual metals are separated from the resulting solution using hydrometallurgical, electrometallurgical, vapometallurgical, and pyrometallurgical methods such as chemical precipitation, electrowinning, hydrogen reduction, ion exchange, and solvent extraction (Farjana et al. 2019; USGS 2017).

Tables 5-1 and 5-2 summarize information on companies that reported the production, import, or use of cobalt or cobalt compounds, respectively, for the Toxics Release Inventory (TRI) in 2022 (TRI22 2024). TRI data should be used with caution since only certain types of industrial facilities are required to report. This is not an exhaustive list.

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

State[a]	Number of facilities	Minimum amount on site in pounds[b]	Maximum amount on site in pounds[b]	Activities and uses[c]
AL	7	10,000	99,999	8, 12
AR	2	10,000	99,999	8
AZ	5	1,000	999,999	8, 11
CA	17	0	999,999	2, 3, 7, 8, 11, 12
CO	2	10,000	99,999	11
CT	10	0	999,999	8, 11, 12
FL	3	100	99,999	8
GA	7	1,000	49,999,999	8, 12
IA	4	10,000	999,999	8, 14
ID	2	10,000	99,999	1, 5, 12
IL	10	1,000	9,999,999	7, 8
IN	25	1,000	9,999,999	1, 5, 7, 8, 9, 11, 12, 13, 14
KS	10	1,000	9,999,999	8, 12, 14
KY	5	100	999,999	2, 3, 7, 8, 11, 12
LA	2	10,000	99,999	8, 10
MA	12	100	999,999	1, 5, 8, 9, 11, 12
ME	2	1,000	99,999	8
MI	17	0	9,999,999	2, 3, 5, 7, 8, 9, 11, 12, 14
MN	7	100	999,999	8
MO	6	1,000	999,999	8
MS	4	10,000	999,999	8
NC	12	0	9,999,999	1, 2, 3, 4, 7, 8, 9, 12
NE	1	1,000	9,999	8
NH	3	1,000	9,999	2, 3, 8, 11, 12
NJ	6	100	999,999	2, 3, 4, 8, 9, 11, 12
NV	2	10,000	999,999	1, 3, 4, 7, 8, 12
NY	12	1,000	9,999,999	2, 3, 7, 8, 9, 12, 14
OH	30	0	999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12, 14
OK	5	1,000	9,999,999	1, 5, 8, 13, 14
OR	5	10,000	99,999	2, 3, 7, 12
PA	28	100	999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12, 13
PR	2	1,000	99,999	8
SC	9	1,000	999,999	2, 3, 6, 7, 8
SD	1	1,000	9,999	8
TN	8	1,000	999,999	2, 3, 4, 5, 6, 7, 8, 9, 12
TX	12	0	999,999	1, 4, 5, 8, 11, 12
UT	1	10,000	99,999	8
VA	3	0	999,999	2, 3, 4, 8, 12
WI	21	1,000	999,999	7, 8, 10

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

State[a]	Number of facilities	Minimum amount on site in pounds[b]	Maximum amount on site in pounds[b]	Activities and uses[c]
WV	2	100,000	999,999	2, 3, 7, 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: TRI22 2024 (Data are from 2022)

Table 5-2. Facilities that Produce, Process, or Use Cobalt 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	999,999	1, 5, 12, 13, 14
AL	10	0	999,999	1, 2, 3, 4, 5, 6, 7, 8, 10, 13, 14
AR	5	1,000	999,999	1, 2, 3, 5, 7, 8, 9, 12
AZ	11	100	999,999	1, 3, 5, 7, 8, 9, 10, 11, 12, 13
CA	16	1,000	999,999	1, 2, 3, 5, 7, 8, 9, 10, 12, 14
CO	2	0	99,999	1, 13
CT	1	10,000	99,999	8
DE	1	10,000	99,999	8
FL	5	1,000	999,999	1, 2, 3, 4, 5, 8, 9, 13, 14
GA	7	1,000	999,999	1, 2, 3, 4, 5, 6, 7, 8, 13, 14
IA	7	10,000	99,999	2, 3, 7
ID	2	1,000	99,999	1, 2, 3, 4, 5, 7, 9, 12, 13, 14
IL	21	100	999,999	1, 3, 5, 6, 7, 8, 9, 10, 12, 13
IN	15	0	999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14
KS	5	1,000	99,999	1, 5, 6, 7, 8, 9, 10, 12
KY	11	1,000	999,999	1, 2, 3, 4, 5, 6, 7, 10, 12, 13
LA	20	0	9,999,999	1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14
ME	1	0	99	1, 5
MI	17	0	9,999,999	1, 2, 3, 4, 5, 7, 8, 10, 12, 13, 14
MN	6	1,000	999,999	1, 2, 5, 7, 8, 9, 10, 12, 13
MO	4	100	9,999	1, 5, 9, 13
MS	8	1,000	99,999	1, 2, 3, 5, 6, 7, 8, 9, 10, 13, 14
MT	3	10,000	999,999	1, 3, 4, 5, 6, 12, 13, 14
NC	8	1,000	99,999	1, 5, 6, 7, 9, 12, 14

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

State[a]	Number of facilities	Minimum amount on site in pounds[b]	Maximum amount on site in pounds[b]	Activities and uses[c]
ND	5	100	99,999	1, 3, 5, 10, 12, 13, 14
NE	2	1,000	9,999	1, 5, 7, 12
NJ	3	10,000	999,999	7, 10
NM	4	100	99,999	1, 3, 4, 5, 9, 11, 12, 13, 14
NV	13	0	999,999	1, 2, 3, 4, 7, 8, 12, 13, 14
NY	3	10,000	99,999	7, 14
OH	24	0	9,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14
OK	9	0	999,999	1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 12, 14
OR	2	1,000	9,999	8
PA	24	0	9,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14
SC	19	100	999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
TN	19	100	999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13, 14
TX	34	0	999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14
UT	3	1,000	99,999	1, 5, 8, 10
VA	3	10,000	99,999	1, 3, 5, 6, 7, 10
WA	2	10,000	999,999	2, 3, 4, 7, 10, 11
WI	5	0	99,999	7, 8, 10, 12
WV	7	1,000	99,999	1, 3, 4, 5, 8, 9, 12, 13, 14
WY	1	1,000	9,999	1, 5

[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: TRI22 2024 (Data are from 2022)

5.2.2 Import/Export

According to the U.S. Geological Survey (USGS 2023), an estimated 13,600 metric tons of cobalt were imported into the United States in 2022. Annual imports ranged from 11,400 to 12,800 between 2015 and 2018 (USGS 2020). Between 2015 and 2018, Norway, Japan, China, and Canada supplied 17, 13, 11, and 11% of cobalt, respectively (USGS 2020). Imports for 2016 by form included (form, metric tons cobalt content): metal, 10,800; oxides and hydroxides, 1,410; acetates, 30; carbonates, 263; chlorides, 8; and sulfates, 377 (USGS 2019).

Cobalt exports in the United States ranged from 3,430 to 6,960 metric tons between 2018 and 2021; exports in 2022 are estimated to be 5,100 metric tons (USGS 2023).

5.2.3 Use

In 2019, the estimated apparent consumption of cobalt in the United States was 12,400 metric tons (USGS 2020). Due to cobalt's hardness, ferromagnetic properties, and resistance to oxidation, it can be added to steels to produce alloys for applications requiring metals with high tensile strength, heat and corrosion resistance, and high magnetic strength. It is used in many commercial, industrial, and military applications, and is often used in medical devices and prosthetics.

The leading use of cobalt globally is in rechargeable battery electrodes (USGS 2020). Cobalt is also an important component in energy storage for sustainable and alternative energies, which are on the rise world-wide, including solar photovoltaics, wind turbines, fuel cells, and nuclear reactors (Karduri 2023; Sovacool et al. 2020). In the United States, the need for cobalt to support production of electric vehicles is expected to increase considerably over the next few decades in order to support the U.S. mandate to phase out fossil fueled activities from 2023 to 2050 (WH 2021a, 2021b). The U.S. DOE (2023) classifies cobalt as a "critical" energy resource. However, since most cobalt mining processes occur outside of the United States, development of alternate technology (such as lithium iron phosphate or lithium iron-manganese-phosphate batteries) would decrease dependency on the D.R. Congo and China for cobalt supply (DOE 2023).

Another major use for cobalt is production of superalloys (USGS 2020). Other uses include cemented carbides and diamond tools; controlled-expansion; and corrosion- and wear-resistant alloys, high-speed and strong yet ductile steels, and magnets. Uses of cobalt metal and compounds also include animal feed additives, catalysts in the chemical and petroleum industries, drying agents, dyes and pigments, glass decolorizers, ground coats for porcelain enamels, humidity indicators, magnetic recording media, rubber adhesion promoters for steel-belted radial tires, vitamin B_{12}, and protective catalysts for corrosive and biofouling environments (Sun et al. 2022; USGS 2019; Wang et al. 2022a). Cobalt is present as an accelerator in polyester resins, which are found in coating, lacquers, and finishes (Anavekar and Nixon 2006; Cahill and Andersen 2010). In 2019, 46% of cobalt consumed in the United States was used in superalloys (mainly for aircraft gas turbine engines), 9% in cemented carbides for cutting and wear-resistant applications, 14% in various metallic applications, and 31% in various chemical applications (USGS 2020).

Cobalt compounds are used as catalysts during the manufacture of PET plastics and PET/polycarbonate blends (Kovacheva-Ninova et al. 2018; Pereira et al. 2007). In sustainable chemistry research, cobalt oxides, cobalt phosphide, and cobalt-molybdenum are being evaluated as potential catalysts in the chemical recycling of PET and polybutylene terephthalate (PBT) (Fuentes et al. 2019; Wang et al. 2022b; Wu et al. 2021).

Some artist pastels contain cobalt as a pigment (Brock and Stopford 2003). The colors of some cobalt compounds (sometimes complexed with other metals) in dyes and pigments are blue (cobalt aluminate), pink/violet (cobalt phosphate, cobalt magnesium), green (cobalt nickel zinc titanite, cobalt chromite, cobalt titanate), blue-green (cobalt hydroxide), and blue-black (cobalt tetraoxide) (Anaissi et al. 2020; Haynes 2015; Müller et al. 2012). Cobalt aluminum oxide nanoparticles are used in pigments and inks (Brown et al. 2018).

5.2.4 Disposal

There is a paucity of data on the methods of disposal of cobalt and its compounds. Due to the lack of natural sources of economically extractable ores in the United States, cobalt is mostly imported or produced from scrap material in the United States, and it is considered a strategic mineral. It is economical to recycle certain cobalt wastes rather than to dispose of them. Recycling of superalloy scrap is an important method for the recovery of cobalt. Cobalt recycled from purchased scrap accounted for about 29% of reported consumption in 2019 (USGS 2020). Wastewater containing cobalt can be treated before disposal, for instance, by precipitation of carbonate or hydroxide of cobalt or by passage through an ion-exchange resin (Clifford et al. 1986).

In August 1998, EPA issued a final rule listing spent hydrotreated and hydrorefined catalysts as hazardous waste under the Resource Conservation and Recovery Act (EPA 1998). Listing under this act requires that releases of these substances will be subject to certain management and treatment standards and emergency notification requirements. Information regarding effluent guidelines and standards for cobalt may be found in Title 40 of the Code of Federal Regulations, Parts 421.230, 421.310, and 471.30 (EPA 2023a, 2023b, 2023c). However, in May 2023, EPA's position was that recycling lithium-ion batteries returns valuable critical minerals to the economy. EPA now allows them to be managed under streamlined hazardous waste management standards for universal waste until they reach a destination facility for recycling or to be discarded (EPA 2023e).

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 2022b). 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's North American Industry Classification System (NAICS) codes is covered under EPCRA Section 313 or is a federal facility; and if their facility manufactures (defined to include importing) or processes any TRI chemical in excess of 25,000 pounds, or otherwise uses any TRI chemical in excess of 10,000 pounds, in a calendar year (EPA 2022b).

5.3.1 Air

Estimated releases of 7,480 pounds (~3.39 metric tons) of cobalt to the atmosphere from 320 domestic manufacturing and processing facilities in 2022, accounted for about 1.28% of the estimated total environmental releases from facilities required to report to the TRI (TRI22 2024). These releases are summarized in Table 5-3.

Estimated releases of 33,253 pounds (~15.08 metric tons) of cobalt compounds to the atmosphere from 367 domestic manufacturing and processing facilities in 2022, accounted for about 0.66% of the estimated total environmental releases from facilities required to report to the TRI (TRI22 2024). These releases are summarized in Table 5-4.

Table 5-3. Releases to the Environment from Facilities that Produce, Process, or Use Cobalt[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	7	607	11	0	20,035	18,400	20,616	18,438	39,054
AR	2	0	0	0	33	0	0	33	33
AZ	5	34	0	0	147,000	0	147,034	1	147,034
CA	17	90	19	0	41,416	122	28,160	13,486	41,646
CO	2	0	0	0	41,000	0	41,000	0	41,000

Table 5-3. Releases to the Environment from Facilities that Produce, Process, or Use Cobalt[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
CT	10	85	269	0	751	1,020	99	2,026	2,125
FL	3	344	2	0	0	17	344	19	363
GA	7	156	38	0	287	566	158	889	1,047
IA	4	27	0	0	3	0	28	3	31
ID	2	4	0	0	46,400	0	46,404	0	46,404
IL	9	157	6	0	21	1,078	157	1,105	1,262
IN	25	2,151	197	0	11,884	24	13,167	1,089	14,256
KS	10	319	1	0	357	8	324	361	685
KY	5	7	2	0	765	0	7	767	774
LA	2	0	200	9,700	0	0	9,900	0	9,900
MA	12	188	42	0	1,943	5,302	228	7,248	7,476
ME	2	43	0	0	0	6	43	6	49
MI	17	569	109	0	535	1,465	569	2,109	2,678
MN	7	95	0	0	1,294	0	95	1,294	1,390
MO	6	259	0	0	91,179	0	91,433	5	91,438
MS	4	7	90	0	0	0	97	0	97
NC	11	33	214	0	16,310	151	16,298	409	16,708
NE	1	95	0	0	18	0	95	18	113
NH	3	6	0	0	1,226	2	6	1,228	1,234
NJ	6	124	6	0	9,427	58	124	9,491	9,615
NV	2	2	7	0	255	0	2	262	264
NY	12	108	24	0	415	635	112	1,070	1,182
OH	30	608	221	0	13,295	206	5,929	8,402	14,331
OK	5	0	0	0	0	0	0	0	0
OR	5	392	23	0	27,039	261	23,370	4,345	27,715
PA	28	224	54	0	9,187	28,372	268	37,570	37,838
PR	2	0	0	0	5	0	0	5	5
SC	9	119	56	0	7,333	0	140	7,369	7,509
SD	1	0	0	0	0	0	0	0	0
TN	8	137	104	0	6,795	0	147	6,889	7,036
TX	12	55	20	0	3,025	390	64	3,426	3,490
UT	1	8	0	0	0	0	8	0	8
VA	3	11	5	0	0	90	11	95	106
WI	21	128	787	0	6,869	195	128	7,851	7,979

Table 5-3. Releases to the Environment from Facilities that Produce, Process, or Use Cobalt[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
WV	1	290	156	0	0	0	290	156	446
Total	320	7,480	2,666	9,700	506,103	58,369	446,853	137,465	584,318

[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: TRI22 2024 (Data are from 2022)

Table 5-4. Releases to the Environment from Facilities that Produce, Process, or Use Cobalt 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	1	85	0	227,428	0	227,514	0	227,514
AL	10	834	16,074	0	83,008	657	16,837	83,736	100,572
AR	5	68	9	0	92,501	4,720	92,282	5,017	97,299
AZ	11	751	835	0	442,697	0	442,198	2,085	444,283
CA	16	73	27	0	236,674	3,663	232,934	7,502	240,436
CO	2	8	4	0	171	0	183	0	183
CT	1	125	0	0	0	0	125	0	125
DE	1	0	0	0	0	129	0	129	129
FL	5	0	0	0	34,000	6,800	0	40,800	40,800
GA	7	62	0	0	5,800	4,949	5,862	4,949	10,811
IA	7	238	0	0	0	20,230	238	20,230	20,468
ID	2	1	0	0	220	0	217	4	221

Table 5-4. Releases to the Environment from Facilities that Produce, Process, or Use Cobalt 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
IL	20	1,887	1,083	24	86,981	116,656	86,095	120,536	206,632
IN	15	307	52	0	118,348	1,372	96,344	23,735	120,078
KS	5	75	7	0	4	2,662	84	2,663	2,748
KY	11	190	285	0	85,361	1,644	80,620	6,859	87,479
LA	20	1,174	7,079	558	110,978	960	97,534	23,215	120,749
MD	1	0	0	0	0	0	0	0	0
ME	1	14	0	0	211	0	14	211	225
MI	16	96	64	0	472,069	1,055	455,318	17,967	473,285
MN	6	92	27	0	531	329	119	860	978
MO	4	128	0	0	4,436	0	4,564	0	4,564
MS	8	236	126	43,551	29,439	6,970	51,191	29,131	80,322
MT	3	40	0	0	357,589	0	357,629	0	357,629
NC	8	47	48	0	42,178	258	42,208	323	42,531
ND	4	1,063	0	0	55,676	0	43,691	13,048	56,739
NE	2	0	0	0	0	0	0	0	0
NH	1	0	0	0	0	0	0	0	0
NJ	3	1	483	0	1,049	25,325	1	26,857	26,857
NM	4	53	1	0	57,140	7,716	57,194	7,716	64,910
NV	9	12,785	222	0	831,345	1	815,886	28,468	844,354
NY	3	402	2	0	194	12	403	206	610
OH	24	1,655	601	11,843	145,843	74,865	110,249	124,558	234,807
OK	9	63	13	0	26,368	1,545	20,436	7,553	27,990
OR	2	0	322	0	29	0	0	351	351
PA	24	2,691	1,811	0	45,795	3,458	30,314	23,440	53,754
SC	19	138	33,550	0	106,481	2,586	129,842	12,913	142,755
TN	19	423	4,857	0	118,740	501	117,825	6,697	124,522
TX	35	5,677	1,000	302	514,596	11,366	505,008	27,933	532,941
UT	3	261	5	0	16,205	0	16,461	10	16,471
VA	3	12	1,851	0	0	775	1,636	1,002	2,638
VT	1	0	0	0	0	0	0	0	0
WA	2	11	7	0	191	10,030	18	10,220	10,238
WI	5	67	0	0	376	7,435	111	7,767	7,878
WV	7	868	46	0	208,840	340	183,754	26,340	210,094

Table 5-4. Releases to the Environment from Facilities that Produce, Process, or Use Cobalt 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
WY	1	637	0	0	11,473	0	12,110	0	12,110
Total	367	33,253	70,577	56,279	4,570,965	319,008	4,335,051	715,031	5,050,082

[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: TRI22 2024 (Data are from 2022)

The sources of cobalt in the atmosphere are both natural and anthropogenic (Barceloux 1999). Natural sources include wind-blown continental dust, seawater spray, volcanoes, forest fires, and continental and marine biogenic emissions. The worldwide emission of cobalt from natural sources has been estimated to range from 13 to 15 million pounds/year (Lantzy and Mackenzie 1979; Nriagu 1989). The global atmospheric emission of cobalt from anthropogenic sources is an estimated 9.7 million pounds/year. Therefore, natural sources contribute slightly more to cobalt emissions in the atmosphere than anthropogenic sources (Lantzy and Mackenzie 1979). That balance could change due to increasing cobalt production and recycling to support electric vehicle battery production and recycling to meet the U.S. mandate to phase out fossil fueled activities from 2023 to 2050 (WH 2021a, 2021b). Shen et al. (2021) reported that dust containing cobalt, among eight target metals, is the main source of heavy metal exposure for residents around battery factories.

The primary anthropogenic sources of cobalt in the atmosphere are the burning of fossil fuels and sewage sludge, phosphate fertilizers, mining and smelting of cobalt-containing ores, processing of cobalt-containing alloys, and industries that use, process, or recycle cobalt metal and compounds. Loven et al. (2023) identified that cobalt represented 0.1% of the metals in airborne particle emissions generated during recycling of waste from electrical and electronic equipment, but cobalt was essentially absent in emissions from metal scrap and cable recycling. Small amounts of cobalt are found in coal, crude oils, and oil shales. Therefore, burning of these fossil fuels for power generation will emit cobalt into the atmosphere. The cobalt contents of the fly ash and flue gases of a coal-burning power plant are approximately 25 and 100–700 mg/m^3, respectively. Gasoline contains <0.1 mg cobalt/kg and catalytic converters may contain cobalt; therefore, emissions from vehicular exhaust may also be a source of atmospheric cobalt (Abbasi et al. 1989; Holcombe et al. 1985; Ondov et al. 1982; Smith and Carson 1981). Cobalt metal has been detected in tobacco from U.S. cigarettes at mean values of 0.44–1.11 µg/g dry tobacco (Fresquez et al. 2013). Therefore, smoking is a potential source of atmospheric cobalt that could impact indoor air quality.

5.3.2 Water

Estimated releases of 2,666 pounds (~1.21 metric tons) of cobalt to surface water from 320 domestic manufacturing and processing facilities in 2022, accounted for about 0.46% of the estimated total environmental releases from facilities required to report to the TRI (TRI22 2024). This estimate includes releases to wastewater treatment and publicly owned treatment works (POTWs) (TRI22 2024). These releases are summarized in Table 5-3.

Estimated releases of 70,577 pounds (~32.01 metric tons) of cobalt compounds to surface water from 367 domestic manufacturing and processing facilities in 2022, accounted for about 1.40% of the estimated total environmental releases from facilities required to report to the TRI (TRI22 2024). These releases are summarized in Table 5-4.

Compounds of cobalt occur naturally in seawater and in some surface, spring, and groundwater (Smith and Carson 1981). Cobalt is also released into water from anthropogenic sources. Cobalt production in the United States is primarily a byproduct or coproduct of the refining of other mined metals such as copper and nickel. Historic mining operations that processed cobalt containing ores may continue to release cobalt into surface water and groundwater. Wastewater from the recovery of cobalt from imported matte or scrap metal, refining of copper and nickel, or during the manufacture of cobalt chemicals are sources of cobalt in water (Smith and Carson 1981). Process water and effluent from coal gasification and residue from solvent-refined coal contain cobalt. The accidental discharge of activated sludge and sewage may be important sources of cobalamins in waterways, together with bioconcentration by benthic organisms (Smith and Carson 1981). The discharge of wastewater by user industries, such as paint and pigment manufacture, also contributes to the release of cobalt into water. In one case, manufacturers of nickel-cadmium batteries operating between 1953 and 1979 discharged cobalt from a battery factory to the Hudson River in Foundry Cove, New York, of which 1.2 metric tons are estimated to be present in the eastern cove (Knutson et al. 1987). Clean-up efforts in 1994–1995 resulted in reduced dissolved and particulate cobalt levels; however, suspended particles still remained high as of 2005, compared to levels in the lower Hudson River near New York City (Mackie et al. 2007). Atmospheric deposition is an additional source of cobalt in water. Lake Huron receives an estimated 76% of its cobalt input from natural sources and 24% from anthropogenic sources. The corresponding estimated values for Lake Superior are 85.4 and 14.6% (Smith and Carson 1981). In these Great Lakes, it therefore appears that natural inputs of cobalt far exceed anthropogenic ones.

5.3.3 Soil

Estimated releases of 506,103 pounds (~229.56 metric tons) of cobalt to soil from 320 domestic manufacturing and processing facilities in 2022, accounted for about 87% of the estimated total environmental releases from facilities required to report to the TRI (TRI22 2024). An additional 9,700 pounds (~4.40 metric tons), constituting about 2% of the total environmental emissions, were released via underground injection (TRI22 2024). These releases are summarized in Table 5-3.

Estimated releases of 4,570,965 pounds (~2,073.35 metric tons) of cobalt compounds to soil from 367 domestic manufacturing and processing facilities in 2022, accounted for about 91% of the estimated total environmental releases from facilities required to report to the TRI (TRI22 2024). An additional 56,279 pounds (~25.53 metric tons), constituting about 1% of the total environmental emissions, were released via underground injection (TRI22 2024). These releases are summarized in Table 5-4.

Cobalt occurs naturally in the earth's crust and, therefore, in soil. However, elevated levels of cobalt in soil may result from anthropogenic activities such as mining and processing of cobalt-bearing ores, application of cobalt-containing sludge or phosphate fertilizers to soil, disposal of cobalt containing wastes, and atmospheric deposition from activities such as burning of fossil fuels, smelting, and metal refining (Smith and Carson 1981).

Release of ^{60}Co from an inactive therapy machine resulted in likely the largest release of radioactive material in the history of North America. In December 1983, maintenance workers at a hospital in Juarez, Mexico scrapped a medical machine containing about 6,000 pellets of ^{60}Co, with a total source activity of approximately 16.6 TBq (terabecquerels) (UNSCEAR 2011). It was estimated that the release was probably the worst spill of radioactive material in North America, exposing the public to gamma radiation 100 times more intense than that at Three Mile Island in 1979 (Marshall 1984). The scrapped medical machine and its radioactive material were sold to a local scrapyard and eventually to steel foundries in Mexico and the United States. The foundries began processing the contaminated material and incorporating the metal into construction materials, such as steel rebar, which was shipped throughout North America. The accident was discovered when a truck carrying the contaminated rebar passed the entrance of Los Alamos National Laboratories in New Mexico, setting off radiation detectors and alarms (UNSCEAR 2011).

5.4 ENVIRONMENTAL FATE

5.4.1 Transport and Partitioning

Air. Finely ground cobalt dust is auto explosive, but cobalt compounds are nonvolatile; thus, cobalt is emitted to the atmosphere in particulate form. The transport of cobalt in air depends on its particle size and density, and meteorological conditions. It can be returned to land or surface water by rain, or it may settle to the ground by dry deposition. In areas that are not arid, wet deposition may exceed dry deposition (Arimoto et al. 1985; Erlandsson et al. 1983). Coarse particles, with aerodynamic diameters >2 μm (such as those obtained during ore processing) may deposit within 10 km from the point of emission; finer particles may travel longer distances. It is the larger particles that may be responsible for elevated local concentrations around emission sources. The mass median diameter for cobalt particles emitted from a power generator with a stack emission controlled by an electrostatic precipitator or scrubber ranged from <2 to 12 μm. The mass median diameter of cobalt in the ambient atmosphere is about 2.6 μm (Milford and Davidson 1985). Golomb et al. (1997) reported average total (wet+dry) deposition rates of cobalt to Massachusetts Bay during the period of September 15, 1992 to September 16, 1993. The total deposition rate was 58 $\mu g/m^2$-year, of which 47 $\mu g/m^2$-year was dry deposition and 12 $\mu g/m^2$-year was wet deposition. Total cobalt deposition flux at a site in the Rhone delta in southern France in 1988–1989 was 0.42±0.23 kg/km^2-year, with 0.15 kg/km^2-year in the form of wet deposition (Guieu et al. 1991).

Water. As with most metals, sediment and soil are frequently the final repository for cobalt released into the environment, although the process is dynamic, and cobalt can be released into the water depending upon conditions. Cobalt released into waterways may sorb to particles and settle into the sediment or be sorbed directly into the sediment. However, complexation of cobalt to dissolved organic substances can significantly reduce sorption to sediment particles (Albrecht 2003). Studies by Jackman et al. (2001) suggest that interparticle migration of cobalt can influence the transport of metal ions, including cobalt, in sediments. For example, migration of a metal ion from a highly mobile sediment particle, such as clay, to less mobile gravels will slow the transport of that metal. Cobalt can also be transported in dissolved form or as suspended sediment by rivers to lakes and the sea or by ocean currents. Sediment in areas of active sedimentation would receive a large portion of the suspended sediment. In the case of the Peach Bottom Atomic Power Station where ^{60}Co was released into the Conowingo Reservoir, an impoundment of the lower Susquehanna River, <20% of the radionuclide was trapped in the reservoir sediment (<1% of that would remain after >38 years due to radioactive decay), and the rest was thought to have been transported downstream and into the Chesapeake Bay (McLean and Summers 1990). ^{60}Co was not detected in environmental samples of publicly-relevant surface and drinking water, fish, sediment, air particulates, milk, and food products in the Chesapeake Bay area (Exelon 2019). It is often assumed that the primary mode of transport of heavy metals in aquatic systems is as suspended solids (Beijer and Jernelov 1986). However, in the case of cobalt, the percent that is transported by suspended solids is highly variable. Examples of the percentage of cobalt transported in suspended solids include (water body, percent): Main River (Germany), 33.4–42.2%; Susquehanna River (near its source in New York), 9%; New Hope River (North Carolina), 92%; Yukon River, >98%; Danube River (1961–1970), 27.4–85.9%; Columbia River (^{60}Co, downstream of the Hanford site), 95–98%; Strait of Juan de Fuca (Puget Sound, Washington), 11–15%; North Sea, 34%; and Lake Washington (Washington), 0% (Smith and Carson 1981). In the oxic zones of many surface waters, dissolved cobalt levels decrease with increasing depth. This may be due to cobalt's continuous input into surface water from discharges or to increased adsorption and precipitation of the soluble forms with increasing depth. The fact that cobalt concentration profiles in deep water follow manganese and aluminum profiles strongly suggests that dissolved cobalt is precipitated in the adsorbed state with oxides of iron and manganese and with crystalline sediments such as aluminosilicate and goethite. A part of the cobalt may also precipitate out as carbonate and hydroxide in water. The higher concentration of organic pollutants in polluted water probably results in the formation of higher concentrations of soluble organic complexes. In a deep sediment where the water was anoxic and contained hydrogen sulfide, some mobilization of cobalt was observed, probably due to the formation of bisulfide and polysulfide complexes (Bargagli 2000; Brugmann 1988; Finney and Huh 1989;

Glooschenko et al. 1981; Knauer et al. 1982; Nriagu and Coker 1980; Shine et al. 1995; Smith and Carson 1981; Szefer et al. 1996; Windom et al. 1989).

Sediment and Soil. Cobalt strongly binds to humic substances naturally present in aquatic environments. Humic acids can be modified by ultraviolet (UV) light and bacterial decomposition, which may change their binding characteristics over time. The lability of the complexes is strongly influenced by pH, the nature of the humic material, and the metal-to-humic substance ratio. The lability of cobalt-humate complexes decreases with time ("aging effect") (Burba et al. 1994). The "aging effect" indicates that after a period of time (~12 hours), complexes that were initially formed are transformed into stronger ones from which the metal ion is less readily dislodged. In the Scheldt Estuary and the Irish Sea, between 45 and 100% of dissolved cobalt was found to occur in these very strong complexes (Zhang et al. 1990).

The distribution coefficient of cobalt may vary considerably in the same sediment in response to conditions affecting the pH, redox conditions, ionic strength, and amount of dissolved organic matter (Mahara and Kudo 1981). Uptake of ^{60}Co from the water by sediment increased rapidly as the pH was increased from 5 to 7–7.5 and then slightly decreased (Benes et al. 1989). Therefore, pH would be an important factor affecting the migration of cobalt in surface water.

The mobility of cobalt in soil is inversely related to how strongly it is adsorbed by soil constituents. Cobalt may be retained by mineral oxides such as iron and manganese oxide, crystalline materials such as aluminosilicate and goethite, and natural organic substances in soil. Sorption of cobalt to soil occurs rapidly (within 1–2 hours). Soil-derived oxide materials were found to adsorb greater amounts of cobalt than other materials examined, although substantial amounts were also adsorbed by organic materials. Clay minerals sorbed relatively smaller amounts of cobalt (McLaren et al. 1986). In addition, little cobalt was desorbed from soil oxides while substantial amounts desorbed from humic acids and montmorillonite. In clay soil, adsorption may be due to ion exchange at the cationic sites on clay with either simple ionic cobalt or hydrolyzed ionic species such as $CoOH^+$. Adsorption of cobalt onto iron and manganese increases with increasing pH (Brooks et al. 1998). In addition, as pH increases, insoluble hydroxides or carbonates may form, which would also reduce cobalt mobility. Conversely, sorption onto mobile colloids would enhance its mobility. In most soils, cobalt is more mobile than lead, chromium(II), zinc, and nickel, but less mobile than cadmium (Baes and Sharp 1983; King 1988; Mahara and Kudo 1981; Smith and Carson 1981). In several studies, the K_d of cobalt in a variety of soils ranged from 0.2 to 3,800. In 11 U.S. soils, the mean Freundlich K_F and n values were 37 L/kg and 0.754, respectively; K_F values ranged from 2.6 to 363 L/kg and correlated with soil pH and CEC (Buchter et al. 1989). In 13 soils from the southeastern United States with soil pH values of 3.9–6.5, cobalt sorption ranged from 15 to 93%; soil pH accounted for 84–95% of the variation in sorption (King 1988).

Organic complexing agents, such as EDTA, that are used for decontamination operations at nuclear facilities, greatly enhance the mobility of cobalt in soil. Other organic complexing agents, such as those obtained from plant decay, may also increase cobalt mobility in soil. However, both types of complexes decrease cobalt uptake by plants (Killey et al. 1984; McLaren et al. 1986; Toste et al. 1984). Addition of sewage sludge to soil also increases the mobility of cobalt, perhaps due to organic complexation of cobalt (Gerritse et al. 1982; Williams et al. 1985). Leaching of cobalt has been observed from municipal and low-level radioactive waste sites (Cyr et al. 1987; DOE 1988; NRC 1981). The mobility of cobalt was assessed in two soils from the Cabriolet and Little Feller event sites at the Nevada Test site as a function of various parameters such as pH, ionic strength, cobalt concentrations, soil solids concentrations, and particle size distribution (DOE 1996). Cobalt was quantitatively sorbed on these soils (at least 90% sorbed) when the pH was above 7 and the solid concentration was at least 20 g/L. The experiments suggest that binding is principally on amphoteric surface-hydroxyl surfaces. Since the pH of these soils is around 8, cobalt would bind strongly under normal environmental conditions. Migration would be severely retarded under all but the most extreme conditions (e.g., pH of ≤4 and high ionic strength soil solutions [approximately 0.1 M]). In addition, unrealistically large quantities of water would be needed to displace cobalt from the upper layers of the soil profile.

Other Media. Cobalt may be taken up from soil by plants. Surface deposition of cobalt on leaves of plants from airborne particles may also occur. Elevated levels of cobalt have been found in the roots of sugar beets and potato tubers in soils with high cobalt concentrations (e.g., fly ash-amended soil) due to absorption of cobalt from soil. However, the translocation of cobalt from roots to above-ground parts of plants is not significant in most soils, as indicated by the lack of cobalt in seeds of barley, oats, and wheat grown in high-cobalt soil (Mermut et al. 1996; Smith and Carson 1981). Mermut et al. (1996) found 0.01–0.02 mg/kg in 10 samples of durum wheat grain from different areas of Saskatchewan where surface soil cobalt levels ranged from 3.7 to 16.4 mg/kg. The enrichment ratio, defined as the concentration in a plant grown in amended soil (fly ash) over the concentration in unamended soil, was about 1. Other study authors have determined the transfer coefficient (concentration in plant/concentration in soil) for cobalt to be 0.01–0.3.

Concentration factors have also been reported for various other aquatic organisms. Freshwater mollusks have concentration factors of 100–14,000 (~1–300 in soft tissue). Much of the cobalt taken up by mollusks and crustacea from water or sediment is adsorbed to the shell or exoskeleton; very little cobalt is generally accumulated in the edible parts (Amiard and Amiard-Triquet 1979; Smith and Carson 1981).

5.4.2 Transformation and Degradation

Air. There is a paucity of data in the literature regarding the chemical forms of cobalt in air and their transformations in the atmosphere. It is generally assumed that anthropogenic cobalt originating from combustion sources exists primarily as the oxide and most commonly as cobalt (II) oxide as a result of interactions with oxidants in the atmosphere (Schroeder et al. 1987). In addition, cobalt may be released into the atmosphere as its arsenide or sulfide during ore extraction processes. Cobalt speciation was evaluated during typical roasting recycling of lithium-ion batteries; cobalt was changed into sulfide, phosphate, and complex oxides (Takaya et al. 2023). It is not clear if these species are transformed in the atmosphere. Should a relatively insoluble species such as the oxide be transformed into a more soluble form such as the sulfate, greater quantities would be expected to be washed out of the atmosphere in rain.

Water. Many factors control the speciation and fate of cobalt in natural waters and sediments. These include the presence of organic ligands (e.g., humic acids, EDTA), the presence and concentration of anions (Cl^-, OH^-, CO_3^{-2}, HCO_3^-, SO_4^{-2}), pH, and redox potential (Eh). Watanabe et al. (2023) reported that free Co(II) decreased by ~80% in the presence of humic substances in water. Modeling the chemical speciation of a metal in water depends upon the environmental factors assumed and the stability constants of the various complexes. Mantoura et al. (1978) predicted the equilibrium levels of Co^{2+} species in fresh water to follow the order: free $Co^{+2} \geq CoCO_3 > CoHCO_3^+ >>$ cobalt sulfate $\geq$ Co•humic acid. However, the mole percent of various cobalt species in a Welsh lake was found to be free Co^{+2}, 76%; $CoCO_3$, 9.8%; $CoHCO_3^+$, 9.6%; humate complexes, 4.0%; and cobalt sulfate, 0.4%. The rank order of species concentration in seawater was estimated to be: $CoCO_3 >$ free $Co^{+2} >$ cobalt sulfate $\geq CoHCO_3^+$ (Mantoura et al. 1978). In another model, the speciation of cobalt was completely different with $CoCl^+ >$ free $Co^{+2} > CoCO_3 >$ cobalt sulfate (Smith and Carson 1981).

Tipping et al. (1998) estimated the equilibrium speciation of cobalt in riverine, estuarine, and marine surface water of the Humber system (England). In all but seawater, cobalt complexed with carbonate (HCO_3^- and CO_3^{2-}) and constituted about 70% of dissolved cobalt, while the free Co^{2+} ion was the major species representing ~25% of the total, which is much lower than the 61% predicted by Mantoura et al. (1978). As the alkalinity of the water increases, the proportion of cobalt complexed with carbonate increases at the expense of free Co^{2+}. The proportion, but not the concentration, of cobalt that exists as the free ion and the carbonate complexes in river water is independent of the level of fulvic acid in the water. In seawater, the carbonate species and the free aqua species assume roughly equal importance. The proportion of dissolved cobalt complexed with fulvic acid decreased with increasing salinity. About 20% of cobalt in seawater was estimated to be present as complexes with sulfate.

In a bioconcentration study in which cobalt chloride was initially added to the seawater, at month's end, the cationic form of cobalt was progressively converted into anionic and neutral forms, possibly as a result of complexation with organic ligands (Carvalho 1987). Addition of humic acid to natural waters may merely increase the concentration of colloidal dispersed metal rather than form truly soluble humic complexes. In water that contains high organic wastes such as was the case in the Rhone River in France, cobalt was almost completely complexed. A study determined that the distribution of ^{60}Co in the Rhone River sampled at Arles, France was 45% in the particulate phase, 30% in the dissolved phase, and 25% in the colloidal phase (Eyrolle and Charmasson 2001). Cobalt forms complexes with EDTA that are very stable environmentally. EDTA is often used in agriculture, food and drug processing, photography, and textile and paper manufacturing, and therefore, it is a likely constituent of industrial discharges. Acidity and redox potential have an effect on the behavior of cobalt in water. The adsorption of cobalt by particulate matter decreases with decreasing pH since the increasing H^+ concentration competes with metal binding sites. This may lead to increased concentrations of dissolved cobalt at low pH. The effect of Eh (redox potential) on the speciation of cobalt has been shown by the increase in the concentration of dissolved cobalt by orders of magnitude with increasing depth in certain parts of Baltic waters. The increase in the concentration of dissolved cobalt may be due to the formation of soluble bisulfide and polysulfide complexes in the anoxic zones. The residence time of soluble cobalt in seawater has been estimated to range from <1 to 52 years (Brugmann 1988; Knauer et al. 1982; Smith and Carson 1981). Vitamin B_{12}, which contains cobalt, is synthesized by 58 species of seven genuses of bacteria as well as blue-green algae and actinomycetes (mold-like bacteria). Consequently, vitamin B_{12} levels in marine water range from very low levels in some open ocean water to much higher levels in some coastal waters. Freshwater environments have comparable levels of vitamin B_{12}.

The high level of cobalamins in coastal water appears to be related to the occurrence of macrophytes in these areas with their high concentrations of vitamin B_{12}. Cobalamins are released into the water when the organisms die (Smith and Carson 1981). Alkaline thermal groundwater in granitic areas have been studied as possible waste disposal sites for radioactive waste (Alaux-Negrel et al. 1993). Water in these areas is characterized by high pH, low CO_2 partial pressure, and generally low redox potential; sulfide concentrations are in the range of 10^{-4}–10^{-3} mol/L. The solubility of cobalt is controlled by the solubility of cobalt sulfide (log K_1 and log K_2 being 5.7 and 8.7 at 25°C) and therefore, levels of cobalt are very low, 10^{-8}–10^{-10} mol/L. The ^{60}Co(III) picolinate complex that is released into water by some nuclear reactors does not break down immediately on release into seawater, but rather can coexist with the ^{60}Co(II) forms for lengthy periods in the environment (Leonard et al. 1993a, 1993b). Studies indicate that several processes occur to the cobalt (III) organic complexes, including reduction to the inorganic form, sorption of both species to particulate matter, and transformations of the uncomplexed species. This applies to both stable and radioactive cobalt compounds.

Sediment and Soil. The speciation of cobalt in soil or sediment depends on the nature of the soil or sediment, concentration of chelating/complexing agents, pH, and redox potential (Eh) of the soil. Dissolved cobalt may be absorbed by ion exchange and other mechanisms, or may form complexes with fulvic acids, humic acid, or other organic ligands in soil. The humic and fulvic complexes of cobalt are not very stable compared with those of copper, lead, iron, and nickel. Cobalt was found to bind to different species in arid calcareous soil around a nonferrous metal smelting area in the order of: residual (76.0%) > bound to organic matter (10.3%) > bound to easily reducible oxides (7.1%) > bound to reducible oxides (5.1%) > bound to carbonates (1.3%) (Chu et al. 2022). The speciation of cobalt in sediment from nine sites in the Red Sea, a sea that is unique in that it has no permanent streams flowing into it, was assessed using a sequential extraction technique (Hanna 1992). The mean percentages contained in the various fractions were exchangeable, 5.5%; carbonate, 5%; iron/manganese oxides, 24%; organic, 30.4%; sulfides, 13%; and lithogenous, 22%. While the mean concentration of cobalt in the sediment increased from 0.003 to 0.006 ppb between 1934 and 1984, its distribution among the different phases did not change appreciably. The reduction of soil Eh, which may occur when soil is flooded or in deeper layers of soil that are oxygen-depleted, may change the speciation of cobalt. This may result in the reduction of soil iron and manganese and the subsequent release of adsorbed cobalt from the mineral oxides. Similarly, a decrease in soil pH may result in the solubilization of precipitated cobalt and desorption of sorbed cobalt, resulting in increased cobalt mobility (Smith and Carson 1981). Co^{2+} may also be oxidized to Co^{3+} by manganese oxides, a common component of soils and aquifer material, with subsequent surface precipitation (Brusseau and Zachara 1993). This process may affect transport of cobalt in the subsurface environment. EDTA complexes of cobalt are very stable and are likely to form in soils containing EDTA. EDTA is widely used as a decontaminating agent at nuclear facilities. Although cobalt-EDTA complexes are adsorbed by some soils, the mobility of cobalt in soil may increase as a result of complex formation (DOE 1984; Schnitzer 1969; Smith and Carson 1981). ^{60}Co that is disposed of in shallow land trenches have sometimes been found to migrate more rapidly than expected from the disposal sites. Organic chelating agents are frequently present at these sites and would possibly increase the solubility and transport of the radionuclide.

Bacterial action can affect the mobility of a substance by mediating reactions or by participating in reactions that lower the pH. Another way of influencing mobility is by degrading complexing agents used in cleaning reactors (e.g., citric acid), thereby releasing the element. However, experiments on the fate and transport of cobalt released upon the biodegradation of the complexing ligand indicate that results are not always predictable; the means of ligand removal and the geochemical environment are important factors that must be considered (Brooks et al. 1998).

Bioaccumulation factors for cobalt of 0.19–1.43 were calculated from cobalt concentrations in soil and wheat crops. The samples were collected from areas with industrial and mining activities, and plots were irrigated with groundwater, sewage water, or industrial water. The highest bioconcentration factor (BCF) was observed in crops irrigated with industrial wastewater, but that water gave the lowest transfer factor from shoot to grain. The resulting hazard index was virtually the same for all three sources of water, and the grain concentrations were within permissible levels (Chen et al. 2021).

5.5 LEVELS IN THE ENVIRONMENT

Reliable evaluation of the potential for human exposure to cobalt depends, in part, on the reliability of supporting analytical data from environmental samples and biological specimens. Concentrations of cobalt 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 cobalt 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 5-5 shows the limit of detections typically achieved by analytical analysis in environmental media. An overview summary of the range of concentrations detected in environmental media is presented in Table 5-6.

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

Media	Detection limit	Reference
Water	0.02 μg/L	USGS 2006
Marine water	0.02 μg/L	EPA 1997
Ambient air	0.12 ng/m^3 (fine element) 1.08 ng/m^3 (coarse element)	EPA 1999
Soil and sediment	0.004 μg/g	USGS 2006
Urine	0.023 μg/L	CDC 2018
Blood	0.06 μg/L	CDC 2017
Biota	0.004 μg/g	USGS 2006

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

Table 5-6. Summary of Environmental Levels of Cobalt

Media	Low	High	For more information
Outdoor air (ppbv)	0.000016	0.005	Section 5.5.1
Surface water (ppb)	<1	1,806	Section 5.5.2
Groundwater (ppb)	<1	424	Section 5.5.2
Drinking water (ppb)	<1	107	Section 5.5.2
Ocean water (pg/L)	0.078	71	Section 5.5.2
Food (ppb)	0.02	0.86	Section 5.5.4
Soil	0.15 mg/kg	15,000,000 ppb	Section 5.5.3

Detections of cobalt in air, water, and soil at NPL sites are summarized in Table 5-7.

Table 5-7. Cobalt Levels in Water, Soil, and Air of National Priorities List (NPL) Sites

Medium	Median[a]	Geometric mean[a]	Geometric standard deviation[a]	Number of quantitative measurements	NPL sites
Water (ppb)	41.5	64.7	12.5	126	67
Soil (ppb)	15,000	17,200	5.63	203	100
Air (ppbv)	0.0215	0.0109	11.3	4	3

[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.

5.5.1 Air

Atmospheric cobalt is associated with particulate matter. Cobalt in the air, including cobalt compounds, is monitored by EPA, and recorded in the Air Quality System (AQS). Data from 2016–2020 are summarized in Table 5-8. Mean cobalt levels in ambient air are generally <0.002 μg/m^3 (EPA 2020). Annual concentrations of cobalt in ambient air samples are provided in Table 5-9 (EPA 2023d).

Table 5-8. Percentile Distribution of Annual Mean Cobalt (TSP) Concentrations (μg/m^3) Measured in Ambient Air Locations Across the United States

Year	Number of U.S. locations	25th	50th	75th	95th	Maximum
2016	33	0.00018	0.0010	0.0010	0.0011	0.0011
2017	35	0.00014	0.00045	0.0015	0.0018	0.0022
2018	32	0.00019	0.00058	0.00085	0.0011	0.0014
2019	33	0.00012	0.00020	0.00079	0.0011	0.0014
2020	4	0.000025	0.000033	0.000061	0.00013	0.00014

TSP = total suspended particles

Source: EPA 2020

Table 5-9. Summary of Annual Concentration of Cobalt (ppbv) Measured in Ambient Air Samples at Locations Across the United States[a]

Year	Number of monitoring locations	Number of samples	Average of the arithmetic mean at all locations	Maximum concentration
Total solid particulates				
2022	464	1	0.00040	0.0039
2021	575	18	0.00063	0.0044
2020	624	31	0.00051	0.005
2019	22	921	0.00054	0.003
2018	26	1,265	0.00034	0.008
Particulate matter ≤10 μm (PM_{10})				
2022	203	9	0.104	1.38
2021	1,180	12	0.102	1.5
2020	1,194	14	0.117	2.4
2019	15	887	0.101	5.83
2018	16	988	0.105	3.63

[a] 24-hour sampling period at standard temperature and pressure.

Source: EPA 2023d

At the South Pole, cobalt levels of 0.00049±0.00015 ng/m^3 were recorded in 1974–1975 (Maenhaut et al. 1979). Geometric mean cobalt levels in several open-ocean environments ranged from 0.0004 to 0.08 ng/m^3 (Chester et al. 1991). The average annual PM10 (particles with diameters ≤10 μm) cobalt concentration at Nahant, Massachusetts (near Boston) in 1992–1993 was 1.7 ng/m^3 (Golomb et al. 1997). Half of the cobalt was contained in fine particles (<2.5 μm) and half in coarse particles (2.5–10 μm). The mean cobalt level in southern Norway in 1985–1986 (n=346) was 0.10 ng/m^3 with 35% of the samples falling below the detection limit of 0.04 ng/m^3 (Amundsen et al. 1992). Atmospheric cobalt levels in industrial settings may exceed 10 ng/m^3. The highest recorded average cobalt concentration in air was 48 ng/m^3 in Clydach, Wales at the site where nickel and cobalt were refined (Smith and Carson 1981). These data show the contribution of anthropogenic sources in increasing the level of cobalt in the ambient air. Typical occupational cobalt levels are 1.0×10^4–1.7×10^6 ng/m^3 (Barceloux 1999; IARC 1991).

5.5.2 Water

The EPA maintains a Water Quality Portal (WQP) database that aggregates 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 across the United States and at Superfund sites and wastewaters sampled from recent years are reported in Tables 5-10, 5-11, and 5-12 (WQP 2023).

Table 5-10. Summary of Concentrations of Cobalt (ppb) Measured in Surface and Groundwater Samples Across the United States[a]

Year	Average	Maximum concentration	Number of samples[b]	Percent detected
	Surface water (total cobalt)			
2023	4.0	35.2	56	91
2022	1.4	443	1,806	69
2021	4.8	430	1,147	29
2020	1.6	59	974	25
2019	14.8	420	1,196	28
2018	23.0	1,100	1,072	28
	Surface water (dissolved cobalt)			
2023[a]	0.49	23	230	100
2022	0.72	100	864	82
2021	0.76	68	898	83
2020	0.83	60	851	70
2019	1.9	140	1,226	65

Table 5-10. Summary of Concentrations of Cobalt (ppb) Measured in Surface and Groundwater Samples Across the United States[a]

Year	Average	Maximum concentration	Number of samples[b]	Percent detected
2018	1.5	180	1,525	60
	Groundwater (total cobalt)			
2023[a]	22.5	95.6	19	32
2022	7.8	142	191	40
2021	10.8	102	424	21
2020	18.2	191	383	22
2019	13.1	140	424	24
2018	15.7	143	511	24
	Groundwater (dissolved cobalt)			
2023a	3.1	95.7	97	67
2022	2.0	141	867	34
2021	26.5	8,660	2,324	26
2020	15.2	389	2,509	27
2019	1.2	84.5	1,218	44
2018	1.6	98.3	1,136	42

[a] As of September 14, 2023.
[b] Samples collected from the U.S. Geological Survey Water Science Center monitoring sites and other state environmental departments in over 30 U.S. States.

Source: WQP 2023

Table 5-11. Summary of Concentrations of Cobalt (ppb) Measured in Surface and Groundwater Samples at Superfund Sites

Year	Average	Maximum concentration	Number of samples	Percent detected
		Bonita Peak Mining Superfund Site		
	Surface water (total cobalt)			
2021	32.5	233	236	61
2020	41.4	166	153	86
2019	43.6	148	15	100
2018	20.2	198	581	73
	Surface water (dissolved cobalt)			
2021	25	226	238	75
2020	32.8	154	103	97
2019	34.8	133	15	100
2018	17.9	195	581	82
	Groundwater (total cobalt)			
2021	1.81	1.81	2	50

Table 5-11. Summary of Concentrations of Cobalt (ppb) Measured in Surface and Groundwater Samples at Superfund Sites

Year	Average	Maximum concentration	Number of samples	Percent detected
	Groundwater (dissolved cobalt)			
2021	81.6	1,900	61	61
		Midnite Mine Superfund Site		
	Surface water (total cobalt)			
2022	290	2,060	31	58
2021	138	1,180	33	91
2020	225	2,100	33	88
2019	489	5,670	34	62
2018	330	1,230	33	52
	Surface water (dissolved cobalt)			
2022	387	6,450	82	51
2021	198	7,140	87	91
2020	201	5,260	89	73
2019	400	5,330	84	60
2018	298	5,790	87	61

Source: WQP 2023

Table 5-12. Summary of Concentrations of Cobalt (ppb) Measured in Wastewater Samples Across the United States

Year	Average	Maximum concentration	Number of samples	Percent detected
Industrial effluent				
2020–2022	–	–	2	0
2019	1.6	2	8	63
2018	1	1	4	25
	Municipal waste			
2020–2022	–	–	–	–
2019	1	1	27	4
2018	1	1	11	9

Source: WQP 2023

The concentrations of cobalt in surface water and groundwater in the United States are generally low: <1 μg/L in pristine areas and 1–10 μg/L in populated areas (Hamilton 1994; Smith and Carson 1981). However, cobalt levels may be considerably higher in mining or agricultural areas. Levels as high as 4,500 μg/L were reported in Mineral Creek, Arizona, near a copper mine and smelter; levels of 6,500 μg/L were reported in the Little St. Francis River, which receives effluent from cobalt mining and milling operations (Smith and Carson 1981). Mining at Blackbird Mine in Idaho, a large deposit of cobalt in North America, occurred from the early 1900s to 1982. Cobalt concentration in surface water and groundwater samples collected in 1992 from area creeks near this mine were reported to range from <1 to 625,000 μg/L, and from not detected to 315,000 μg/L, respectively (ATSDR 1995). Eckel and Jacob (1988) analyzed U.S. Geological Survey (USGS) data for 6,805 ambient surface water stations and estimated the geometric mean and median dissolved cobalt concentration as 2.9 and 2.0 μg/L, respectively. Mean cobalt levels reported in seawater range from 0.078 μg/L in the Caribbean Sea to 0.39 μg/L in the Indian Ocean (Hamilton 1994). Vitamin B_{12} is synthesized by bacteria, macrophytes, blue-green algae, and actinomycetes, and cobalt levels in oceans often correlate with biological productivity. In the Baltic Sea, dissolved cobalt levels that are 1.0 ng/L near the surface, increase to 71.0 ng/L at a depth of 200 m (Brugmann 1988). The rise in dissolved cobalt is coincident with the onset of anoxic conditions and the presence of hydrogen sulfide, indicating that soluble bisulfide and polysulfide complexes may be present.

EPA analyzed cobalt in drinking water for the Third Unregulated Contaminant Monitoring Rule. Of 62,982 results, 833 were above the Minimum Reporting Level (1 μg/L) and 3 were above the reference concentration (70 μg/L) (EPA 2017). In Canadian finished drinking water, the median and maximum levels of cobalt were <2.0 and 6.0 μg/L (Meranger et al. 1981). Meranger et al. (1981) tested source water and drinking water in 71 municipalities across Canada and concluded that, in general, both surface water and groundwater used for drinking water supplies contain negligible amounts of cobalt. Greathouse and Craun (1978) analyzed 3,834 grab samples of household tap water from 35 geographical areas in the United States for 28 trace elements. Cobalt was found in 9.8% of the samples at concentrations ranging from 2.6 to 107 μg/L. It is not clear whether these higher levels could indicate that cobalt was picked up in the distribution system. In the earlier National Community Water Supply Study (2,500 samples), 62% of the samples contained <1 μg Co/L; the average and maximum cobalt concentrations were 2.2 and 19 μg/L, respectively (Smith and Carson 1981). Cobalt was not detected (detection limit 8 μg/L) in a 1982–1983 survey of drinking water in Norway that covered 384 waterworks serving 70.9% of the Norwegian population (Flaten 1991).

The mean concentrations of cobalt in rain are around 0.03–1.7 μg/L, with levels generally ranging from 0.002 μg/L at Enewetak Atoll to about 2.9 μg/L in the Swansea Valley, Wales (Arimoto et al. 1985; Dasch and Wolff 1989; Hansson et al. 1988; Heaton et al. 1990; Helmers and Schrems 1995; Nimmo and Chester 1993; Nimmo and Fones 1997; Smith and Carson 1981). The highest recorded level of cobalt in precipitation was 68.9 μg/L in the vicinity of a nickel smelter in Monchegorsk in the Russian Arctic

(Reimann et al. 1997). An analysis of rain in the Mediterranean and urban and coastal sites in northwest England showed that about 33–44% of the cobalt occurred as very stable dissolved organic complexes (Nimmo and Chester 1993; Nimmo and Fones 1997).

5.5.3 Sediment and Soil

Cobalt is the 33rd most abundant element in the earth's crust. Its average concentrations in the earth's crust and in igneous rocks are 20–25 and 18 mg/kg, respectively (Abbasi et al. 1989; Merian 1985; Smith and Carson 1981). Trace metals in soils may originate from parent rock or from anthropogenic sources, primarily fertilizers, pesticides, and herbicides. Most soils contain 1–40 mg cobalt/kg. The average cobalt concentration in U.S. soils is 7.2 mg/kg (Smith and Carson 1981). Soils containing <0.5–3 mg cobalt/kg are considered cobalt-deficient because plants growing on them have insufficient cobalt (<0.08–0.1 mg/kg) to meet the dietary requirements of cattle and sheep. Cobalt-deficient soils include the humus podzols of the southeastern United States, and the podzols, brown podzolic soils, and humus groundwater podzols in the northeastern parts of the United States. Podzols are generally coarse textured soils. The cobalt content of surface soils from 13 sites in the brown and dark brown soil zones of southwestern Saskatchewan ranged from 3.7 to 16.0 mg/kg and only in one case was the soil cobalt appreciably elevated above the corresponding parent material (Mermut et al. 1996). Fertilizers used in this agricultural area contained 0.12–102 mg Co/kg, with a median of 5.7 mg/kg.

Mean cobalt concentrations in surface soil from nine sites on two active volcanic islands off of Sicily ranged from 5.1 to 59.0 mg/kg (Bargagli et al. 1991). Soils near ore deposits, phosphate rocks, or ore smelting facilities, and soils contaminated by airport traffic, highway traffic, or other industrial pollution may contain much higher concentrations of cobalt; concentrations up to 800 mg/kg have been detected in such areas (Kloke et al. 1984; Smith and Carson 1981). Cobalt concentrations from 28 samples collected from surface deposits in the Big Deer and Blackbird Creek drainage basins in Idaho near the Blackbird Mine ranged from 26.5 to 7,410 mg/kg (ATSDR 1995). At a metal forge where metal alloys were ground for decades, cobalt concentrations were higher in soil, baghouse dust, and surface dust than in background samples (Suh et al. 2019). Concentrations were 8,000 mg/kg in baghouse dust, 44.6–4503 mg/kg in surface dust, and 32.1–185 mg/kg in soil (Suh et al. 2019). The background concentration in soil was 11.2–15.6 mg/kg (Suh et al. 2019).

Soils around the large copper-nickel smelters in Sudbury, Ontario have been shown to contain high levels of cobalt. Fifty kilometers from the smelters, cobalt levels in surface soil were 19 mg/kg. These levels increased to 48 mg/kg at 19 km, 33 mg/kg at 10 km, and 42–154 mg/kg between 0.8 and 1.3 km from the smelter (Smith and Carson 1981). Soils around a cemented tungsten carbide tool grinding factory contained cobalt levels as high as 12,700 mg/kg, almost 2,000 times the average in U.S. soils (Abraham and Hunt 1995). However, neighborhood soils between 30 and 160 meters from the factory only contained 12–18 mg Co/kg.

Unpolluted freshwater sediment contains about the same levels of cobalt as does cobalt-sufficient soil, generally <20 mg/kg (Smith and Carson 1981). In the Hudson River Estuary, cobalt levels in suspended sediment were an order of magnitude higher than in bottom sediment (Gibbs 1994). This can be attributed to the finer grain size of suspended sediment or local sources. Cobalt levels in core samples (surface to 42 cm deep) from the Upper St. Lawrence Estuary were independent of depth, indicating the lack of any recent significant anthropogenic releases (Coakley et al. 1994).

In soil samples monitored over a 2-year period near industrial and mining sites in Pakistan, samples irrigated with industrial water had the highest cobalt concentrations detected (1.01–1.20 mg/kg), while the lowest concentrations (0.15–0.30 mg/kg) were observed in soils irrigated with groundwater or sewage water (Chen et al. 2021). Cobalt levels in soils near mining sites in the D.R. Congo are much higher with concentrations of 116–311 mg/kg (Cheyns et al. 2014; Michée et al. 2023). Reported mean soil concentrations in regions distant from mining operations in the D.R. Congo were 20 mg/kg (Cheyns et al. 2014).

Sediment and soil monitoring data were available for cobalt in the EPA’s WQP database and are reported in Tables 5-13, 5-14, and 5-15. Because it is a natural component of the earth’s crust, cobalt was frequently detected, and the averages and ranges generally agree with reported background concentration ranges. In 2020, the high reported average and maximum concentrations in soil were reported from monitoring in South Dakota, which were likely impacted by mining operation located in the state. In 2022, the high reported average and maximum concentrations in sediments were reported from monitoring in Washington, which were likely impacted by mining operation at the Midnite Mine located in Washington.

Table 5-13. Summary of Concentrations of Cobalt (ppb) Measured in Sediment Samples Across the United States

Year range	Average	Maximum concentration	Number of samples	Percent detected
2022	22,240	192,000	15	100
2021	6,303	83,000	137	96
2020	5,370	31,000	376	81
2019	9,621	45,000	590	69
2018	7,604	35,000	255	60

Source: WQP 2023

Table 5-14. Summary of Concentrations of Cobalt (ppb) Measured in Soil Samples Across the United States

Year range	Average	Maximum concentration	Number of samples	Percent detected
2022	7,340	23,00	15	100
2021	17,800	24,000	10	100
2020	1,358,897	15,000,000	39	100
2019	6,089	24,700	122	99
2018	7,430	13,000	13	100

Source: WQP 2023

Table 5-15. Summary of Concentrations of Cobalt (ppb) Measured in Soil and Sediment Samples at Superfund Sites

Year	Average	Maximum concentration	Number of samples	Percent detected
		Bonita Peak Mining Superfund Site		
Soil				
2021	16,780	217,000	192	80
2018	8,599	126,000	97	100
Sediment				
2018	14,501	85,900	122	100

Source: WQP 2023

5.5.4 Other Media

The cobalt content of plants depends on the plant, the cobalt content of the soil, and numerous environmental factors. The mean cobalt concentration reported for terrestrial plants was 0.48 µg/g, while the mean and median levels for freshwater vascular plants were 0.48 and 0.32 µg/g, respectively (Outridge and Noller 1991). The median cobalt level in freshwater vascular plants from polluted waters was about the same as in unpolluted waters, 0.37 µg/g, although extremely high levels of cobalt, up to 860 µg/g, was reported in one species, *Myriophyllum verticillatum*, from central Ontario lakes. Grasses normally contain 0.2–0.35 µg/g of cobalt, but grasses from cobalt-deficient regions contain only 0.02–0.06 µg/g of cobalt (Hamilton 1994). Durum wheat grown in southeastern Saskatchewan contained 0.01–0.02 mg/kg dry weight (Mermut et al. 1996). In view of the cobalt content of the soil and the fact that almost half of the cobalt in fertilizers used in the area was in a readily available form, the uptake of cobalt by wheat was negligible. In wheat samples collected from seven industrial and mining sites in Pakistan where fields were irrigated with various water sources with cobalt concentrations ranging from 0.15 to 1.20 mg/kg, cobalt concentrations in the wheat grain samples ranged from 0.12 to 0.57 mg/kg (Chen et al. 2021).

Cobalt concentrations have been reported in various aquatic animals and seabirds. Concentrations of cobalt in biota sampled from 2018 to 2022 across the United States and compiled in the WQP database are reported in Table 5-16 (WQP 2023). Eel and a freshwater fish from three Dutch polder lakes contained 2.5–25.0 and 2.50–5.63 mg cobalt/kg wet weight, respectively (Badsha and Goldspink 1988). Muscle tissue of ocean fish and rock crabs caught near dump sites off of New York City, New Haven, Connecticut, and Delaware Bay contained 10–40 and 16.0 µg/kg, respectively (Greig and Jones 1976). In a study of the levels and distribution of 14 elements in oceanic seabirds, the concentration of cobalt, an essential element, appeared to be highly regulated, with over 80% of the body burden residing in the skeleton. The mean cobalt concentration in the livers of 11 seabird species ranged from 0.048 to 0.078 µg/g dry weight, and cobalt had the lowest coefficient of variation in the different species of the elements studied (Kim et al. 1998). In another study in Antarctica, mean cobalt levels in fish and amphipods were 0.11–0.14 and 1.01 µg/g dry weight, respectively, while those in the tissue of penguin and other sea birds ranged from 0.09 to 0.11 µg/g (Szefer et al. 1993). The concentration of cobalt in the tissue of 14 bluefin tuna caught by various commercial fishing vessels off Newfoundland was essentially the same, 0.01±0.004 µg/g (Hellou et al. 1992a). Similarly, in a broad survey of contaminant levels in nine species of fish and fiddler crabs from 11 sites in the lower Savannah River, Georgia and the Savannah National Wildlife Refuge, mean cobalt levels among different species and sites were statistically indistinguishable (Winger et al. 1990). These and other studies indicate that cobalt does not biomagnify up the food chain (Smith and Carson 1981). While high levels of cobalt were found in sediment from the Tigris River in Turkey and low levels in the water, cobalt was not detected in two species of fish, *Cyprinion macrostomus* and *Garra rufa* (Gumgum et al. 1994). Cobalt was detected in two other species of fish collected between 1995 and 1996 in the upper Sakarya river basin, Turkey. Cobalt concentrations ranged from 0.038 to 0.154 µg/g dry weight for *Cyprinus carpio* and from 0.045 to 0.062 µg/g dry weight for *Barbus plebejus* (Barlas 1999).

Table 5-16. Summary of Concentrations of Cobalt (ppb) Measured in Biota Samples Across the United States

Organism[a]	Average	Maximum concentration	Number of samples	Percent detected
2022	298	795	37	86
Catostomus latipinnis	208.3	686	9	100
Salmo trutta	422.5	678	2	100
Oncorhynchus mykiss	222.8	328	12	58
Pantosteus discobolus	490.3	795	7	100
Catostomus commersonii	203.5	272	4	100
C. commersonii; Catostomus discobolus	473.0	473	1	100
C. commersonii; C. latipinnis	268.5	393	2	100
2021	5,651	1,219,000	3,567	88
Taxon unknown	2,900.0	2,900	1	100
Vertebrata	252.5	276	4	100
Ameiurus natalis	30.5	38.8	3	67
Coregonus clupeaformis	24.2	30.1	6	33
2020	313.7	6,700	162	65
Taxon unknown	1,907.7	6700	13	100
Mylocheilus caurinus	57.0	112	32	63
Catostomus macrocheilus	93.5	287	24	92
O. mykiss	159.7	604	13	54
Ptychocheilus oregonensis	47.7	123	60	48
Catostomus catostomus	102.6	198	14	64
Oncorhynchus clarkii	282.0	824	6	83
2019	57.3	243	185	49%
M. caurinus	60.9	85	24	33
Salvelinus confluentus	33.4	62	8	63
O. mykiss	39.5	41	5	40
P. oregonensis	40.6	54	38	37
Lepomis megalotis	33.6	60	14	43
C. macrocheilus	83.0	243	23	96
Oncorhynchus nerka	43.5	90	23	48
Lepomis macrochirus	39.6	39.6	4	25
Prosopium williamsoni	58.0	58	2	50
Richardsonius balteatus	53.9	89	16	50

Table 5-16. Summary of Concentrations of Cobalt (ppb) Measured in Biota Samples Across the United States

Organism[a]	Average	Maximum concentration	Number of samples	Percent detected
Semotilus atromaculatus	37.0	42.1	4	50
A. natalis	108.0	108	1	100
Lepomis cyanellus	39.5	42.9	4	50
C. commersonii	67.4	74.3	4	75
Perca flavescens	49.0	68	6	33
O. clarkii	86.0	139	2	100
Hybognathus nuchalis	153	153	1	100
2018	14	25.6	19	21
L. macrochirus	9.19	9.19	2	50
Micropterus dolomieu	11.3	11.3	1	100
Lepomis megalotis	25.6	25.6	3	33
Cyprinus carpio	10	10	3	33
Chironomidae[b]	818	10,700	61	93

[a] Only organisms with >5% sample detection listed.
[b] Organism from Bonita Peak Mining Superfund Site.

Source: WQP 2023

Khan et al. (2022) examined the accumulation of heavy metals over a 3-month period in *Poecilia reticulata* in a laboratory aquarium study using five types of industrial wastes: chemical sludge, chemical sludge-ash, boulder slag, converter slag, and marble waste powder with cobalt concentrations of 130.00, 243.21, 50.32, 115.00, and 9.49 mg/kg, respectively. A significantly higher accumulation of cobalt was observed in fish exposed to sludge, sludge-ash, and converter slag. Concentrations of cobalt in the aquariums prepared with chemical sludge, chemical sludge-ash, boulder slag, converter slag, and marble waste powder were approximately 4.09, 8.12, 1.33, 1.51, and 3.82 mg/kg, respectively. Concentrations of cobalt in fish tissues at the end of the study were approximately 4.60, 8.62, 1.59, 1.93, and 3.92 mg/kg, respectively. The control tank and control fish cobalt concentrations were 0.001 and 0.01 mg/kg, respectively.

Some female birds sequester metals into their eggs under certain conditions, a phenomenon that may jeopardize the developing embryos. The geometric mean concentrations of cobalt in tern eggs collected from coastal New Jersey in 1971 and 1982 were 0.48 and 0.50 mg/kg, respectively. Unlike the levels of seven other common metals (e.g., mercury, cadmium, copper, lead, manganese, nickel, and zinc), the level of cobalt in tern eggs (and in the environment) showed no decline over the 11-year period (Burger and Gochfeld 1988).

The level of cobalt in most Canadian foods was low; items with the highest concentrations in this study were waffles (0.076 μg/g), corn cereal (0.074 μg/g), and potato chips (0.070 μg/g) (Dabeka and McKenzie 1995). Green leafy vegetables and fresh cereals were the richest sources of cobalt (0.2–0.6 μg/g dry weight), while dairy products, refined cereals, and sugar contained the least cobalt (0.1–0.3 μg/g dry weight) (Barceloux 1999). The levels of cobalt were determined in 50 different food items, mainly meat, fish, fruit, vegetables, pulses, and cereals on the Swedish market during the years 1983–1990 (Jorhem and Sundstrom 1993). Beef liver and seeds were fairly high in cobalt and fish, fruit, and root and leafy vegetables were under 0.01 μg cobalt/g fresh weight. The cobalt levels in μg/g fresh weight were highest in alfalfa seeds, 0.86; linseed, 0.56; milk chocolate, 0.34; dark chocolate, 0.24; white poppy seeds, 0.30; blue poppy seeds, 0.15; soya beans, 0.084; green lentils, 0.054; and beef liver, 0.043. The cobalt content of 20 brands of alcoholic and nonalcoholic beer widely consumed in Spain ranged from 0.16 to 0.56 μg/L with a median of 0.39 μg/L (Camean et al. 1998). Cobalt, which was at one time added to beer to decrease over foaming of the head in glasses containing residual soap, has been associated with cardiomyopathies (heart disease) in heavy beer drinkers; however, reported liver effects could have been the result of heavy alcohol consumption by the study population.

Cobalt can be released into bottled water stored in transparent PET plastic containers containing cobalt acetate as an anti-yellowing agent, with concentrations increasing with prolonged storage at 20°C (Dogan and Cebi 2019). For example, cobalt levels in a 5-L bottle after 2 and 12 months of storage were 0.05 and 0.70 μg/L, respectively. Small amounts of cobalt (0.01175–0.02150 μg/L) also leached into hot water (100°C) that was stored in disposable fast-food container products such as paper cups, plastic cups, plastic bags, and plastic bowls for 15 minutes (Zeng et al. 2023). Most containers tested were made from transparent polypropylene; however, some products also contained polyethylene and polystyrene. This particular combination of products, temperature, and duration was selected to simulate a take-out food scenario with hot food or freshly boiled liquid.

Cobalt levels in food from the Copperbelt mining region of D.R. Conga are much higher than non-mining regions (Cheyns et al. 2014). Food items with the highest concentrations in the mining regions included leafy vegetables (46 μg/g dry weight), beans (22 μg/g dry weight), cassava leaves (12 μg/g dry weight), fruit vegetable (12 μg/g dry weight), and sweet potato leaves (6.5 μg/g dry weight). Concentrations for the same food items from non-mining regions were 1.2, 0.84, 1.5, 0.58, and 1.1 µg/g dry weight, respectively.

Cobalt is present in various consumer products including cleaners, detergents, and soaps, which have resulted in dermatitis in sensitive individuals (Kokelj et al. 1994; Vilaplana et al. 1987).

The concentration of cobalt in U.S. coal averages about 5 mg/kg, levels in crude oil and fuel oil are 0.001–10 and 0.03–0.3 mg/kg, respectively, and those in gasoline are <0.1 mg/kg (Smith and Carson 1981). Cobalt levels were below the detection limit of 0.05 ppm dry weight in all but 1 of 26 samples of composted yard waste, sewage sludge, and municipal solid waste samples nationwide in 1991. The one positive sample of composted yard waste contained 1.53 ppm of cobalt (Lisk et al. 1992).

5.6 GENERAL POPULATION EXPOSURE

Exposure of the general population to cobalt occurs through inhalation of ambient air and ingestion of food and drinking water. The estimated average intake of cobalt of the U.S. population has been reported as 0.005–0.04 mg Co/day, the U.K. estimated population intake is reported as 0.012 mg/day, and the estimated population intakes in Canada and France have been reported as 0.011 and 0.029 mg Co/day, respectively (EFSA 2009; EPA 1980). In general, intake from food is much greater than from drinking water, which in turn, is much greater than from air. From the monitoring data available, the mean concentration of cobalt in ambient air in the United States is <0.002 µg/m^3 (EPA 2020). However, levels may be orders of magnitude higher in source areas. Therefore, exposure to cobalt in air will vary substantially from non-source areas to areas with cobalt-related industries.

Similarly, the median cobalt concentration in U.S. drinking water is <2.0 µg/L; however, values as high as 107 µg/L have been reported in surveys of water supplies (Smith and Carson 1981). Therefore, exposure from drinking water may vary considerably from one location to another. In Canada, the daily cobalt intake of the average adult from drinking water is ≤2.6 µg; this could increase to 10 µg for those living in areas with the highest cobalt levels (Meranger et al. 1981). Low levels of cobalt (≤1.30 µg/L) have been detected in water stored at room temperature in transparent PET, with higher cobalt levels detected in smaller containers (0.5 versus 5 L) stored for a longer duration (12 versus 2 months) (Dogan and Cebi 2019). Small amounts of cobalt (<0.03 µg/L) may leach into hot beverages stored in plastic or paper to-go containers (Zeng et al. 2023).

Very low levels of cobalt present in some finished waters are not expected to be an exposure concern when showering. Cobalt is not expected to volatilize from water; therefore, there is no potential for vapor inhalation exposure during showering and bathing. Furthermore, dermal exposure is not expected to be a concern. ATSDR's three-compartment Shower and Household-Use Exposure (SHOWER) model predicts dermal exposure based on showering and bathing. These data, along with human activity patterns, are used to calculate a daily time-weighted average (TWA) exposure concentrations from dermal uptake from skin contact. ATSDR's SHOWER model is available by sending a request to showermodel@cdc.gov. Using water levels discussed in Section 5.5.2, Reasonable Maximum Exposure (RME) levels for potential dermal exposure to cobalt were calculated for different exposure groups (Table 5-17).

Table 5-17. Reasonable Maximum Exposure of Cobalt for Daily Administered Dermal Dose in μg/kg/day for the Target Person

Exposure group	Dermal
Birth–<1 year	0.00012
1–<2 years	0.00011
2–<6 years	$9.9\text{x}10^{-5}$
6–<11 years	$8.1\text{x}10^{-5}$
11–<16 years	$6.6\text{x}10^{-5}$
16–<21 years	$6.1\text{x}10^{-5}$
Adult	$5.9\text{x}10^{-5}$
Pregnant and breastfeeding women	$5.9\text{x}10^{-5}$

Source: ATSDR 2023

General population exposure to cobalt from food is highly variable and normally higher than intake from drinking water. In a study published in 1980, the cobalt intake from food was estimated to be 5.0–40.0 μg/day (EPA 1980). The Panel on Additives and Products or Substances used in Animal Feed reported a worst-case calculation for cobalt intake by humans of 14 μg/day based on approximate cobalt concentrations in animal products (EFSA 2009). Small amounts of cobalt (<0.03 μg/L) may leach into hot foods stored in plastic or paper take-out containers (Zeng et al. 2023).

In a 2020 study, children's weekly intake of cobalt from snacks was estimated to be 0.69 μg/kg, equivalent to about 1.5 μg/day (Gao et al. 2020). The greatest dietary contributors were flour products (0.16 mg/kg; 23.59%), bean products (0.15 mg/kg; 22.38%), and preserved fruit (0.1 mg/kg; 14.18%). In an earlier study, the daily cobalt intake, including food, water, and beverages of two men that were followed for 50 weeks was much higher, 310 and 470 µg (Smith and Carson 1981). The U.S. Department of Agriculture (USDA) conducted a special exploratory study in 1985–1986 to determine the concentration of trace metals in tissue of healthy livestock and poultry randomly selected from those slaughtered. Between 0.6 and 5.9% of samples in the 11 production classes had levels of cobalt that exceeded the lowest reliable quantitation level of 0.15 ppm (0.15 mg/kg) and the mean of positive samples ranged from 0.20 to 0.23 ppm in all classes but heifer/steer, which had a level of 1.92 ppm (Coleman et al. 1992). The estimated average daily cobalt intake from the diet in Canada was 11 µg/day; the intake varied from 4 to 15 µg/day between the various age/sex groups (Barceloux 1999; Dabeka and McKenzie 1995). The contributions of various food groups to cobalt intake in this study were (category, contribution of dietary intake): bakery goods and cereals, 29.8%; vegetables, 21.9%; beverages, 9.8%; milk and milk products, 9.4%; meat and poultry, 9.1%; soups, 6.4%; fruit and fruit juices, 5.0%; sugar and candies, 2.8%; fish, 2.7%; fats and oils, 2.2%; and miscellaneous, 1.1%. The average daily intake of cobalt in France was estimated to be 29 µg/day (Biego et al. 1998). In this study, foods were divided into nine categories. The foods accounting for the greatest contributions of cobalt intake were milk and dairy products, fish-crustaceans, and condiments-sugar oil, respectively, contributing 32, 20, and 16% to the daily intake. A long-term (2013–2018) total diet study of the Japanese population determined that the average intake was 0.17 µg Co/kg/day (12 µg/day for a 70-kg person), with comparable intakes for total mercury and lead. The food concentrations (µg Co/g) were greatest in seasonings (0.0075), pulses (0.0056), sugars and confectionaries (0.0033), green vegetables (0.0023), fish and shellfish (0.0022), and mushrooms and seaweed (0.0021) (Watanabe et al. 2022).

Cobalt, which had been added to beer to decrease over foaming, was associated with cardiomyopathies (heart disease) in heavy beer drinkers; indications of liver effects could have been the result of heavy alcohol consumption. However, according to Camean et al. (1998), the low levels of cobalt presently found in beer do not make a significant contribution to the total cobalt intake in heavy beer drinkers. The average concentration of cobalt measured in coffee varieties of Brazil, Ethiopia, Kenya, Columbia, and India origin sampled from the Jordanian Market in 2019 was 0.76 µg/g, with a range of 0.27–0.97 µg/g; highest levels were measured in coffee from India (Albals et al. 2021). The daily estimated intake was 1.52 µg Co based on 1 cup/day (2 g of group coffee in 50 mL of tap water). Roasted coffee had higher levels of cobalt (0.97 µg/g) than green coffee (0.71 µg/g) or half-roasted coffee (0.67 µg/g) (Albals et al. 2021).

Since cobalt is used in such a wide variety of applications, the general public may come into contact with cobalt in consumer goods. In a study of cobalt release and skin deposition from short, repetitive contact with metallic items mimicking daily contact, average skin doses were 0.7–1.1 μg/cm^2 (Midander et al. 2014). Midander et al. (2014) concluded that short, repetitive contact with metallic items could be harmful. Bregnbak et al. (2015b) also found that leather was the most frequent exposure source causing dermatitis after non-occupational use of cobalt-containing tools. Eleven water-based acrylic paint colors (lemon yellow, viridian, scarlet, titanium white, burnt umber, yellow ochre, ultramarine, phthalocyanine blue, emerald green, vermilion, and burnt sienna) intended for school-age children purchased from a local shop in Riyadh, Saudi Arabia were all found to have cobalt concentrations ranging from 1.04 μg/g in titanium white to 14.09 μg/g in burnt umber (Khan et al. 2021). Cobalt was detected in several jewelry and clothing items in Korea, including belts, bracelets, earrings, rings, hair pins, necklaces, watches, buttons, and zippers (Cheong et al. 2014). Cases of allergic contact dermatitis in several people have been associated with leather furniture containing 800–1,250 ppm cobalt (Bregnbak et al. 2017; Thyssen et al. 2013). Cobalt was detected in 100% of preschool children's clothing samples analyzed from China, India, South Korea, and Southeast Asia. Cobalt concentrations ranged from 0.0176 to 4.64 mg/kg, with a median value of 0.089 mg/kg. Cobalt is likely introduced to fabrics as a catalyst or antimicrobial agent during manufacturing. Significantly higher concentrations of cobalt were observed in clothing samples of non-pure cotton fabrics (Chen et al. 2022). Zhang et al. (2022) measured concentrations of cobalt in various polyethylene, propylene, polyurethane, plush, and wooden toys and reported levels ranging from not detected to 2,610 ng/g; both detection rates and detection levels were highest in plush toys. Cobalt has been quantified at concentrations of 0.1–0.2 ppm in several household products in Italy, including heavy duty powders, hand wash powders, laundry tables, heavy duty liquids, machine and hand wash liquids, fine wash liquids, dishwashing liquids, and liquid and powder cleaners (Basketter et al. 2003).

Laptop computers may release cobalt when in contact with skin, and release rates from an HP laptop into artificial sweat were as much as 0.87 ng/cm^2/hour from the wrist support and as much as 0.07 ng/cm^2/hour from the lid (Midander et al. 2016). Cobalt was detected in 6% of 31 laptops from 5 different brands tested (Midander et al. 2016).

Since cobalt and other heavy metals have been used on top of the glazed surface of hand-painted China, a study was conducted to see whether these metals are released from the paint into food under acidic conditions. Forty-six samples of porcelain dinnerware from Europe or Asia that were manufactured before the mid-1970s and had hand-painted designs over the glaze were filled with 4% acetic acid to within 7 mm of the rim and analyzed after 24 hours (Sheets 1998). Of these, 36 samples released <0.02 μg/mL of cobalt and 10 released 0.020–2.9 μg/mL. High levels of blood cobalt were recorded in the case of lead poisoning in an adult woman by a Greek jug, which was likely released from the underglaze dye due to degradation caused by juice (Selden et al. 2007). The Food and Drug Administration (FDA) has not established dinnerware extraction limits for cobalt.

People may also be exposed to cobalt in cosmetic products. Cobalt levels in eye shadows range from <0.5 t0 253.33 μg/g, with products from China having the highest concentrations (Corazza et al. 2009); (Omolaoye et al. 2010). Sainio et al. (2000) found that eye shadows containing >10 μg/g of cobalt were mainly darker pigmented colors like brown, gray, and black. Face paints for both adults and children produced in China, Spain, the United Kingdom, and the United States were analyzed and found to contain up to 5.5 μg/g cobalt (Corazza et al. 2009). Lipstick contained concentrations up to 1.30 μg/g (Corazza et al. 2009; Liu et al. 2013; Sneyers et al. 2009). Concentrations of cobalt in skin creams ranged from 0.00013 to 2.2 μg (Bocca et al. 2007; Onwordi et al. 2011; Sneyers et al. 2009). Average cobalt concentrations of 4.4 μg/g were reported in various cosmetic face paints used in China. Out of 91 paint samples tested, 11.0% contained cobalt at levels >10 μg/kg. Cobalt was detected in 73.3 and 91.7% of white and yellow paints, respectively, and in 100% of nude, red, green, blue, brown, and black paint samples. Cobalt was detected at levels >10 μg/kg in 7.1, 7.7, 15.4, 37.5, and 71.4% of red, green, blue, brown, and black paints, respectively (Wang et al. 2020). Cobalt concentrations in facial and powdered cosmetic pigments (Unipure yellow LC 182, Unipure Violet LC 581, and Unipure Black LC 990) ranged from 4.1 to 9.4 μg/g. In dissolution tests of these facial and powdered cosmetic pigments with artificial sweat solutions, it was observed that cobalt was not released into the sweat-soluble fraction (Wang et al. 2022a).

Cobalt concentrations were analyzed in tattoo ink samples in Italy in 2019 via inductively coupled plasma mass spectrometry. Cobalt was identified in True Black from Solong Tattoo (China) using a proprietary pigment class (0.28 μg/g), Mario's Blue from Solong Tattoo (China) using a proprietary pigment class (0.14 μg/g), and Grape Violet from Solong Tattoo (China) using a proprietary pigment class (0.14 μg/g). Cobalt was not detected in Light Red from Eternal Ink (USA) using CI 12475 (Pigment Red 170), Golden Yellow from Solong Tattoo (China) using a proprietary pigment class, Light Green from Solong Tattoo (China) using a proprietary pigment class, or Snow White from Solong Tattoo (China) using a proprietary pigment class (Battistini et al. 2020); those colors are not typically associated with cobalt compound colorants.

Higher urinary cobalt concentrations were related to older housing built before 1990 (Shiue and Bramley 2015). Smokers may be exposed to cobalt in mainstream smoke, but the level of exposure has not been assessed (Barceloux 1999).

Urinary cobalt (uncorrected and creatinine-corrected) was measured in the U.S. general population during NHANES 1999–2018 and blood cobalt was measured in 2015–2018 (CDC 2022). Table 5-18 shows the geometric mean and selected percentiles of urinary cobalt in the U.S. population surveyed for NHANES 2011–2012, 2013–2014, 2015–2016, and 2017–2018. Table 5-19 shows the geometric mean and selected percentiles of urinary cobalt (creatinine corrected) in the U.S. population surveyed for NHANES 2011–2012, 2013–2014, 2015–2016, and 2017–2018. Table 5-20 shows the geometric mean and selected percentiles of blood cobalt in the U.S. population from NHANES 2015–2016 and 2017–2018.

In an evaluation of pregnant and delivering women conducted in Spain from March 2016 to March 2017, maternal blood and urine samples and cord blood samples were collected and analyzed (Bocca et al. 2019). Maternal blood samples (n=48) in the first trimester had cobalt levels of 0.1–0.8 µg/L, which was similar to cobalt levels in blood samples (n=40) collected at delivery (0.1–0.9 µg/L). Cobalt levels in cord blood sampled (n=31) at delivery ranged from 0.1 to 0.6 µg/L. Cobalt levels in non-creatinine-adjusted maternal urine samples collected in the first, second, and third trimesters were 0.1–2.3, 0.1–3.2, and 0.1–3.4 µg/L, respectively. In creatinine-adjusted maternal urine samples collected in the first, second, and third trimesters, cobalt levels were 0.1–6.5, 0.1–6.2, and 0.1–6.9 µg/L, respectively. These levels were similar to previous study results in pregnant women from South Africa, Western Australia, and North Norway, with maternal blood concentrations of 0.1–0.6 µg/L, a cord blood concentration of 0.27 µg/L, and a maternal urine concentration of 1.17 µg/L (Bocca et al. 2019). Maternal blood and urine concentrations were positively associated with intake of seafood and fresh cheese using Spearman's correlations; however, this association was not observed using a multiple linear regression analysis (Bocca et al. 2020). In a study of pregnant women in Puerto Rico from 2011 to 2017, the mean urinary concentration of cobalt was 1.0 ng/mL and the mean blood concentration was 0.34 ng/mL (Ashrap et al. 2020). Reported urinary and blood values in Ashrap et al. (2020) were in the NHANES 90thh and 90th–95th percentiles, respectively, for Hispanics in Tables 5-18 and 5-20. Smoking and consuming milk was associated with significantly higher urinary cobalt concentrations, while no predictors for blood cobalt were reported (Ashrap et al. 2020). In China, cobalt was detectable in 27.2% of both maternal and umbilical cord samples, and the median concentration in maternal and cord blood was below the detection limit (1.1 ng/g) (Hu et al. 2015). Cobalt concentrations were 0.52–0.61 in maternal serum of Polish mothers with fetuses with neonatal abnormalities and 0.24–0.27 µg/L in amniotic fluid (Kocylowski et al. 2019).

Table 5-18. Geometric Mean and Selected Percentiles of Urinary Cobalt (in µg/L) for the U.S. Population from NHANES

	Survey years	Geometric mean (95% CI)	Selected percentiles (95% CI)				Sample size
			50th	75th	90th	95th	
Total							
	2011–2012	0.326 (0.309–0.344)	0.323 (0.306–0.347)	0.543 (0.510–0.577)	0.860 (0.800–0.979)	1.27 (1.09–1.45)	2,504
	2013–2014	0.391 (0.373–0.411)	0.408 (0.382–0.435)	0.687 (0.662–0.713)	1.04 (0.976–1.09)	1.35 (1.23–1.48)	2,664
	2015–2016	0.414 (0.394–0.435)	0.434 (0.415–0.455)	0.687 (0.658–0.725)	1.06 (0.983–1.12)	1.53 (1.34–1.71)	3,061
	2017–2018	0.424 (0.398–0.451)	0.437 (0.412–0.451)	0.710 (0.673–0.756)	1.16 (1.07–1.27)	1.61 (1.37–1.83)	2,808
Age group							
3–5 years	2015–2016	0.426 (0.397–0.456)	0.466 (0.410–0.512)	0.739 (0.662–0.833)	1.08 (0.947–1.25)	1.55 (1.23–2.07)	486
	2017–2018	0.472 (0.410–0.542)	0.526 (0.448–0.627)	0.854 (0.749–0.917)	1.22 (1.04–1.52)	1.64 (1.34–1.78)	403
6–11 years	2011–2012	0.397 (0.356–0.442)	0.452 (0.361–0.510)	0.704 (0.616–0.772)	1.00 (0.846–1.38)	1.42 (1.00–1.78)	399
	2013–2014	0.447 (0.411–0.487)	0.479 (0.408–0.522)	0.789 (0.718–0.877)	1.05 (0.991–1.33)	1.55 (1.14–1.84)	402
	2015–2016	0.534 (0.494–0.577)	0.599 (0.525–0.636)	0.886 (0.773–0.948)	1.20 (0.992–1.40)	1.63 (1.20–2.05)	379
	2017–2018	0.519 (0.459–0.586)	0.559 (0.474–0.642)	0.877 (0.787–0.942)	1.45 (1.18–1.83)	1.88 (1.57–2.21)	333
12–19 years	2011–2012	0.416 (0.358–0.484)	0.429 (0.341–0.527)	0.700 (0.622–0.806)	1.12 (0.960–1.30)	1.56 (1.16–1.96)	390
	2013–2014	0.549 (0.462–0.653)	0.602 (0.491–0.701)	0.936 (0.783–1.05)	1.43 (1.08–1.75)	1.76 (1.49–3.07)	451
	2015–2016	0.571 (0.527–0.620)	0.604 (0.535–0.659)	0.892 (0.840–1.08)	1.48 (1.32–1.74)	1.92 (1.57–2.23)	402
	2017–2018	0.516 (0.488–0.545)	0.583 (0.514–0.656)	0.879 (0.835–0.948)	1.33 (1.20–1.39)	1.49 (1.39–1.65)	364
≥20 years	2011–2012	0.307 (0.288–0.327)	0.308 (0.289–0.328)	0.491 (0.457–0.534)	0.800 (0.695–0.940)	1.16 (0.984–1.36)	1,715
	2013–2014	0.367 (0.349–0.386)	0.382 (0.357–0.410)	0.647 (0.614–0.673)	0.930 (0.882–1.04)	1.23 (1.17–1.34)	1,811
	2015–2016	0.385 (0.364–0.408)	0.403 (0.379–0.427)	0.638 (0.599–0.666)	0.949 (0.877–1.06)	1.41 (1.21–1.66)	1,794
	2017–2018	0.401 (0.371–0.433)	0.409 (0.384–0.438)	0.650 (0.619–0.702)	1.08 (0.981–1.20)	1.61 (1.27–1.88)	1,708
Sex							
Males	2011–2012	0.317 (0.299–0.336)	0.316 (0.293–0.339)	0.496 (0.452–0.547)	0.715 (0.659–0.798)	0.963 (0.858–1.03)	1,262
	2013–2014	0.380 (0.355–0.407)	0.414 (0.374–0.452)	0.641 (0.604–0.684)	0.883 (0.820–0.951)	1.11 (1.04–1.26)	1,318
	2015–2016	0.397 (0.376–0.420)	0.434 (0.405–0.466)	0.651 (0.609–0.692)	0.860 (0.815–0.954)	1.08 (0.960–1.19)	1,524
	2017–2018	0.419 (0.375–0.468)	0.427 (0.388–0.466)	0.679 (0.611–0.738)	1.03 (0.906–1.15)	1.47 (1.20–1.88)	1,381

Table 5-18. Geometric Mean and Selected Percentiles of Urinary Cobalt (in µg/L) for the U.S. Population from NHANES

	Survey years	Geometric mean (95% CI)	Selected percentiles (95% CI)				Sample size
			50th	75th	90th	95th	
Females	2011–2012	0.335 (0.310–0.361)	0.340 (0.308–0.382)	0.591 (0.554–0.643)	1.07 (0.891–1.20)	1.49 (1.30–1.74)	1,242
	2013–2014	0.402 (0.374–0.432)	0.398 (0.366–0.438)	0.741 (0.701–0.789)	1.16 (1.06–1.23)	1.5 (1.36–1.75)	1,346
	2015–2016	0.432 (0.397–0.469)	0.433 (0.391–0.489)	0.752 (0.675–0.865)	1.33 (1.20–1.43)	1.82 (1.54–2.13)	1,537
	2017–2018	0.428 (0.391–0.469)	0.446 (0.410–0.487)	0.760 (0.694–0.835)	1.26 (1.19–1.33)	1.61 (1.47–1.79)	1,427
Race/ethnicity							
Mexican American	2011–2012	0.350 (0.322–0.381)	0.350 (0.307–0.377)	0.550 (0.490–0.598)	0.891 (0.721–1.18)	1.41 (1.14–2.08)	317
	2013–2014	0.415 (0.378–0.456)	0.439 (0.400–0.482)	0.686 (0.610–0.766)	0.918 (0.866–1.09)	1.15 (1.06–1.56)	453
	2015–2016	0.469 (0.431–0.511)	0.488 (0.431–0.558)	0.777 (0.688–0.852)	1.21 (1.01–1.42)	1.81 (1.32–2.14)	585
	2017–2018	0.431 (0.397–0.468)	0.437 (0.410–0.474)	0.708 (0.626–0.815)	1.14 (0.997–1.27)	1.39 (1.23–1.70)	435
Non-Hispanic black	2011–2012	0.340 (0.311–0.373)	0.333 (0.304–0.358)	0.519 (0.489–0.576)	0.909 (0.790–0.986)	1.44 (1.06–1.60)	669
	2013–2014	0.468 (0.410–0.535)	0.471 (0.402–0.561)	0.796 (0.691–0.877)	1.26 (1.03–1.39)	1.5 (1.35–1.67)	581
	2015–2016	0.461 (0.422–0.503)	0.478 (0.436–0.513)	0.740 (0.660–0.845)	1.20 (0.956–1.40)	1.52 (1.34–1.85)	671
	2017–2018	0.470 (0.443–0.499)	0.476 (0.430–0.514)	0.718 (0.657–0.806)	1.26 (1.04–1.55)	1.86 (1.29–2.35)	639
Non-Hispanic white	2011–2012	0.320 (0.295–0.348)	0.320 (0.296–0.357)	0.543 (0.485–0.591)	0.858 (0.750–0.995)	1.2 (1.03–1.35)	820
	2013–2014	0.374 (0.349–0.401)	0.387 (0.345–0.429)	0.681 (0.638–0.723)	1.02 (0.930–1.10)	1.34 (1.21–1.56)	985
	2015–2016	0.402 (0.374–0.432)	0.422 (0.386–0.454)	0.675 (0.627–0.734)	1.00 (0.938–1.11)	1.49 (1.24–1.71)	924
	2017–2018	0.411 (0.372–0.454)	0.428 (0.391–0.446)	0.702 (0.640–0.759)	1.11 (0.958–1.33)	1.57 (1.31–1.89)	918
All Hispanic	2011–2012	0.338 (0.321–0.357)	0.326 (0.306–0.350)	0.530 (0.490–0.583)	0.891 (0.763–1.14)	1.41 (1.10–1.81)	573
	2013–2014	0.412 (0.384–0.442)	0.442 (0.409–0.481)	0.674 (0.631–0.731)	0.964 (0.891–1.07)	1.2 (1.09–1.36)	701
	2015–2016	0.440 (0.417–0.465)	0.465 (0.431–0.514)	0.718 (0.662–0.795)	1.16 (0.991–1.34)	1.69 (1.34–2.03)	982
	2017–2018	0.441 (0.420–0.463)	0.451 (0.427–0.478)	0.742 (0.696–0.829)	1.20 (1.07–1.30)	1.41 (1.31–1.70)	676

Table 5-18. Geometric Mean and Selected Percentiles of Urinary Cobalt (in µg/L) for the U.S. Population from NHANES

	Survey years	Geometric mean (95% CI)	Selected percentiles (95% CI)				Sample size
			50th	75th	90th	95th	
Asian	2011–2012	0.317 (0.282–0.357)	0.323 (0.300–0.355)	0.519 (0.445–0.634)	0.968 (0.723–1.58)	1.78 (0.980–2.31)	353
	2013–2014	0.362 (0.315–0.416)	0.354 (0.312–0.434)	0.653 (0.578–0.789)	1.05 (0.854–1.25)	1.57 (1.09–2.26)	292
	2015–2016	0.376 (0.334–0.424)	0.365 (0.342–0.438)	0.610 (0.533–0.698)	0.990 (0.734–1.37)	1.44 (0.990–2.31)	332
	2017–2018	0.416 (0.386–0.449)	0.462 (0.399–0.508)	0.759 (0.655–0.809)	1.15 (0.966–1.37)	1.64 (1.12–2.18)	365

CI = confidence interval; NHANES = National Health and Nutrition Examination Survey

Source: CDC (2022)

Table 5-19. Geometric Mean and Selected Percentiles of Urinary Cobalt (Creatinine Corrected) (in µg/g of Creatinine) for the U.S. Population from NHANES

	Survey years	Geometric mean (95% CI)	Selected percentiles (95% CI)				Sample size
			50th	75th	90th	95th	
Total							
	2011–2012	0.370 (0.349–0.391)	0.347 (0.330–0.371)	0.557 (0.513–0.593)	0.880 (0.768–1.03)	1.29 (1.12–1.46)	2,502
	2013–2014	0.452 (0.437–0.466)	0.443 (0.427–0.454)	0.656 (0.625–0.688)	0.969 (0.920–1.03)	1.31 (1.18–1.47)	2,663
	2015–2016	0.465 (0.447–0.484)	0.444 (0.421–0.464)	0.682 (0.636–0.722)	1.07 (0.999–1.16)	1.39 (1.24–1.52)	3,058
	2017–2018	0.462 (0.437–0.490)	0.435 (0.410–0.463)	0.697 (0.644–0.733)	1.12 (1.03–1.20)	1.55 (1.33–1.81)	2,806
Age group							
3–5 years	2015–2016	0.980 (0.919–1.05)	0.952 (0.875–1.01)	1.35 (1.22–1.48)	1.94 (1.65–2.10)	2.45 (2.03–2.98)	485
	2017–2018	0.974 (0.916–1.04)	0.978 (0.916–1.05)	1.31 (1.24–1.41)	1.91 (1.45–2.28)	2.29 (1.91–2.81)	403
6–11 years	2011–2012	0.567 (0.535–0.602)	0.571 (0.526–0.611)	0.778 (0.713–0.834)	1.19 (0.974–1.30)	1.38 (1.10–1.67)	398
	2013–2014	0.667 (0.614–0.725)	0.646 (0.593–0.704)	0.914 (0.853–0.986)	1.26 (1.09–1.40)	1.57 (1.24–2.13)	402
	2015–2016	0.757 (0.701–0.817)	0.732 (0.658–0.785)	1.03 (0.957–1.11)	1.37 (1.17–1.50)	1.7 (1.28–2.64)	379
	2017–2018	0.724 (0.667–0.787)	0.708 (0.653–0.755)	0.966 (0.873–1.04)	1.42 (1.17–1.75)	1.82 (1.29–2.69)	332
12–19 years	2011–2012	0.398 (0.349–0.455)	0.373 (0.316–0.441)	0.585 (0.454–0.700)	0.832 (0.688–1.09)	1.26 (0.830–2.77)	390
	2013–2014	0.497 (0.463–0.534)	0.480 (0.446–0.525)	0.692 (0.597–0.769)	0.920 (0.819–1.10)	1.3 (1.09–1.61)	451
	2015–2016	0.534 (0.504–0.565)	0.508 (0.455–0.552)	0.799 (0.697–0.939)	1.16 (1.05–1.42)	1.5 (1.33–1.78)	402
	2017–2018	0.465 (0.437–0.495)	0.423 (0.392–0.455)	0.723 (0.596–0.780)	1.00 (0.848–1.13)	1.23 (1.05–1.38)	364
≥20 years	2011–2012	0.349 (0.330–0.369)	0.327 (0.300–0.341)	0.508 (0.467–0.552)	0.803 (0.711–0.982)	1.24 (1.10–1.50)	1,714
	2013–2014	0.428 (0.412–0.444)	0.417 (0.390–0.441)	0.607 (0.580–0.643)	0.929 (0.853–0.994)	1.27 (1.10-1.46)	1,810
	2015–2016	0.420 (0.402–0.439)	0.404 (0.384–0.426)	0.582 (0.551–0.616)	0.900 (0.809–1.03)	1.2 (1.05–1.41)	1,792
	2017–2018	0.425 (0.397–0.454)	0.397 (0.367–0.432)	0.591 (0.544–0.665)	1.02 (0.892–1.16)	1.46 (1.20–1.81)	1,707
Sex							
Males	2011–2012	0.297 (0.280–0.315)	0.276 (0.254–0.294)	0.426 (0.397–0.456)	0.637 (0.564–0.750)	0.865 (0.748–1.17)	1,261
	2013–2014	0.379 (0.362–0.398)	0.368 (0.344–0.390)	0.529 (0.493–0.560)	0.758 (0.689–0.852)	1.02 (0.871–1.29)	1,317
	2015–2016	0.377 (0.360–0.395)	0.348 (0.334–0.379)	0.526 (0.483–0.550)	0.839 (0.746–0.913)	1.08 (0.966–1.18)	1,524
	2017–2018	0.390 (0.363–0.420)	0.360 (0.334–0.392)	0.563 (0.508–0.593)	0.924 (0.799–1.08)	1.33 (1.11–1.59)	1,380

Table 5-19. Geometric Mean and Selected Percentiles of Urinary Cobalt (Creatinine Corrected) (in µg/g of Creatinine) for the U.S. Population from NHANES

	Survey years	Geometric mean (95% CI)	Selected percentiles (95% CI)				Sample size
			50th	75th	90th	95th	
Females	2011–2012	0.455 (0.418–0.496)	0.433 (0.407–0.466)	0.660 (0.600–0.729)	1.10 (0.900–1.36)	1.54 (1.28–1.84)	1,241
	2013–2014	0.534 (0.515–0.553)	0.532 (0.502–0.549)	0.774 (0.733–0.816)	1.12 (0.991–1.27)	1.48 (1.27–1.77)	1,346
	2015–2016	0.568 (0.540–0.598)	0.533 (0.511–0.563)	0.799 (0.760–0.869)	1.24 (1.16–1.40)	1.7 (1.48–1.98)	1,534
	2017–2018	0.544 (0.513–0.577)	0.498 (0.468–0.543)	0.815 (0.764–0.866)	1.22 (1.14–1.36)	1.71 (1.45–1.98)	1,426
Race/ethnicity							
Mexican American	2011–2012	0.394 (0.357–0.435)	0.374 (0.322–0.400)	0.576 (0.531–0.637)	1.02 (0.877–1.24)	1.5 (.988–2.02)	317
	2013–2014	0.474 (0.449–0.500)	0.448 (0.425–0.473)	0.669 (0.610–0.721)	0.971 (0.888–1.03)	1.28 (1.03–1.51)	453
	2015–2016	0.512 (0.479–0.548)	0.488 (0.464–0.533)	0.771 (0.690–0.850)	1.18 (1.01–1.40)	1.5 (1.37–1.79)	584
	2017–2018	0.465 (0.432–0.500)	0.437 (0.378–0.497)	0.708 (0.662–0.786)	1.14 (1.00–1.25)	1.45 (1.19–1.57)	433
Non-Hispanic Black	2011–2012	0.265 (0.248–0.282)	0.244 (0.222–0.267)	0.401 (0.342–0.457)	0.645 (0.559–0.816)	1.02 (.737–1.41)	669
	2013–2014	0.356 (0.332–0.382)	0.337 (0.315–0.377)	0.545 (0.490–0.624)	0.841 (0.754–0.952)	1.08 (.930–1.22)	581
	2015–2016	0.366 (0.347–0.386)	0.342 (0.328–0.377)	0.556 (0.504–0.595)	0.799 (0.696–0.972)	1.07 (.929–1.24)	669
	2017–2018	0.355 (0.337–0.375)	0.330 (0.295–0.351)	0.576 (0.500–0.611)	0.885 (0.798–1.02)	1.28 (.979–1.61)	639
Non-Hispanic White	2011–2012	0.387 (0.360–0.417)	0.365 (0.336–0.400)	0.574 (0.513–0.615)	0.860 (0.749–1.09)	1.29 (1.04–1.57)	818
	2013–2014	0.461 (0.442–0.480)	0.447 (0.430–0.469)	0.669 (0.613–0.703)	0.987 (0.912–1.13)	1.32 (1.19–1.61)	984
	2015–2016	0.475 (0.453–0.497)	0.457 (0.427–0.471)	0.686 (0.629–0.746)	1.07 (0.972–1.20)	1.41 (1.19–1.63)	924
	2017–2018	0.476 (0.439–0.517)	0.446 (0.415–0.473)	0.700 (0.605–0.760)	1.14 (1.02–1.33)	1.64 (1.29–1.98)	918
All Hispanic	2011–2012	0.379 (0.351–0.409)	0.361 (0.322–0.384)	0.572 (0.520–0.626)	0.944 (0.809–1.15)	1.33 (1.13–1.91)	573
	2013–2014	0.460 (0.444–0.475)	0.448 (0.429–0.464)	0.663 (0.619–0.703)	0.952 (0.888–1.00)	1.17 (1.03–1.35)	701
	2015–2016	0.497 (0.468–0.527)	0.465 (0.436–0.503)	0.748 (0.669–0.837)	1.16 (1.04–1.28)	1.46 (1.35–1.70)	981
	2017–2018	0.475 (0.450–0.503)	0.454 (0.423–0.498)	0.719 (0.671–0.781)	1.13 (1.02–1.24)	1.45 (1.25–1.57)	674

Table 5-19. Geometric Mean and Selected Percentiles of Urinary Cobalt (Creatinine Corrected) (in µg/g of Creatinine) for the U.S. Population from NHANES

	Survey years	Geometric mean (95% CI)	Selected percentiles (95% CI)				Sample size
			50th	75th	90th	95th	
Asian	2011–2012	0.424 (0.378–0.475)	0.386 (0.329–0.457)	0.659 (0.531–0.785)	1.18 (0.907–1.51)	1.61 (1.14–2.72)	353
	2013–2014	0.567 (0.516–0.624)	0.540 (0.482–0.567)	0.814 (0.670–0.931)	1.38 (1.07–1.97)	2.09 (1.39–3.78)	292
	2015–2016	0.514 (0.473–0.559)	0.475 (0.421–0.548)	0.736 (0.624–0.885)	1.30 (1.11–1.57)	1.66 (1.44–2.12)	332
	2017–2018	0.544 (0.504–0.588)	0.511 (0.450–0.569)	0.830 (0.768–0.882)	1.39 (1.04–1.70)	1.86 (1.40–2.28)	365

CI = confidence interval; NHANES = National Health and Nutrition Examination Survey

Source: CDC (2022)

Table 5-20. Geometric Mean and Selected Percentiles of Blood Cobalt (in µg/L) for the U.S. Population from NHANES

	Survey years	Geometric mean (95% CI)	Selected percentiles (95% CI)[a]				Sample size
			50th	75th	90th	95th	
Total	2015–2016	0.151 (0.146–0.156)	0.130 (0.130–0.140)	0.170 (0.170–0.180)	0.280 (0.250–0.300)	0.400 (0.370–0.450)	3,454
	2017–2018	0.173 (0.167–0.180)	0.160 (0.150–0.160)	0.200 (0.190–0.210)	0.310 (0.280–0.330)	0.430 (0.380–0.480)	3,520
Age group							
40–59 years	2015–2016	0.144 (0.138–0.150)	0.130 (0.120–0.130)	0.160 (0.150–0.170)	0.260 (0.220–0.290)	0.360 (0.300–0.440)	1,726
	2017–2018	0.166 (0.158–0.175)	0.150 (0.150–0.160)	0.180 (0.180–0.200)	0.270 (0.250–0.320)	0.420 (0.330–0.450)	1,587
≥60 years	2015–2016	0.162 (0.155–0.168)	0.140 (0.140–0.150)	0.190 (0.180–0.200)	0.300 (0.270–0.370)	0.450 (0.390–0.520)	1,728
	2017–2018	0.183 (0.176–0.189)	0.160 (0.160–0.170)	0.210 (0.200–0.230)	0.340 (0.310–0.370)	0.470 (0.380–0.570)	1,933
Sex							
Male	2015–2016	0.135 (0.129–0.142)	0.120 (0.120–0.130)	0.150 (0.140–0.160)	0.210 (0.190–0.240)	0.360 (0.250–0.400)	1,661
	2017–2018	0.162 (0.154–0.170)	0.150 (0.140–0.150)	0.180 (0.180–0.180)	0.250 (0.230–0.280)	0.380 (0.290–0.500)	1,717
Female	2015–2016	0.167 (0.161–0.173)	0.150 (0.140–0.150)	0.200 (0.190–0.210)	0.320 (0.280–0.360)	0.460 (0.410–0.550)	1,793
	2017–2018	0.185 (0.178–0.191)	0.170 (0.160–0.170)	0.220 (0.200–0.240)	0.340 (0.310–0.390)	0.470 (0.410–0.560)	1,803
Race/ethnicity							
Mexican American	2015–2016	0.151 (0.146–0.157)	0.130 (0.120–0.140)	0.170 (0.160–0.190)	0.300 (0.240–0.360)	0.440 (0.350–0.610)	592
	2017–2018	0.172 (0.162–0.183)	0.160 (0.150–0.160)	0.180 (0.170–0.200)	0.280 (0.240–0.340)	0.400 (0.290–0.660)	440
Non-Hispanic Black	2015–2016	0.148 (0.138–0.159)	0.130 (0.120–0.140)	0.180 (0.160–0.190)	0.280 (0.250–0.340)	0.440 (0.390–0.500)	718
	2017–2018	0.163 (0.154–0.173)	0.150 (0.140–0.160)	0.190 (0.180–0.200)	0.270 (0.240–0.310)	0.370 (0.310–0.430)	816
Non-Hispanic White	2015–2016	0.151 (0.145–0.157)	0.130 (0.130–0.140)	0.170 (0.160–0.190)	0.270 (0.240–0.290)	0.390 (0.330–0.450)	1,198
	2017–2018	0.176 (0.169–0.184)	0.160 (0.150–0.160)	0.200 (0.190–0.220)	0.320 (0.280–0.370)	0.450 (0.380–0.590)	1,272
All Hispanic	2015–2016	0.150 (0.145–0.154)	0.130 (0.120–0.140)	0.170 (0.160–0.180)	0.300 (0.240–0.360)	0.440 (0.350–0.560)	1,067
	2017–2018	0.169 (0.161–0.177)	0.150 (0.150–0.160)	0.180 (0.180–0.190)	0.290 (0.260–0.320)	0.410 (0.330–0.530)	775

Table 5-20. Geometric Mean and Selected Percentiles of Blood Cobalt (in μg/L) for the U.S. Population from NHANES

	Survey years	Geometric mean (95% CI)	Selected percentiles (95% CI)[a] 50th	75th	90th	95th	Sample size
Asian	2015–2016	0.152 (0.145–0.160)	0.140 (0.130–0.150)	0.170 (0.160–0.180)	0.290 (0.210–0.370)	0.380 (0.290–0.620)	368
	2017–2018	0.181 (0.173–0.189)	0.170 (0.160–0.170)	0.200 (0.190–0.220)	0.290 (0.270–0.330)	0.420 (0.310–0.480)	486

[a] The LOD for 2015–2016 and 2017–2018 is 0.06 μg/L.

CI = confidence interval; LOD = limit of detection; NHANES = National Health and Nutrition Examination Survey

Source: CDC (2023)

Junque et al. (2020) analyzed urinary cobalt in 4-year-old children in a heavily industrialized zone in Spain. Higher urinary cobalt was associated with consumption of sweets, inhalation of traffic pollution, and iron deficiency anemia. Cao et al. (2014) found that children living near the largest coking plant in China had median blood cobalt levels of 1.12 μg/dL. Mean cobalt concentrations were measured in the soil (12.0 mg/kg), dust (8.85 mg/kg), ambient air (0.03 μg/m^3), drinking water (0.14 μg/m^3), vegetables (0.11 mg/kg), and staple food (0.22 mg/kg) (Cao et al. 2014). Children may also be exposed to cobalt in costume jewelry, detergents, and cosmetics (Brandao and Gontijo 2012).

Dabeka and McKenzie (1995) estimated that the dietary cobalt intake by Canadian children ages 1–19 years ranged from 7 to 14 μg/day. Milk constitutes a larger part of children's diets than that of adults, and infants may consume infant formula. Cobalt concentrations ranging from 0.3 to 0.8 ng/g in cow's milk were reported by Iyengar (IAEA 1982). The levels of cobalt in human breast milk from Nigeria, Zaire, Guatemala, Hungary, Philippines, and Sweden ranged from 150 ng/g (Hungary) to 1,400 ng/g (Philippines), median 320 ng/g (Nriagu 1992). Garg et al. (1993) reported much lower cobalt levels in three samples of human breast milk in India, 2.42 ng/g, and reported a cobalt concentration of 5.07 ng/g in cow's milk in India. Dabeka (1989) determined cobalt levels in various infant formulas. Milk-based infant formulas and evaporated milk contained <1 ng/g of cobalt on a "ready-to-use" basis. Milk-based formulas with added iron contained about twice the cobalt as those with no added iron, and soy-based formulas contained about 5 times more cobalt. Using literature values of cobalt in food, Dabeka (1989) also estimated that infants 0–12 months old ingest an average of 0.52 μg Co/kg-day (3.93 μg/day) from food and water and that the total dietary cobalt intake would range from 0.42 μg/kg-day (3.39 μg/day) for a breastfed or milk-based formula-fed infant to 1.0 μg/kg-day (7.33 μg/day) for an infant fed soy-based formula powder. In a 1967 study of the total dietary intake of some trace elements, excluding drinking water, of institutionalized children aged 9–12 years in 28 U.S. cities, cobalt intake ranged from 0.297 to 1.767 mg/day, with a mean value of 1.024 mg/day (Murthy et al. 1971).

5.7 POPULATIONS WITH POTENTIALLY HIGH EXPOSURES

Workers in the hard metal industry (tool production, grinding, etc.); coal mining; metal mining, smelting, and refining; lithium-cobalt battery production or recycling (including electric vehicle batteries); cobalt dye painting industry; and cobalt chemical production can be exposed to higher levels of cobalt via airborne dust and direct contact. Of these industries, the largest group is the hard metal industry. Kennedy et al. (2017) estimates that through 2008, up to 14,348 individuals in the United States worked in the hard metal industry. Industrial foundry processes generate metal dust and fumes, and occupational exposure has been demonstrated in some metal workers (Freire et al. 2021; Linauskiene et al. 2021). Exposure to cobalt during the wet grinding of hard metal tools is especially high when local exhausts are not in use (Sesana et al. 1994). However, with increases in electric vehicle battery production and recycling in the early 2020s to meet the U.S. mandate to phase out fossil fueled activities from 2023 to 2050 (WH 2021a, 2021b), the population of workers with greatest risk of exposure may shift in future years.

The majority of occupational exposure data is from the hard metal industry. Historical concentrations of cobalt in the air of hard metal manufacturing, welding, and grinding factories may range from 1 to 300 μg/m^3, compared to normal atmospheric levels of 0.4–2.0 ng/m^3 (Haddad and Zikovsky 1985; Koponen et al. 1982; Lichtenstein et al. 1975; Marsh et al. 2017a, 2017b; NIOSH 1989; Sauni et al. 2017; Svartengren et al. 2017). Data collected in hard metal factories since 2000 show a decrease in the uppermost reported concentrations, ranging from 0.9 to 190 μg/m^3 (Al-Abcha et al. 2021; Andersson et al. 2020, 2021; Hamzah et al. 2014; Hedbrant et al. 2022; Lantin et al. 2011, 2013). The maximum Occupational Safety and Health Administration (OSHA) permissible level is 100 μg/m^3.

The concentration of cobalt in the dust of an electric welding factory was 4.2 μg/g compared to its normal dust level of 0.1–1.0 μg/g (Baumgardt et al. 1986). The higher rate of exposure to cobalt for occupational groups is also reflected in the higher cobalt content in tissues and body fluids of living and deceased workers in this group. The levels of cobalt in the urine of workers in the hard metal industry varied with the levels of cobalt concentration in the working atmosphere. At a concentration of 0.09 mg/m^3, the urinary excretion of cobalt exceeded normal values by orders of magnitude. When the cobalt concentration in the working atmosphere was ≤0.01 mg/m^3, urinary cobalt excretion was 4–10 times higher than normal level (Alexandersson 1988; Scansetti et al. 1985). At high exposure levels, the cobalt concentration in blood was 20 times higher than normal; in the low exposure group, it was only slightly higher than in the control group (Alexandersson 1988).

In the hard metal industry in Japan, Kumagai et al. (1996) found that mean 8-hour TWAs of airborne cobalt were >50 μg/m^3 for workers involved in powder preparation (shift rotation that included varied work hours that were less than full time), powder preparation (full-time), rubber press, and shaping operations; mean atmospheric concentrations were 459, 147, 339, and 97 μg/m^3, respectively. Workers involved in the manufacture and maintenance of hard metal and Stellite^{TM} blades in Finland were exposed to breathing zone cobalt concentrations ranging from 2 to 240 μg/m^3, with a geometric mean of 17 μg/m^3 (Linnainmaa et al. 1996). The average proportion of water-soluble cobalt in airborne cobalt was 68%

(range 14–100%). Wet grinding was not sufficient to adequately control cobalt levels and coolant cobalt levels were high. In a group of 12 factories in Italy in which 48 workers who had been exposed to cobalt in operations such as sharpening with diamond grinding stones were tested; the mean concentrations of cobalt in air were 21.2 and 137.7 μg/m^3 (PEL-TWA 100 μg/m^3) in workplaces with and without dust ventilation, respectively (Imbrogno and Alborghetti 1994).

In a metal finishing plant located in Turkey, aerosol samples were collected over an 8-hour period from the breathing zone at a dipping bath (Onat et al. 2020). Cobalt in total suspended particles was 69.9×10^{-6} mg/m^3. In different fractions, cobalt was identified at concentrations of approximately 2.9×10^{-6} mg/m^3 in size fraction PM<0.25, 14.6×10^{-6} mg/m^3 in size fraction $PM_{0.25–0.5}$, 6.3×10^{-6} mg/m^3 in size fraction $PM_{0.5}$–1.0, 23.8×10^{-6} mg/m^3 in size fraction $PM_{1.0}$, 12.1×10^{-6} mg/m^3 in size fraction $PM_{1.0–2.5}$, 35.9×10^{-6} mg/m^3 in size fraction $PM_{2.5}$, and 34.0×10^{-6} mg/m^3 in size fraction $PM_{>2.5}$. Concentrations of cobalt detected in the air of an industrial foundry (Brazilian ferrous foundry industry producing automobile parts) ranged from 0.006 to 0.344 μg/m^3, with an average concentration of 0.047±0.062 μg/m^3. In urine (n=194) and blood (n=167) samples collected from the foundry workers, cobalt concentrations ranged from 0.05 to 1.44 μg/L (mean 0.51±0.23 μg/L, NHANES 75th percentile for men) and from 0.05 to 1.82 μg/L (mean 0.12±0.15 μg/L, NHANES 50th percentile for men), respectively. Cobalt concentrations in urine increased with employment duration. Additionally, cobalt particulate concentrations correlated linearly with urine levels from workers performing pan operation and furnace activities (Freire et al. 2021).

Gallorini et al. (1994) found that the ratio of inorganic to organic cobalt in the urine of hard metal workers was 2.3 compared to 1.01 in controls; the ratio was constant over the range of urinary cobalt levels analyzed (180–1,254 μg/L). Exposure to cobalt during the wet grinding of hard metal tools (Widia tools) used in the wood industry produced exposure to cobalt above the PEL-TWA of 100 μg/m^3 (Sesana et al. 1994). However, exhausts added to reduce breathing zone concentrations near the grinding wheels were shown to substantially reduce exposure levels. In the processing department of a small company producing carbide tip saw blades for the woodworking industry, area air sampling showed that exposure levels were low in all departments except tip grinding processes. Wet and dry tip grinding areas were assessed for total airborne cobalt and contained 55 and 21 μg/m^3 of cobalt, respectively (Stebbins et al. 1992). For the method collecting respirable particles, cobalt levels ranged from 2 to 28 μg/m^3. Wet grinding is a traditional method for controlling dust during grinding. However, some coolants may contain significant concentrations of cobalt (in this case, 61–538 mg/mL) that can contribute to exposure during grinding (Stebbins et al. 1992).

Measurements of hair, blood, and urine samples of non-exposed males, steel mill production workers, and steel mill quality control workers aged 22–55 years showed that cobalt concentrations in biological samples of exposed workers are significantly higher than non-exposed individuals, indicating different exposure extent (Afridi et al. 2009). Horng et al. (2003) also found that mean urinary cobalt levels were significantly higher in steel plant production workers (8.18±2.73 µg/L) and quality control workers (7.39±1.26 µg/L) than in the control population (0.92±8.13 µg/L). Mean urinary cobalt increased 1.5–3-fold in workers during a shift in a digital video cassette manufacturing plant (Fujio et al. 2009). Cobalt concentrations then decreased before the next shift, supporting that the results were occupationally derived. These urinary concentrations also had a significant correlation with cobalt oxide measurements in the air (Fujio et al. 2009).

A study in the United States determined the concentrations of trace metals in seminal plasma in industrial workers in a petroleum refinery, smelter, and chemical plant as compared with those of hospital workers (control group). There were four groups each with 50 adult men. The mean cobalt concentrations (µg/dL), including standard errors, were determined to be 31±2 (hospital workers), 25±0.8 (metal ore smelter workers), 19±0.6 (petroleum refinery workers), and 22±1 (chemical workers) (Dawson et al. 2000). Ferdenzi et al. (1994) obtained a correlation between Friday TWA air cobalt levels and Friday end-of-shift urine levels among women in the powder sintering industry. Median urinary cobalt concentrations were 25 µg/L (range 1–51 µg/L) and 29 (range 3–159 µg/L), on Monday and Friday before the shift, respectively, and 85 µg/L (range 6–505 µg/L) on Friday after the shift. Imbrogno and Alborghetti (1994) evaluated the levels of occupational exposure to cobalt during dry and/or wet hard metal sharpening. The mean urine cobalt level in the workers in 12 factories was found to range from 0 to 40.3 µg/L and the maximum was 86 µg/L. The average urinary cobalt level among workers using wet/mixed sharpening methods was 4 times higher than those using dry sharpening methods (21.38 µg/L as compared to 5 µg/L, respectively).

In a study of metal exposure in three cemented tungsten carbide production facilities, cobalt was found on the surfaces of all the work areas sampled (Day et al. 2009). Cobalt concentrations were significantly higher in the powder-handling facility than in the metal separation facility and the forming/machining facility, and on control panels, hand tools, containers, and ventilation equipment than on other surfaces (Day et al. 2009). The highest mean concentrations of cobalt on skin were measured on workers in the powder-handling facility, ranging from 154 to 1,328 µg on hands and from 7.8 to 342 µg on necks (Day et al. 2009). Kettelarij et al. (2018a) studied skin doses and exposure sources of workers in the hard metal industry, finding that the highest skin doses (median 1.51 µg/cm^2, range 0.25–28 µg/cm^2) occurred in workers handling raw materials. Skin doses in raw material workers were significantly higher than those in sintered material workers and office workers. Cobalt was measured on many different types of surfaces, including production equipment, canteen, handles and buttons, common areas, personal work equipment, private items, changing rooms, and office items (Kettelarij et al. 2018a). Julander et al. (2010) studied skin deposition in 24 workers who worked in the development and manufacturing of gas turbines and space propulsion structures; study participants were tasked with sharpening tools, producing combustion structures, and thermal application of metal-containing powders. Cobalt could be found on all skin surfaces of the forehead and hands. The department with the highest cobalt exposure was the tools sharpening department, in which the highest level detected was 4.5 µg/cm^2/hour on the thumb.

Lungs taken from deceased, occupationally exposed workers also had higher levels of cobalt than lungs from control groups. Lungs of deceased hard metal industry workers in Sweden contained 2.5–4 times higher levels of cobalt than control lungs (Gerhardsson et al. 1988). Similarly, the lungs of coal miners from England contained 6 times higher cobalt levels than control lungs (Hewitt 1988).

Exposure information in other industries is limited. In a Japanese nickel-hydrogen battery plant, workers were exposed to a mixture of metallic cobalt, cobalt oxyhydroxide, and nickel hydroxide dust (Yokota et al. 2007). Measured breathing zone air levels of cobalt over 2 consecutive working days ranged from 4 to 330 µg/m^3 (mean of 67 µg/m^3). On day 1, urinary cobalt levels increased from 10.7 µg pre-shift to 38.6 µg post-shift. Day 2 levels were more stable, at 25.7 µg pre-shift and 28.2 µg post-shift. Urinary levels were not well correlated with air levels; the study authors attributed this to use of respirators by workers (Yokota et al. 2007). Among cobalt blue dye plate painters in a porcelain factory in Denmark, the blood and urine cobalt levels were, respectively, 2–4 and 5–15 times higher than in control groups (Raffin et al. 1988).

In addition to occupational exposure, the general population living near these industrial sites, hazardous waste sites, and agricultural areas that use sewage sludge, cobalt-containing fertilizers, or soil amendments may be exposed to high levels of cobalt in air and in soil. No experimental evidence of higher-than-normal exposures for populations near agricultural areas was found in the literature. People who live in areas that naturally contain higher levels of cobalt minerals may also be exposed to higher levels of cobalt from both the inhalation and dermal contact routes.

Exposure to stable cobalt in communities near current or historic mining and smelting facilities or metal shops where cobalt is used in grinding tools could be a public health concern. Concern is higher for infants and children due to closer proximity to the floor/ground, hand-to-mouth behavior, and intentional ingestion of soil that could contain cobalt contaminants (Hamel et al. 1998). In the case of children playing in and around unrestricted landfill sites, exposure via inhalation, oral, and dermal routes is possible. Cobalt-containing dust may be brought home in the clothing of parents working in cobalt-related industries and transferred to flooring on which children crawl and play. Data from communities near mining operations in the D.R. Congo confirm increased risk of exposure in children. Median measured urinary cobalt levels in children were nearly 3 times higher than values measured in adults from the same community; approximately 150 and 50 μg/g creatinine, respectively, based on graphically presented data (Banza Lubaba Nkulu 2018). This is consistent with children ingesting up to 1,800 mg/day of soil from typical mouthing behavior as they play and lie on grass and soil (ATSDR 2001).

A study of trace elements in dust, hair, nail, and serum samples in Punjab, Pakistan found that cobalt concentrations in dust samples were slightly higher in urban areas (3.0 ppm) than in industrial (2.0 ppm) or rural areas (1.7 ppm) (Mohmand et al. 2015). Cobalt levels were 0.04–0.5 ppm in hair samples and were similar at all sites. Levels in nail samples and serum were the highest in rural areas (Mohmand et al. 2015). A study of metal concentrations in air was conducted in four communities near metal recyclers in Houston, Texas (Han et al. 2020). Mean concentrations in the four communities ranged from 0.59 to 14.85 ng/m^3 (Han et al. 2020). Han et al. (2020) estimated that the cancer risks due to inhalation of cobalt were 0.25–6.9 cases per million at the fence line, 0.07–1.4 cases per million in near neighborhoods, and 0.05–0.30 cases per million in far neighborhoods. In a mining area of the D.R. Congo, mean urinary concentrations of cobalt were significantly higher in individuals living <3 km from the mining and refining operations (15.7 μg/g creatinine) than in control subjects (1.34 μg/g creatinine) (Banza et al. 2009). Mean urinary cobalt concentrations were 5.72 μg/g creatinine in individuals living between 3 and 10 km from mining and refining (Banza et al. 2009). Urinary cobalt exceeded 15 μg/g creatinine in 53% of all subjects living very close to mine pollution areas and in 87% of children living closest to mining and smelting sites (Banza et al. 2009). These levels are within or above the NHANES 95th percentile levels in Table 5-19. Cheyns et al. (2014) measured the concentrations of cobalt in urine samples and environmental media in communities close to metal mining and refining plants, lakes receiving effluents from metal refining plants, and control areas without pollution from the metal mining and refining industry. Mean urinary cobalt was 4.5 times higher in adults and 6.6 times higher in children in polluted areas (Cheyns et al. 2014). Mean cobalt concentrations were significantly higher in soil, outdoor and indoor dust, drinking water, maize flour, tubers, cassava leaves, sweet potato leaves, and other vegetable samples in polluted areas than in control areas (Cheyns et al. 2014).

Individuals working in other occupations who use cobalt-containing materials may also be at higher risk of cobalt exposure. Richter et al. (2002) found that opera singers were exposed to cobalt as pigment components in swept dust while working on stage. Cobalt was found at a concentration of 7.17 mg/kg dust in the fine dust swept from the stage (Richter et al. 2002). Cases of dermatitis have been reported in individuals who worked with polyester resins that contained cobalt as an accelerator (Anavekar and Nixon 2006; Cahill and Andersen 2010). Dental technicians who work with alloys and tools that release cobalt are at greater risk of exposure than the general population. A study of dental technicians in Sweden found that technicians exposed to a cobalt and chromium (CoCr) alloy in a 2-hour period without handwashing had more cobalt on the skin than non-exposed technicians (Kettelarij et al. 2016). Before work, the median concentrations of CoCr were 0.0012 μg/cm^3 in exposed technicians and 0.0017 μg/cm^3 in non-exposed technicians (Kettelarij et al. 2016). After 2 hours of work without hand washing, concentrations had increased to 0.15 μg/cm^3 for exposed individuals and 0.0026 μg/cm^3 for non-exposed individuals (Kettelarij et al. 2016). At the end of the day, the median concentrations had increased overall to 0.014 μg/cm^3 in exposed individuals and 0.0057 μg/cm^3 in non-exposed individuals (Kettelarij et al. 2016). Cobalt was found in all 10 air samples taken during this study at concentrations ranging from 0.22 to 155 μg/m^3 (Kettelarij et al. 2016). Metal urine concentrations were normal (Kettelarij et al. 2016). The exposed technicians had been preparing prostheses, metal constructions for dental crowns, and porcelain parts of dental crowns (Kettelarij et al. 2016). At least one case of occupational exposure to cobalt resulting in contact dermatitis has been reported in a baker, who frequently used metallic tools and baking sheets (Bregnbak et al. 2015a).

Surgical implants for knee and hip replacements often use cobalt-containing alloys, which may lead to elevated cobalt levels in body fluids. Indeed, cobalt levels in serum and urine have been used as an index of prosthesis wear. In some cases, significant increases in cobalt levels have been observed, while in other cases, elevations were much lower or only sporadic (IARC 1991). These differences have been ascribed to greater release rates from metal-to-metal than metal-to-polyethylene articular surfaces as well as to differences in the cobalt-containing alloys. The higher exposure of cobalt in patients with cobalt-chromium knee implants has been demonstrated by the slightly higher levels of cobalt in whole blood, serum, and urine, and by very high levels of cobalt in bone of these patients (IARC 1991; Ostapczuk et al. 1985; Sunderman et al. 1989). While the normal range of blood cobalt is 0.05–0.1 μg/L, one man who had undergone a hip replacement had a blood cobalt level of 14.3 μg/L (Briani et al. 2015). Prosthetic devices that contain polyethylene components to avoid metal-to-metal contact do not appear to cause elevated levels of cobalt in tissues or body fluids (IARC 1991; Ostapczuk et al. 1985; Sundaram et al. 2001). There has been at least one case of a cobalt allergy in a person with a prosthetic leg (Arslan et al. 2015). The potential for ototoxicity to be associated with cobalt exposure was addressed in several case and case control studies, primarily in patients with metal-on-metal hip replacements for which it was known or assumed that cobalt was a component. The health effects in these case-studies were self-reported, often lacked a dose-response relative to cobalt blood concentration, had a very small sample population, were not classifiable as to clinical dysfunction, or were not discernable between individuals whose implants did or did not contain cobalt (Ho et al. 2017; Leikin et al. 2013; Leyssens et al. 2021; Leyssens et al. 2020; Prentice et al. 2014). Two cases of hearing loss caused by massive deterioration or failure of metal hips were associated with neuropathy (Pazzaglia et al. 2011) or death (Zywiel et al. 2013). Transient hearing loss was reported in individuals undergoing cobalt therapy attempting to increase hematocrit (Bowie and Hurley 1975). Using data from the NHANES database of U.S. individuals surveyed between 2015 and 2018, it was observed that people with metal implants tended to have higher blood concentrations of cobalt; however, the study indicted several shortcomings, including a lack of controlled parameters to demonstrate a clear relationship between metal implants and blood cobalt ion levels (He et al. 2023). Similar to joint implants, individuals with cobalt-chrome alloy dental implants may have elevated exposure to cobalt (Thyssen et al. 2010, 2011).

People who use cobalt supplements as a treatment for anemia and those who take large amounts of vitamin B_{12} as a dietary supplement would have higher intakes of cobalt than the general population. In a study of four healthy adult males who volunteered to take cobalt supplements of 0.4 mg Co/day, after 15 or 16 days, mean whole blood cobalt was 3.6 μg/L, with a range of 1.8–5.1 μg/L (Tvermoes et al. 2013). Whole blood concentrations decreased to 1.1 μg/L 2 weeks post-dose (Tvermoes et al. 2013). Background concentrations are reported to be 0.1–0.4 μg/L (Tvermoes et al. 2013). Using a cobalt specific biokinetic model, Unice et al. (2012) estimated that 10 days of taking cobalt supplements at the recommended daily dose values of the European Food Safety Authority and the U.K. Expert Group on Vitamins and Minerals (600–1,400 μg/day) would result in mean whole blood concentrations of 5–12 μg/L and urinary concentrations of 57–130 μg/L after 30 days. After 1 year, mean whole blood concentrations would increase to 5.7–13 μg/L and urinary concentrations would increase to 66–150 μg/L (Unice et al. 2012).

Cobalt has been detected in tobacco from U.S. cigarettes at mean values of 0.44–1.11 μg/g dry tobacco and in popular smokeless tobacco products at concentrations of 0.26±0.02–1.22±0.05 μg/g (Fresquez et al. 2013; Pappas et al. 2008). People who smoke cigarettes or use smokeless tobacco products may be at higher risk of cobalt exposure.

Exposures to acute-duration radiation doses of 0.09–1.91 Gy and chronic-duration doses of 0.13–15.16 Gy were estimated from mathematical models and cytogenic dosimetry of two scrapyard employees and eight individuals living near a truck carrying contaminated rebar. The contaminated rebar was a result of a release of ^{60}Co from an incident in December 1983, in which steel foundries in Mexico and the United States processed contaminated material into construction materials that were shipped throughout North America (UNSCEAR 2011).