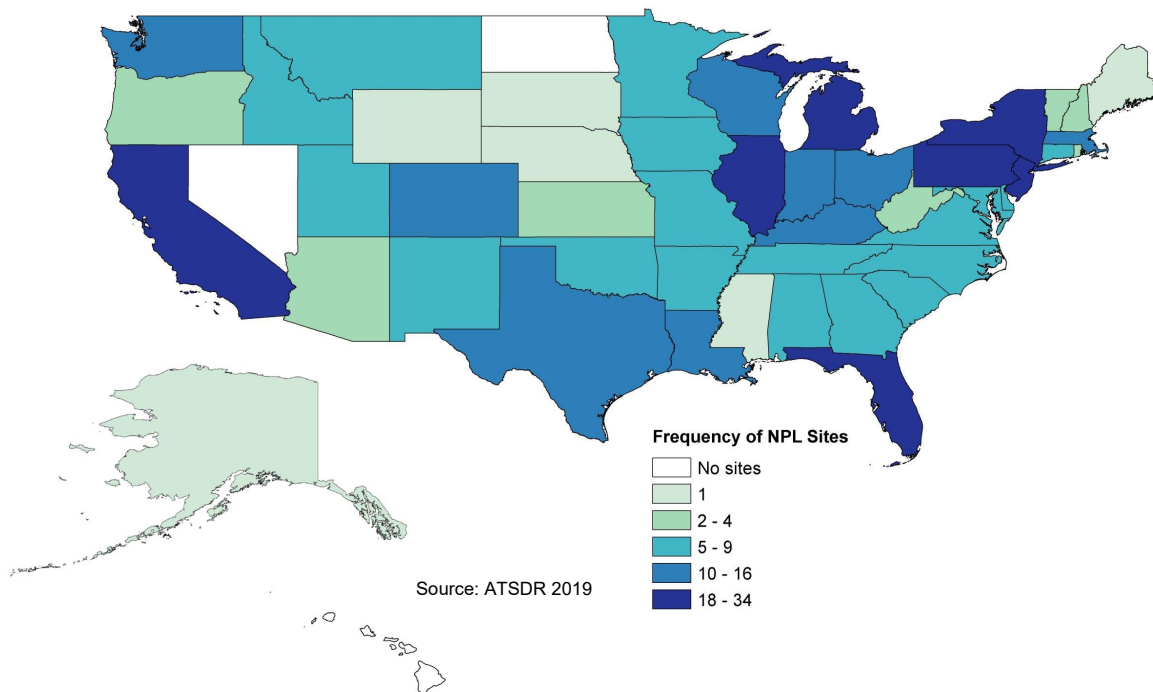


CHAPTER 5. POTENTIAL FOR HUMAN EXPOSURE

5.1. OVERVIEW

Cobalt has been identified in at least 425 of the 1,867 hazardous waste sites that have been proposed for inclusion on the Environmental Protection Agency (EPA) National Priorities List (NPL) (ATSDR 2019). However, the number of sites evaluated for cobalt is not known. The number of sites in each state is shown in Figure 5-1. Of these sites, 420 are located within the United States, 1 is located in the Virgin Islands, 3 are located in Puerto Rico, and 1 is located in Guam (not shown).

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



- In the U.S. cobalt is produced from deposits as a by-product of other metals. Cobalt is used in several commercial, industrial, and military applications. The leading use is in rechargeable batteries, followed by superalloys, and 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

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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 less than $0.002 \mu\text{g}/\text{m}^3$ (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, like 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 hard metal industry (tool production, grinding, etc.) and industries such as coal mining, metal mining, smelting, and refining, cobalt dye painters, and cobalt chemical production are exposed to higher levels of cobalt via airborne dust and direct contact. Populations living near these industrial sites are also exposed to higher levels of cobalt.

Cobalt occurs naturally in the earth's crust, and therefore, in soil. Low levels of cobalt also occur naturally in seawater and in some surface water and groundwater (Smith and Carson 1981). However, elevated levels of cobalt in soil and water may result from anthropogenic activities such as the mining and processing of cobalt-bearing ores, the application of cobalt-containing sludge or phosphate fertilizers to soil, the disposal of cobalt-containing wastes, and atmospheric deposition from activities such as the burning of fossil fuels and smelting and refining of metals (Smith and Carson 1981). Cobalt is released into the atmosphere from both anthropogenic and natural sources. However, emissions from natural sources are estimated to slightly exceed those from manufactured sources. Natural sources include windblown soil, seawater spray, volcanic eruptions, and forest fires. Primary anthropogenic sources include fossil fuel and waste combustion, 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).

Cobalt compounds are non-volatile, 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 $>2 \mu\text{m}$ (such as those obtained during ore processing), may deposit within 10 km

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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; King 1988; McLaren et al. 1986; Schnitzer 1969; Smith and Carson 1981; Swanson 1984). 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/m³. In several open-ocean environments, geometric mean concentrations ranged from 0.0004 to 0.08 ng/m³ (Chester et al. 1991). However, in source areas, cobalt levels may exceed 10 ng/m³; the highest average cobalt concentration recorded was 48 ng/m³ 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

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water is $<1\text{--}2\ \mu\text{g/L}$, although levels as high as $107\ \mu\text{g/L}$ 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 $20\text{--}25\ \text{mg/kg}$ (Abbasi et al. 1989; Greathouse and Craun 1978; Merian 1985; Smith and Carson 1981). Most soils contain $1\text{--}40\ \text{mg cobalt/kg}$; the average cobalt concentration in U.S. soils is $7.2\ \text{mg/kg}$ (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 $800\ \text{mg/kg}$ 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 $11\ \mu\text{g/day}$. 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 third most abundant element in the earth's crust, averaging approximately $17.3\ \text{ppm}$ (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 ($\text{Cu}(\text{Co},\text{Ni})_2\text{S}_4$), pentlandite ($(\text{Fe},\text{Ni},\text{Co})_9\text{S}_8$), linnaeite (Co_3S_4), siegenite ($(\text{Co},\text{Ni})_3\text{S}_4$), skutterudite ($(\text{Co},\text{Fe},\text{Ni})\text{As}_{2-3}$), safflorite ($(\text{Co},\text{Fe})\text{As}_2$), cobaltite (CoAsS), glaucodot ($(\text{Co},\text{Fe},\text{Ni})\text{AsS}$), erythrite ($\text{Co}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$), heterogenite ($\text{CoO}(\text{OH})$), and asbolane ($(\text{Ni},\text{Co})_{2-x}\text{Mn}(\text{O},\text{OH})_4 \cdot n\text{H}_2\text{O}$) (USGS 2017). The largest cobalt reserves are in the Congo (Kinshasa), Australia, Cuba, the Philippines, and Russia (USGS 2020). There is an estimated 1 million tons of cobalt resources in the United States; most of the U.S. cobalt deposits are in Minnesota, but other important

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deposits are in Alaska, California, Idaho, Michigan, Missouri, Montana, Oregon, and Pennsylvania (USGS 2020). Cobalt production from these deposits, except those in Idaho and Missouri, would be as a byproduct of another metal (USGS 2020). 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). The U.S. supply of cobalt is comprised mostly of imports and scrap (secondary production) (USGS 2020). In 2019, an estimated 2,700 metric tons of cobalt were recycled from scrap, while 500 metric tons were mined (USGS 2020). Cobalt is also found in meteorites and deep-sea nodules.

Cobalt is mined using a combination of conventional underground and open pit methods (Farjana et al. 2019). 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 Cu-Co 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).

Table 5-1 lists facilities in each state that manufacture, process, or use cobalt or cobalt compounds, the intended use, and the range of maximum amounts of these substances that are stored on site. In 2019, there were 331 reporting facilities that produced, processed, or used cobalt and 380 that produced, processed, or used cobalt compounds in the United States. The data listed in Table 5-1 are derived from the Toxics Chemicals Release Inventory (TRI) (TRI19 2020). Only certain types of facilities were required to report. Therefore, this is not an exhaustive list.

Table 5-1. Facilities that Produce, Process, or Use Cobalt or 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	1	10000	99999	1, 5, 12, 13, 14
AL	22	0	999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14
AR	8	1000	99999	1, 3, 5, 7, 8, 12,
AZ	12	1000	999999	1, 2, 5, 7, 8, 9, 10, 11, 12, 13, 14
CA	30	1000	999999	1, 2, 3, 6, 7, 8, 9, 10, 12, 13, 14
CO	4	1000	99999	1, 10, 11, 12, 13, 14
CT	12	100	999999	8, 11, 12
DE	1	1000	9999	8
FL	9	100	999999	1, 2, 3, 5, 8, 9, 10, 12, 14

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Table 5-1. Facilities that Produce, Process, or Use Cobalt or 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
GA	14	1000	999999	1, 2, 3, 4, 5, 6, 7, 8, 12, 13, 14
IA	10	10000	999999	7, 8
ID	3	100	99999	1, 2, 3, 4, 5, 7, 9, 12, 13, 14
IL	30	1000	9999999	1, 5, 7, 8, 10, 12, 13,
IN	42	0	999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
KS	16	0	9999999	1, 2, 3, 5, 6, 7, 8, 9, 10, 12, 14
KY	21	100	999999	1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13,
LA	24	0	999999	1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14
MA	11	100	999999	7, 8, 9, 11, 12
ME	3	0	99999	1, 5, 8
MI	35	0	999999	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14
MN	10	100	999999	1, 2, 5, 8, 9, 10, 12, 13
MO	8	0	999999	1, 5, 8, 12, 14
MS	10	1000	999999	1, 2, 3, 5, 7, 8, 9, 10, 13, 14
MT	2	10000	99999	1, 3, 4, 5, 6, 12, 13, 14
NC	31	0	9999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14
ND	3	100	99999	1, 5, 12, 13, 14
NE	4	1000	9999	1, 3, 4, 5, 7, 8, 9, 12, 13
NH	2	10000	99999	2, 3, 8, 11
NJ	9	100000	999999	2, 3, 4, 7, 8, 9, 10, 11, 12
NM	4	100	99999	1, 3, 4, 5, 9, 11, 12, 13
NV	12	0	9999999	1, 3, 4, 5, 7, 8, 12, 13, 14
NY	12	1000	9999999	2, 3, 7, 8, 9, 12, 14
OH	60	0	9999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
OK	18	1000	9999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14
OR	6	1000	999999	1, 2, 3, 7, 8, 12
PA	62	0	9999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12, 13, 14
PR	2	1000	99999	8
RI	1	10000	99999	7
SC	25	100	999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13
SD	2	1000	9999	8
TN	26	100	999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14
TX	46	0	999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
UT	3	100	99999	1, 3, 4, 8, 9, 10, 12, 13
VA	5	10000	999999	2, 3, 4, 6, 7, 8
WA	3	10000	999999	1, 2, 3, 4, 7, 10, 11, 14
WI	22	0	999999	1, 5, 7, 8, 10, 12
WV	10	100	999999	1, 2, 3, 4, 5, 7, 8, 9, 12, 13, 14

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Table 5-1. Facilities that Produce, Process, or Use Cobalt or 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
WY	3	1000	99999	1, 5, 10, 12, 13

^aPost office state abbreviations used.

^bAmounts on site reported by facilities in each state.

^cActivities/Uses:

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

Source: (TRI19 2020); Data are from 2019

5.2.2. Import/Export

According to USGS (2020) an estimated 13,600 metric tons of cobalt were imported into the United States in 2019. 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 3,830 to 6,960 metric tons between 2015 and 2019; exports in 2019 are estimated to be 4,000 metric tons (USGS 2020).

5.2.3 Use

In 2019 the estimated apparent consumption of cobalt in the U.S. 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, while another major use is in superalloys (USGS 2020). Other uses for cobalt include cemented carbides and diamond tools, controlled-expansion, and corrosion- and wear-resistant alloys, high-speed and strong yet ductile steels, and magnets. Chemical uses for cobalt include animal feed additives, catalysts in the chemical and petroleum industries, drying agents, dyes and pigments, glass decolorizers, ground coats for porcelain enamels,

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humidity indicators, magnetic recording media, rubber adhesion promoters for steel-belted radial tires, and vitamin B₁₂ (USGS 2019). 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). Some artist pastels contain cobalt as a pigment (Brock and Stopford 2003). In 2019, 46% of cobalt consumed in the U.S. 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).

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). According to TRI (TRI19 2020), 3.09 and 15 million pounds of cobalt were recycled onsite and offsite, respectively, in 2019. For cobalt compounds, 0.7 million pounds were recycled onsite and 3.04 million pounds were recycled offsite in 2019. Waste water 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.

5.3. RELEASES TO THE ENVIRONMENT

According to the Toxic Chemical Release Inventory (TRI), in 2019, total releases of cobalt to the environment (including air, water, soil, and underground injection) from 331 reporting facilities that produced, processed, or used cobalt were 445,819 pounds (TRI19 2020). Total releases of cobalt compounds from 380 reporting facilities were 4,620,079 pounds (TRI19 2020). Table 5-2 and Table 5-3 list the amounts released from these facilities grouped by state. Industrial sectors producing, processing, or using cobalt that contributed the greatest environmental releases in 2019 were metal mining and hazardous waste with 120,000 and 111,103 pounds, respectively. Industrial sectors producing, processing,

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or using cobalt compounds that contributed the greatest environmental releases in 2019 were hazardous waste and metal mining with 1,235,185 and 1,228,152, pounds, respectively.

The Toxics Release Inventory (TRI) data should be used with caution because only certain types of facilities are required to report (EPA 2005). This is not an exhaustive list. Manufacturing and processing facilities are required to report information to the TRI only if they employ ≥ 10 full-time employees; if their facility is included in Standard Industrial Classification (SIC) Codes 10 (except 1011, 1081, and 1094), 12 (except 1241), 20–39, 4911 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4931 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4939 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4953 (limited to facilities regulated under RCRA Subtitle C, 42 U.S.C. section 6921 et seq.), 5169, 5171, and 7389 (limited S.C. section 6921 et seq.), 5169, 5171, and 7389 (limited to facilities primarily engaged in solvents recovery services on a contract or fee basis); and if their facility produces, imports, or processes $\geq 25,000$ pounds of any TRI chemical or otherwise uses $>10,000$ pounds of a TRI chemical in a calendar year (EPA 2005).

Table 5-2. Releases to the Environment from Facilities that Produce, Process, or Use Cobalt

State ^c	RF ^d	Air ^e	Water ^f	UI ^g	Land ^h	Other ⁱ	Reported amounts released in pounds per year ^b		
							Total Release		On and off-site
							On-site ^j	Off-site ^k	
AL	8	164	66	0	24,023	38,000	24,230	38,024	62,253
AZ	2	56	0	0	78,000	0	78,056	0	78,056
AR	3	503	28	0	45	0	503	73	576
CA	18	125	23	0	62,720	1,539	58,182	6,225	64,407
CO	2	0	0	0	42,000	0	42,000	0	42,000
CT	11	576	275	0	501	1,005	587	1,770	2,357
FL	2	219	3	0	103	303	219	409	628
GA	6	475	63	0	360	3	477	424	900
ID	1	0	0	0	0	0	0	0	0
IL	12	480	7	0	33	28	481	67	548
IN	27	1,927	197	0	1,620	0	1,932	1,812	3,744
IA	6	42	0	0	0	0	42	0	42
KS	11	379	0	0	215	9	384	219	603
KY	6	12	3	0	1,920	59	14	1,980	1,994
LA	3	0	40	11,400	0	0	11,440	0	11,440
ME	2	40	0	0	0	357	40	357	397

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Table 5-2. Releases to the Environment from Facilities that Produce, Process, or Use Cobalt

Reported amounts released in pounds per year^b

State ^c	RF ^d	Air ^e	Water ^f	UI ^g	Land ^h	Other ⁱ	Total Release		
							On-site ^j	Off-site ^k	On and off-site
MA	11	74	27	0	2,547	3,809	88	6,369	6,457
MI	18	2,088	157	0	5,758	90	2,113	5,980	8,093
MN	5	2	0	0	0	0	2	0	2
MS	4	1	190	0	128	0	191	128	319
MO	5	268	0	0	5	0	273	0	273
NE	1	78	0	0	270	0	78	270	348
NV	5	1,102	3	0	28,953	0	29,913	145	30,058
NH	2	3	1	0	2,064	0	3	2,065	2,068
NJ	8	255	8	0	30,374	45	255	30,427	30,682
NY	11	288	24	0	29	2,367	293	2,415	2,708
NC	16	67	10	0	116	113	69	236	305
OH	29	171	192	0	22,361	15,023	5,729	32,017	37,747
OK	8	0	0	0	0	0	0	0	0
OR	4	335	25	0	3,496	148	342	3,662	4,004
PA	29	348	24	0	2,254	25,670	357	27,939	28,296
SC	9	102	40	0	6,440	0	119	6,463	6,582
SD	1	0	0	0	0	0	0	0	0
TN	9	885	64	0	866	0	1,351	464	1,816
TX	10	98	19	0	6,473	2	107	6,486	6,592
UT	1	10	5	0	5	0	10	10	20
VA	3	9	5	0	31	49	9	85	95
WV	1	240	47	0	0	0	240	47	287
WI	19	133	1,923	0	7,013	49	133	8,985	9,118
PR	2	0	0	0	5	0	0	5	5
Total	331	11,553	3,470	11,400	330,728	88,668	260,261	185,559	445,819

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.

^bData in TRI are maximum amounts released by each facility.

^cPost office state abbreviations are used.

^dNumber of reporting facilities.

^eThe sum of fugitive and point source releases are included in releases to air by a given facility.

^fSurface water discharges, wastewater treatment-(metals only), and publicly owned treatment works (POTWs) (metal and metal compounds).

^gClass I wells, Class II-V wells, and underground injection.

^hResource Conservation and Recovery Act (RCRA) subtitle C landfills; other onsite landfills, land treatment, surface impoundments, other land disposal, other landfills.

ⁱStorage only, solidification/stabilization (metals only), other off-site management, transfers to waste broker for disposal, unknown.

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Table 5-2. Releases to the Environment from Facilities that Produce, Process, or Use Cobalt

State ^c	RF ^d	Air ^e	Water ^f	UI ^g	Land ^h	Other ⁱ	Reported amounts released in pounds per year ^b		
							Total Release		On and off-site
							On-site ^j	Off-site ^k	

^jThe sum of all releases of the chemical to air, land, water, and underground injection wells.

^kTotal amount of chemical transferred off-site, including to POTWs.

RF = reporting facilities; UI = underground injection
Source: TRI19 2020; Data are from 2019

Table 5-3. Releases to the Environment from Facilities that Produce, Process, or Use Cobalt Compounds

State ^c	RF ^d	Air ^e	Water ^f	UI ^g	Land ^h	Other ⁱ	Reported amounts released in pounds per year ^b		
							Total Release		On and off-site
							On-site ^j	Off-site ^k	
AL	14	3,244	21,214	0	47,586	361	30,455	41,949	72,405
AK	1	1	7	0	14,000	0	14,008	0	14,008
AZ	10	526	255	0	331,754	152	330,630	2,057	332,687
AR	5	77	7	0	58,401	627	55,034	4,078	59,112
CA	13	84	32	0	46,295	1,163	44,545	3,030	47,574
CO	2	10	4	0	0	0	14	0	14
CT	1	750	0	0	0	0	750	0	750
DE	1	0	0	0	0	6	0	6	6
FL	7	125	0	0	11,796	0	11,921	0	11,921
GA	8	113	994	0	24,762	0	12,813	13,056	25,868
ID	2	1	0	0	231	0	228	4	232
IL	18	413	725	0	192,134	1,984	193,098	2,158	195,256
IN	15	880	173	0	143,261	1,058	124,570	20,802	145,372
IA	4	276	0	0	0	0	276	0	276
KS	5	23	7	0	22,502	803	32	23,303	23,335
KY	15	248	689	0	109,321	2,702	104,325	8,635	112,960
LA	21	1,282	6,534	31	244,993	5,849	213,425	45,264	258,689
ME	1	13	0	0	366	0	13	366	379
MI	17	606	105	0	513,839	5	491,880	22,675	514,555
MN	5	253	29	0	77	393	282	470	752
MS	6	30	303	45,873	3,092	406	47,060	2,644	49,704
MO	3	112	0	0	10,173	0	10,285	0	10,285
MT	2	64	0	0	20,603	22	20,667	22	20,689

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Table 5-3. Releases to the Environment from Facilities that Produce, Process, or Use Cobalt Compounds

State ^c	RF ^d	Reported amounts released in pounds per year ^b							Total Release	
		Air ^e	Water ^f	UI ^g	Land ^h	Other ⁱ	On-site ^j	Off-site ^k	On and off-site	
NE	3	21	0	0	2,768	0	1,371	1,418	2,789	
NV	8	1	19	0	669,232	0	648,148	38,324	686,472	
NJ	1	0	0	0	318	507	0	825	825	
NM	4	35	0	0	70,624	14,018	70,659	14,018	84,677	
NY	1	0	0	0	0	37	0	37	37	
NC	15	265	72	0	204,306	228	109,688	95,182	204,870	
ND	3	1,101	6	0	51,025	0	43,646	8,486	52,132	
OH	31	2,075	824	14,060	155,138	9,244	130,008	51,333	181,341	
OK	10	169	14	0	46,935	1,510	38,404	10,224	48,628	
OR	2	0	160	0	14	53	0	227	227	
PA	33	5,641	3,078	0	86,070	5,809	47,443	53,156	100,598	
RI	1	0	0	0	0	0	0	0	0	
SC	16	146	39,953	0	26,069	4,884	51,974	19,077	71,051	
SD	1	0	0	0	0	0	0	0	0	
TN	17	308	6,935	0	136,300	485	119,891	24,137	144,028	
TX	36	7,572	4,577	3,542	836,180	47,356	841,979	57,248	899,227	
UT	2	258	0	0	15,500	0	15,758	0	15,759	
VA	2	12	0	0	0	567	12	567	579	
WA	3	32	17	0	2,106	0	49	2,106	2,155	
WV	9	866	26	0	212,704	24	160,095	53,525	213,620	
WI	3	70	1	0	703	0	165	609	774	
WY	3	586	0	0	11,176	1,700	11,762	1,700	13,462	
Total	380	45,507	86,761	63,506	4,322,354	101,951	3,997,360	622,718	4,620,079	

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.

^bData in TRI are maximum amounts released by each facility.

^cPost office state abbreviations are used.

^dNumber of reporting facilities.

^eThe sum of fugitive and point source releases are included in releases to air by a given facility.

^fSurface water discharges, wastewater treatment-(metals only), and publicly owned treatment works (POTWs) (metal and metal compounds).

^gClass I wells, Class II-V wells, and underground injection.

^hResource Conservation and Recovery Act (RCRA) subtitle C landfills; other onsite landfills, land treatment, surface impoundments, other land disposal, other landfills.

ⁱStorage only, solidification/stabilization (metals only), other off-site management, transfers to waste broker for disposal, unknown.

^jThe sum of all releases of the chemical to air, land, water, and underground injection wells.

^kTotal amount of chemical transferred off-site, including to POTWs.

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Table 5-3. Releases to the Environment from Facilities that Produce, Process, or Use Cobalt Compounds

State ^c	RF ^d	Air ^e	Water ^f	UI ^g	Land ^h	Other ⁱ	Reported amounts released in pounds per year ^b		
							Total Release		
							On-site ^j	Off-site ^k	On and off-site

RF = reporting facilities; UI = underground injection

Source: TRI19 2020; Data are from 2019

5.3.1 Air

Estimated releases of 11,553 pounds (~5.2 metric tons) of cobalt to the atmosphere from 331 domestic manufacturing and processing facilities in 2019 accounted for about 2.6% of the estimated total environmental releases from facilities required to report to the TRI (TRI19 2020). The releases of cobalt which refers to CAS 7440-48-4 are summarized in Table 5-2. Estimated releases of 45,507 pounds (~20.6 metric tons) of cobalt compounds to the atmosphere from 380 domestic manufacturing and processing facilities in 2019 accounted for about 98% of the estimated total environmental releases from facilities required to report to the TRI (TRI19 2020). Cobalt compounds refer to any unique chemical substance that contains cobalt (EPA 2005). These releases are summarized in Table 5-3.

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). 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 or process cobalt compounds. 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 mg/kg and 100–700 mg/m³, respectively. Gasoline contains <0.1 mg cobalt/kg, but catalytic converters may contain cobalt; therefore, emissions from vehicular exhaust are also 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

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U.S. cigarettes at mean values of 0.44 to 1.11 $\mu\text{g/g}$ dry tobacco (Fresquez et al. 2013). Therefore, smoking is a potential source of atmospheric cobalt that could impact indoor air quality.

Cobalt has been identified in air samples collected at 3 of the 425 current or former NPL hazardous waste sites where it was detected in some environmental media (i.e., air, soil, sediment, or water) (ATSDR 2019).

5.3.2 Water

Estimated releases of 3,470 pounds (~1.6 metric tons) of cobalt to surface water from 331 domestic manufacturing and processing facilities in 2019, accounted for about 0.8% of the estimated total environmental releases from facilities required to report to the TRI (TRI19 2020). An additional 728 pounds (~0.3 metric tons) were released to publicly owned treatment works (POTWs) (TRI19 2020). These releases are summarized in Table 5-2.

Estimated releases of 86,761 pounds (~39 metric tons) of cobalt compounds to surface water from 380 domestic manufacturing and processing facilities in 2019, accounted for about 1.9% of the estimated total environmental releases from facilities required to report to the TRI (TRI19 2020). An additional 6,154 pounds (~2.8 metric tons) were released to publicly owned treatment works (POTWs) (TRI19 2020). These releases are summarized in Table 5-3.

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. While there has been no mine production of cobalt in the United States in recent years, cobalt is 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). 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

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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.

Cobalt has been identified in water at 66 sites, respectively, of the 426 NPL hazardous waste sites, where it was detected in some environmental media (i.e., air, soil, sediment, or water) (ATSDR 2019).

5.3.3. Soil

Estimated releases of 330,728 pounds (~150 metric tons) of cobalt to soils from 331 domestic manufacturing and processing facilities in 2019, accounted for about 74% of the estimated total environmental releases from facilities required to report to the TRI (TRI19 2020). An additional 11,400 pounds (~5.2 metric tons), constituting about 2.6% of the total environmental emissions, were released via underground injection (TRI19 2020). These releases are summarized in Table 5-2. Estimated releases of 4.3 million pounds (~1,950 metric tons) of cobalt compounds to soils from 380 domestic manufacturing and processing facilities in 2019, accounted for about 94% of the estimated total environmental releases from facilities required to report to the TRI (TRI19 2020). An additional 63,506 pounds (~29 metric tons), constituting about 1.4% of the total environmental emissions, were released via underground injection (TRI19 2020). These releases are summarized in Table 5-3.

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 the mining and processing of cobalt-bearing ores, the application of cobalt-containing sludge or phosphate fertilizers to soil, the disposal of cobalt containing wastes, and atmospheric deposition from activities such as burning of fossil fuels, smelting, and metal refining (Smith and Carson 1981).

Cobalt has been identified in soil at 97 of the 425 NPL hazardous waste sites, where it was detected in some environmental media (i.e., air, soil, sediment, or water) (ATSDR 2019).

5.4. ENVIRONMENTAL FATE

5.4.1 Transport and Partitioning

Air. Cobalt compounds are nonvolatile, and 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 $>2 \mu\text{m}$ (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

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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 $12\ \mu\text{m}$. The mass median diameter of cobalt in the ambient atmosphere is about $2.6\ \mu\text{m}$ (Milford and Davidson 1985). Golomb et al. (1997) report 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 $58\ \mu\text{g}/\text{m}^2\text{-year}$, of which $47\ \mu\text{g}/\text{m}^2\text{-year}$ was dry deposition and $12\ \mu\text{g}/\text{m}^2\text{-year}$ was wet deposition. Total cobalt deposition flux at a site in the Rhone delta in southern France in 1988–1989 was $0.42\pm 0.23\ \text{kg}/\text{km}^2\text{-year}$ with $0.15\ \text{kg}/\text{km}^2\text{-year}$ 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 ($<2\%$ of that would remain after >30 years due to radioactive decay), and the rest was thought to have been transported downstream and into the Chesapeake Bay (McLean and Summers 1990). Environmental samples of publicly-relevant surface and drinking water, fish, sediment, air particulates, milk, and food products in the Chesapeake Bay area do not detect ^{60}Co (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

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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 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 montmorillonate. 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

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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 whose soil pH ranged from 3.9 to 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 ethylenediaminetetraacetic acid (EDTA), which 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; Czyscinski et al. 1981; Friedman and Kelmers 1988). The mobility of cobalt was assessed in two soils from the Cabriole 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 or below 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

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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 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. 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, one would expect greater quantities 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). 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 $\text{Co}^{+2} \geq \text{CoCO}_3 > \text{CoHCO}_3^+ >> \text{CoSO}_4 \geq \text{Co} \cdot \text{humic acid}$. 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 CoSO_4 , 0.4%. The rank order of species concentration in seawater was estimated to be: $\text{CoCO}_3 > \text{free Co}^{+2} > \text{CoSO}_4 \geq \text{CoHCO}_3^+$ (Mantoura et al. 1978). In another model, the speciation of cobalt was completely different with $\text{CoCl}^+ > \text{free Co}^{+2} > \text{CoCO}_3 > \text{CoSO}_4$ (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

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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 CoCl_2 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 genera 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

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characterized by high pH, low CO₂ partial pressure, and generally low redox potential; sulfide concentrations are in the range of 10⁻⁴ to 10⁻³ mol/L. The solubility of cobalt is controlled by the solubility of CoS (log K₁ and log K₂ being 5.7 and 8.7 at 25°C) and therefore, levels of cobalt are very low, 10⁻⁸–10⁻¹⁰ mol/L. The ⁶⁰Co (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 ⁶⁰Co (II) forms for lengthy periods in the environment (Leonard et al. 1993a, 1993b). Studies indicate that several processes occur to the Co(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. 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%; Fe/Mn 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). Co²⁺ may also be oxidized to Co³⁺ 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 (Schnitzer 1969; Smith and Carson 1981; Swanson 1984). ⁶⁰Co 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.

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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).

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 5-4 shows the limit of detections typically achieved by analytical analysis in environmental media.

Table 5-4. 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)

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

Stable cobalt has been identified in a variety of environmental media (air, surface water, leachate, groundwater, soil, and sediment) collected at 425 of 1,867 current or former NPL hazardous waste sites (ATSDR 2019). Presented in Table 5-5 is a summary of the range of concentrations detected in environmental media at NPL sites.

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Table 5-5. 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 (mg/L)	0.042	0.064	12.7	124	66
Soil (mg/kg)	15	17.1	5.71	199	97
Air (mg/m ³)	5.17 x 10 ⁻⁵	2.62 x 10 ⁻⁵	11.3	4	3

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

5.5.1 Air

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. Data from 2016-2020 is summarized in Table 5-6. Mean cobalt levels in ambient air are generally less than 0.002 µg/m³ (EPA 2020).

Table 5-6. Percentile Distribution of Annual Mean Cobalt (TSP) Concentrations (µg/m³) Measured in Ambient Air Locations Across the United States

Year	Number of U.S. locations	25 th	50 th	75 th	95 th	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

At the South Pole, cobalt levels of 0.00049±0.00015 ng/m³ 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/m³ (Chester et al. 1991). The average annual PM-10 (particles with diameters ≤10 µm) cobalt concentration at Nahant, Massachusetts (near Boston) in 1992–1993 was 1.7 ng/m³ (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/m³ with 35% of the samples falling below the detection limit of 0.04 ng/m³ (Amundsen et al. 1992). Atmospheric cobalt levels in industrial settings may exceed 10 ng/m³. The highest recorded average cobalt concentration in air was 48 ng/m³ in Clydach, Wales at the site where nickel and cobalt were refined (Smith and Carson 1981). These

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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/m³ (Barceloux 1999; IARC 1991).

5.5.2 Water

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 B₁₂ 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–

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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 is 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

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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).

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.

Cobalt concentrations have been reported in various aquatic animals and seabirds. 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 New York City, New Haven, Connecticut, and Delaware Bay contained 10–40 and 16.0 µg/kg,

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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 $\mu\text{g/g}$ 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 $\mu\text{g/g}$ dry weight, respectively, while those in the tissue of penguin and other sea birds ranged from 0.09 to 0.11 $\mu\text{g/g}$ (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 $\mu\text{g/g}$ (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 $\mu\text{g/g}$ dry weight for *Cyprinus caprio* and from 0.045 to 0.062 $\mu\text{g/g}$ dry weight for *Barbus plebejus* (Barlas 1999).

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 $\mu\text{g/g}$), corn cereal (0.074 $\mu\text{g/g}$), and potato chips (0.070 $\mu\text{g/g}$) (Dabeka and McKenzie 1995). Green leafy vegetables and fresh cereals were the richest sources of cobalt (0.2–0.6 $\mu\text{g/g}$ dry weight), while dairy products, refined cereals, and sugar contained the least cobalt (0.1–0.3 $\mu\text{g/g}$ 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 $\mu\text{g/g}$ 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;

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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 $\mu\text{g/L}$ with a median of 0.39 $\mu\text{g/L}$ (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 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. 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 less than 0.002 $\mu\text{g/m}^3$ (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 $\mu\text{g/L}$; however, values as high as 107 $\mu\text{g/L}$ 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).

General population exposure to cobalt from food is highly variable and normally higher than intake from drinking water. Most of the cobalt ingested is inorganic; vitamin B₁₂, which occurs almost entirely in food of animal origin, constitutes only a very small fraction of cobalt intake. The cobalt intake in food has been estimated to be 5.0–40.0 $\mu\text{g/day}$ (Jenkins 1980). 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 estimated average daily cobalt intake from the diet in Canada was 11 $\mu\text{g/day}$; the intake varied from 4 to 15 $\mu\text{g/day}$ between the various age/sex groups (Barceloux 1999; Dabeka and

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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. 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 health 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). 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 a recent Spanish study, the low levels of cobalt presently found in beer do not make a significant contribution to the total cobalt intake in heavy beer drinkers (Camean et al. 1998).

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/cm² (Midander et al. 2014). Midander et al. (2014) concluded that short, repetitive contact with metallic items could be harmful. Alinaghi et al. (2019) found that leather and jewelry were clinically relevant exposure sources to 475 cobalt-allergic patients in Denmark from 2002 to 2017. Exposure sources included leather shoes, gloves, furniture, clothing, other leather items, jewelry, tools, cutting oil, mobile phones, chemicals, cement, and paints. However, the sources of most cases (84.8%) of cobalt allergy were unknown (Alinaghi et al. 2019). Bregnbak et al. (2015b) also found that leather was the most frequent exposure source causing dermatitis after non-occupational use of cobalt-containing tools. 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 800-1250 ppm cobalt (Bregnbak et al. 2017; Thyssen et al. 2013). 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

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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/cm²/hr from the wrist support and as much as 0.07 ng/cm²/hr 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 hand-painted china, a study was conducted to see whether these metals are released 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 less than 0.5-253.33 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 more than 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 UK, and the U.S. 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 0.00013-2.2 µg (Bocca et al. 2007; Onwordi et al. 2011; Sneyers et al. 2009).

Higher urinary cobalt concentrations were related to older housing built after 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 has been measured in the U.S. general population during NHANES 1999-2018, blood cobalt was measured in 2015-2018, and urinary cobalt (creatinine corrected) was measured in 1999-2018 (CDC 2022). Table 5-7 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 5-8 shows the geometric mean and selected percentiles of blood cobalt in the U.S. population from NHANES 2015-2016 and 2017-2018. Table 5-9 shows the geometric mean and selected percentiles of urinary cobalt

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(creatinine corrected) in the U.S. population surveyed for NHANES 2011-2012, 2013-2014, 2015-2016, and 2017-2018.

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Table 5-7. Geometric Mean and Selected Percentiles of Urinary Cobalt (in µg/L) for the U.S. Population from the National Health and Nutrition Examination Survey (NHANES) (CDC 2022)

	Survey years	Geometric mean (95% CI)	Selected percentiles (95% confidence interval)				Sample size
			50 th	75 th	90 th	95 th	
Total							
	2011-2012	.326 (.309-.344)	.323 (.306-.347)	.543 (.510-.577)	.860 (.800-.979)	1.27 (1.09-1.45)	2,504
	2013-2014	.391 (.373-.411)	.408 (.382-.435)	.687 (.662-.713)	1.04 (.976-1.09)	1.35 (1.23-1.48)	2,664
	2015-2016	.414 (.394-.435)	.434 (.415-.455)	.687 (.658-.725)	1.06 (.983-1.12)	1.53 (1.34-1.71)	3,061
	2017-2018	.424 (.398-.451)	.437 (.412-.451)	.710 (.673-.756)	1.16 (1.07-1.27)	1.61 (1.37-1.83)	2,808
Age Group							
3-5 years	2015-2016	.426 (.397-.456)	.466 (.410-.512)	.739 (.662-.833)	1.08 (.947-1.25)	1.55 (1.23-2.07)	486
	2017-2018	.472 (.410-.542)	.526 (.448-.627)	.854 (.749-.917)	1.22 (1.04-1.52)	1.64 (1.34-1.78)	403
6-11 years	2011-2012	.397 (.356-.442)	.452 (.361-.510)	.704 (.616-.772)	1.00 (.846-1.38)	1.42 (1.00-1.78)	399
	2013-2014	.447 (.411-.487)	.479 (.408-.522)	.789 (.718-.877)	1.05 (.991-1.33)	1.55 (1.14-1.84)	402
	2015-2016	.534 (.494-.577)	.599 (.525-.636)	.886 (.773-.948)	1.20 (.992-1.40)	1.63 (1.20-2.05)	379
	2017-2018	.519 (.459-.586)	.559 (.474-.642)	.877 (.787-.942)	1.45 (1.18-1.83)	1.88 (1.57-2.21)	333
12-19 years	2011-2012	.416 (.358-.484)	.429 (.341-.527)	.700 (.622-.806)	1.12 (.960-1.30)	1.56 (1.16-1.96)	390
	2013-2014	.549 (.462-.653)	.602 (.491-.701)	.936 (.783-1.05)	1.43 (1.08-1.75)	1.76 (1.49-3.07)	451
	2015-2016	.571 (.527-.620)	.604 (.535-.659)	.892 (.840-1.08)	1.48 (1.32-1.74)	1.92 (1.57-2.23)	402
	2017-2018	.516 (.488-.545)	.583 (.514-.656)	.879 (.835-.948)	1.33 (1.20-1.39)	1.49 (1.39-1.65)	364
20 years and older	2011-2012	.307 (.288-.327)	.308 (.289-.328)	.491 (.457-.534)	.800 (.695-.940)	1.16 (.984-1.36)	1,715
	2013-2014	.367 (.349-.386)	.382 (.357-.410)	.647 (.614-.673)	.930 (.882-1.04)	1.23 (1.17-1.34)	1,811
	2015-2016	.385 (.364-.408)	.403 (.379-.427)	.638 (.599-.666)	.949 (.877-1.06)	1.41 (1.21-1.66)	1,794
	2017-2018	.401 (.371-.433)	.409 (.384-.438)	.650 (.619-.702)	1.08 (.981-1.20)	1.61 (1.27-1.88)	1,708
Sex							
Males	2011-2012	.317 (.299-.336)	.316 (.293-.339)	.496 (.452-.547)	.715 (.659-.798)	0.963 (.858-1.03)	1,262
	2013-2014	.380 (.355-.407)	.414 (.374-.452)	.641 (.604-.684)	.883 (.820-.951)	1.11 (1.04-1.26)	1,318
	2015-2016	.397 (.376-.420)	.434 (.405-.466)	.651 (.609-.692)	.860 (.815-.954)	1.08 (.960-1.19)	1,524
	2017-2018	.419 (.375-.468)	.427 (.388-.466)	.679 (.611-.738)	1.03 (.906-1.15)	1.47 (1.20-1.88)	1,381

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Table 5-7. Geometric Mean and Selected Percentiles of Urinary Cobalt (in µg/L) for the U.S. Population from the National Health and Nutrition Examination Survey (NHANES) (CDC 2022)

	Survey years	Geometric mean (95% CI)	Selected percentiles (95% confidence interval)				Sample size
			50 th	75 th	90 th	95 th	
Females	2011-2012	.335 (.310-.361)	.340 (.308-.382)	.591 (.554-.643)	1.07 (.891-1.20)	1.49 (1.30-1.74)	1,242
	2013-2014	.402 (.374-.432)	.398 (.366-.438)	.741 (.701-.789)	1.16 (1.06-1.23)	1.5 (1.36-1.75)	1,346
	2015-2016	.432 (.397-.469)	.433 (.391-.489)	.752 (.675-.865)	1.33 (1.20-1.43)	1.82 (1.54-2.13)	1,537
	2017-2018	.428 (.391-.469)	.446 (.410-.487)	.760 (.694-.835)	1.26 (1.19-1.33)	1.61 (1.47-1.79)	1,427
Race/ethnicity							
Mexican American	2011-2012	.350 (.322-.381)	.350 (.307-.377)	.550 (.490-.598)	.891 (.721-1.18)	1.41 (1.14-2.08)	317
	2013-2014	.415 (.378-.456)	.439 (.400-.482)	.686 (.610-.766)	.918 (.866-1.09)	1.15 (1.06-1.56)	453
	2015-2016	.469 (.431-.511)	.488 (.431-.558)	.777 (.688-.852)	1.21 (1.01-1.42)	1.81 (1.32-2.14)	585
	2017-2018	.431 (.397-.468)	.437 (.410-.474)	.708 (.626-.815)	1.14 (.997-1.27)	1.39 (1.23-1.70)	435
Non-Hispanic black	2011-2012	.340 (.311-.373)	.333 (.304-.358)	.519 (.489-.576)	.909 (.790-.986)	1.44 (1.06-1.60)	669
	2013-2014	.468 (.410-.535)	.471 (.402-.561)	.796 (.691-.877)	1.26 (1.03-1.39)	1.5 (1.35-1.67)	581
	2015-2016	.461 (.422-.503)	.478 (.436-.513)	.740 (.660-.845)	1.20 (.956-1.40)	1.52 (1.34-1.85)	671
	2017-2018	.470 (.443-.499)	.476 (.430-.514)	.718 (.657-.806)	1.26 (1.04-1.55)	1.86 (1.29-2.35)	639
Non-Hispanic white	2011-2012	.320 (.295-.348)	.320 (.296-.357)	.543 (.485-.591)	.858 (.750-.995)	1.2 (1.03-1.35)	820
	2013-2014	.374 (.349-.401)	.387 (.345-.429)	.681 (.638-.723)	1.02 (.930-1.10)	1.34 (1.21-1.56)	985
	2015-2016	.402 (.374-.432)	.422 (.386-.454)	.675 (.627-.734)	1.00 (.938-1.11)	1.49 (1.24-1.71)	924
	2017-2018	.411 (.372-.454)	.428 (.391-.446)	.702 (.640-.759)	1.11 (.958-1.33)	1.57 (1.31-1.89)	918
All Hispanic	2011-2012	.338 (.321-.357)	.326 (.306-.350)	.530 (.490-.583)	.891 (.763-1.14)	1.41 (1.10-1.81)	573
	2013-2014	.412 (.384-.442)	.442 (.409-.481)	.674 (.631-.731)	.964 (.891-1.07)	1.2 (1.09-1.36)	701
	2015-2016	.440 (.417-.465)	.465 (.431-.514)	.718 (.662-.795)	1.16 (.991-1.34)	1.69 (1.34-2.03)	982
	2017-2018	.441 (.420-.463)	.451 (.427-.478)	.742 (.696-.829)	1.20 (1.07-1.30)	1.41 (1.31-1.70)	676
Asian	2011-2012	.317 (.282-.357)	.323 (.300-.355)	.519 (.445-.634)	.968 (.723-1.58)	1.78 (.980-2.31)	353
	2013-2014	.362 (.315-.416)	.354 (.312-.434)	.653 (.578-.789)	1.05 (.854-1.25)	1.57 (1.09-2.26)	292
	2015-2016	.376 (.334-.424)	.365 (.342-.438)	.610 (.533-.698)	.990 (.734-1.37)	1.44 (.990-2.31)	332
	2017-2018	.416 (.386-.449)	.462 (.399-.508)	.759 (.655-.809)	1.15 (.966-1.37)	1.64 (1.12-2.18)	365

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Table 5-8. Geometric Mean and Selected Percentiles of Blood Cobalt (in µg/L) for the U.S. Population from the National Health and Nutrition Examination Survey (NHANES) (CDC 2022)

	Survey years	Geometric mean (95% CI)	Selected percentiles (95% confidence interval) ^a				Sample size
			50 th	75 th	90 th	95 th	
Total	2015-2016	Not calculated	<LOD	<LOD	.700 (.540-.900)	1.08 (.750-1.49)	3,442
	2017-2018	Not calculated	<LOD	<LOD	.460 (<LOD-.600)	.670 (.540-.860)	3,518
Age Group							
40-59 years	2015-2016	Not calculated	<LOD	<LOD	.650 (.470-.970)	1.07 (.710-1.57)	1,719
	2017-2018	Not calculated	<LOD	<LOD	.450 (<LOD-.560)	.620 (.480-.950)	1,585
60+ years	2015-2016	Not calculated	<LOD	<LOD	.750 (.550-.940)	1.13 (.790-1.49)	1,723
	2017-2018	Not calculated	<LOD	<LOD	.490 (<LOD-.720)	.720 (.540-.990)	1,933
Sex							
Male	2015-2016	Not calculated	<LOD	<LOD	.620 (.460-.880)	1.07 (.680-1.58)	1,656
	2017-2018	Not calculated	<LOD	<LOD	.470 (<LOD-.580)	.670 (.560-.740)	1,716
Female	2015-2016	Not calculated	<LOD	<LOD	.740 (.580-.940)	1.08 (.800-1.43)	1,786
	2017-2018	Not calculated	<LOD	<LOD	.460 (<LOD-.640)	.670 (.510-.970)	1,802
Race/ethnicity							
Mexican American	2015-2016	Not calculated	<LOD	<LOD	.570 (.460-.700)	.750 (.550-1.34)	589
	2017-2018	Not calculated	<LOD	<LOD	.450 (<LOD-.580)	.660 (.490-.730)	439
Non-Hispanic Black	2015-2016	Not calculated	<LOD	<LOD	.490 (<LOD-.740)	.870 (.690-1.10)	714
	2017-2018	Not calculated	<LOD	<LOD	.410 (<LOD-.500)	.570 (.430-1.00)	817
Non-Hispanic White	2015-2016	Not calculated	<LOD	<LOD	.750 (.550-1.07)	1.20 (.790-1.57)	1,195
	2017-2018	Not calculated	<LOD	<LOD	.500 (.420-.640)	.700 (.560-.970)	1,271
All Hispanic	2015-2016	Not calculated	<LOD	<LOD	.550 (.430-.690)	.760 (.630-1.06)	1,062
	2017-2018	Not calculated	<LOD	<LOD	<LOD	.590 (.450-.730)	774
Asian	2015-2016	Not calculated	<LOD	<LOD	.800 (.600-.980)	1.03 (.820-1.44)	368
	2017-2018	Not calculated	<LOD	<LOD	.450 (.410-.490)	.600 (.490-.650)	485

^aThe limit of detection for 2015-2016 and 2017-2018 is 0.41 µg/L.
LOD = limit of detection

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Table 5-9. Geometric Mean and Selected Percentiles of Urinary Cobalt (creatinine corrected) (in µg/g of creatinine) for the U.S. Population from the National Health and Nutrition Examination Survey (NHANES) (CDC 2022)

	Survey years	Geometric mean (95% CI)	Selected percentiles (95% confidence interval)				Sample size
			50 th	75 th	90 th	95 th	
Total							
	2011-2012	.370 (.349-.391)	.347 (.330-.371)	.557 (.513-.593)	.880 (.768-1.03)	1.29 (1.12-1.46)	2,502
	2013-2014	.452 (.437-.466)	.443 (.427-.454)	.656 (.625-.688)	.969 (.920-1.03)	1.31 (1.18-1.47)	2,663
	2015-2016	.465 (.447-.484)	.444 (.421-.464)	.682 (.636-.722)	1.07 (.999-1.16)	1.39 (1.24-1.52)	3,058
	2017-2018	.462 (.437-.490)	.435 (.410-.463)	.697 (.644-.733)	1.12 (1.03-1.20)	1.55 (1.33-1.81)	2,806
Age Group							
3-5 years	2015-2016	.980 (.919-1.05)	.952 (.875-1.01)	1.35 (1.22-1.48)	1.94 (1.65-2.10)	2.45 (2.03-2.98)	485
	2017-2018	.974 (.916-1.04)	.978 (.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	.567 (.535-.602)	.571 (.526-.611)	.778 (.713-.834)	1.19 (.974-1.30)	1.38 (1.10-1.67)	398
	2013-2014	.667 (.614-.725)	.646 (.593-.704)	.914 (.853-.986)	1.26 (1.09-1.40)	1.57 (1.24-2.13)	402
	2015-2016	.757 (.701-.817)	.732 (.658-.785)	1.03 (.957-1.11)	1.37 (1.17-1.50s)	1.7 (1.28-2.64)	379
	2017-2018	.724 (.667-.787)	.708 (.653-.755)	.966 (.873-1.04)	1.42 (1.17-1.75)	1.82 (1.29-2.69)	332
12-19 years	2011-2012	.398 (.349-.455)	.373 (.316-.441)	.585 (.454-.700)	.832 (.688-1.09)	1.26 (.830-2.77)	390
	2013-2014	.497 (.463-.534)	.480 (.446-.525)	.692 (.597-.769)	.920 (.819-1.10)	1.3 (1.09-1.61)	451
	2015-2016	.534 (.504-.565)	.508 (.455-.552)	.799 (.697-.939)	1.16 (1.05-1.42)	1.5 (1.33-1.78)	402
	2017-2018	.465 (.437-.495)	.423 (.392-.455)	.723 (.596-.780)	1.00 (.848-1.13)	1.23 (1.05-1.38)	364
20 years and older	2011-2012	.349 (.330-.369)	.327 (.300-.341)	.508 (.467-.552)	.803 (.711-.982)	1.24 (1.10-1.50)	1,714
	2013-2014	.428 (.412-.444)	.417 (.390-.441)	.607 (.580-.643)	.929 (.853-.994)	1.27 (1.10-1.46)	1,810
	2015-2016	.420 (.402-.439)	.404 (.384-.426)	.582 (.551-.616)	.900 (.809-1.03)	1.2 (1.05-1.41)	1,792
	2017-2018	.425 (.397-.454)	.397 (.367-.432)	.591 (.544-.665)	1.02 (.892-1.16)	1.46 (1.20-1.81)	1,707
Sex							
Males	2011-2012	.297 (.280-.315)	.276 (.254-.294)	.426 (.397-.456)	.637 (.564-.750)	0.865 (.748-1.17)	1,261
	2013-2014	.379 (.362-.398)	.368 (.344-.390)	.529 (.493-.560)	.758 (.689-.852)	1.02 (.871-1.29)	1,317
	2015-2016	.377 (.360-.395)	.348 (.334-.379)	.526 (.483-.550)	.839 (.746-.913)	1.08 (.966-1.18)	1,524
	2017-2018	.390 (.363-.420)	.360 (.334-.392)	.563 (.508-.593)	.924 (.799-1.08)	1.33 (1.11-1.59)	1,380
Females	2011-2012	.455 (.418-.496)	.433 (.407-.466)	.660 (.600-.729)	1.10 (.900-1.36)	1.54 (1.28-1.84)	1,241
	2013-2014	.534 (.515-.553)	.532 (.502-.549)	.774 (.733-.816)	1.12 (.991-1.27)	1.48 (1.27-1.77)	1,346
	2015-2016	.568 (.540-.598)	.533 (.511-.563)	.799 (.760-.869)	1.24 (1.16-1.40)	1.7 (1.48-1.98)	1,534
	2017-2018	.544 (.513-.577)	.498 (.468-.543)	.815 (.764-.866)	1.22 (1.14-1.36)	1.71 (1.45-1.98)	1,426

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Race/ethnicity								
Mexican American	2011-2012	.394 (.357-.435)	.374 (.322-.400)	.576 (.531-.637)	1.02 (.877-1.24)	1.5 (.988-2.02)	317	
	2013-2014	.474 (.449-.500)	.448 (.425-.473)	.669 (.610-.721)	.971 (.888-1.03)	1.28 (1.03-1.51)	453	
	2015-2016	.512 (.479-.548)	.488 (.464-.533)	.771 (.690-.850)	1.18 (1.01-1.40)	1.5 (1.37-1.79)	584	
	2017-2018	.465 (.432-.500)	.437 (.378-.497)	.708 (.662-.786)	1.14 (1.00-1.25)	1.45 (1.19-1.57)	433	
Non-Hispanic black	2011-2012	.265 (.248-.282)	.244 (.222-.267)	.401 (.342-.457)	.645 (.559-.816)	1.02 (.737-1.41)	669	
	2013-2014	.356 (.332-.382)	.337 (.315-.377)	.545 (.490-.624)	.841 (.754-.952)	1.08 (.930-1.22)	581	
	2015-2016	.366 (.347-.386)	.342 (.328-.377)	.556 (.504-.595)	.799 (.696-.972)	1.07 (.929-1.24)	669	
	2017-2018	.355 (.337-.375)	.330 (.295-.351)	.576 (.500-.611)	.885 (.798-1.02)	1.28 (.979-1.61)	639	
Non-Hispanic white	2011-2012	.387 (.360-.417)	.365 (.336-.400)	.574 (.513-.615)	.860 (.749-1.09)	1.29 (1.04-1.57)	818	
	2013-2014	.461 (.442-.480)	.447 (.430-.469)	.669 (.613-.703)	.987 (.912-1.13)	1.32 (1.19-1.61)	984	
	2015-2016	.475 (.453-.497)	.457 (.427-.471)	.686 (.629-.746)	1.07 (.972-1.20)	1.41 (1.19-1.63)	924	
	2017-2018	.476 (.439-.517)	.446 (.415-.473)	.700 (.605-.760)	1.14 (1.02-1.33)	1.64 (1.29-1.98)	918	
All Hispanic	2011-2012	.379 (.351-.409)	.361 (.322-.384)	.572 (.520-.626)	.944 (.809-1.15)	1.33 (1.13-1.91)	573	
	2013-2014	.460 (.444-.475)	.448 (.429-.464)	.663 (.619-.703)	.952 (.888-1.00)	1.17 (1.03-1.35)	701	
	2015-2016	.497 (.468-.527)	.465 (.436-.503)	.748 (.669-.837)	1.16 (1.04-1.28)	1.46 (1.35-1.70)	981	
	2017-2018	.475 (.450-.503)	.454 (.423-.498)	.719 (.671-.781)	1.13 (1.02-1.24)	1.45 (1.25-1.57)	674	
Asian	2011-2012	.424 (.378-.475)	.386 (.329-.457)	.659 (.531-.785)	1.18 (.907-1.51)	1.61 (1.14-2.72)	353	
	2013-2014	.567 (.516-.624)	.540 (.482-.567)	.814 (.670-.931)	1.38 (1.07-1.97)	2.09 (1.39-3.78)	292	
	2015-2016	.514 (.473-.559)	.475 (.421-.548)	.736 (.624-.885)	1.30 (1.11-1.57)	1.66 (1.44-2.12)	332	
	2017-2018	.544 (.504-.588)	.511 (.450-.569)	.830 (.768-.882)	1.39 (1.04-1.70)	1.86 (1.40-2.28)	365	

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In a study of pregnant women in Puerto Rico from 2011-2017, 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). Compared to NHANES data, median concentrations of cobalt were two-fold higher (Ashrap et al. 2020). 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 in maternal serum of Polish mothers with fetuses with neonatal abnormalities was 0.52-0.61 µg/L and 0.24-0.27 µg/L in amniotic fluid (Kocylowski et al. 2019).

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, traffic pollution, and iron deficiency anemia. Cao et al. (2014) found that children living near the largest coking plant in China had mean 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/m³), drinking water (0.14 µg/m³), 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 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 (Iyengar 1982). The levels of cobalt in human breast milk from Nigeria, Zaire, Guatemala, Hungary, Philippines, and Sweden ranged from 150 (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 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 for an infant, 0–12 months old, the total dietary cobalt intake would range from 0.42 µg/kg-day (3.39 µg/day) for a breast 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 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).

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5.7. POPULATIONS WITH POTENTIALLY HIGH EXPOSURES

Workers in the hard metal industry (tool production, grinding, etc.) and industries such as coal mining, metal mining, smelting, and refining, cobalt dye painters, and cobalt chemical production are exposed to higher levels of cobalt via airborne dust and direct contact. Kennedy et al. (2017) estimates that through 2008, up to 14,348 individuals in the U.S. worked in the hard metal industry. 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).

Several studies of cobalt concentrations in air in the hard metal industry have been reported. The concentrations of cobalt in the air of hard metal manufacturing, welding, and grinding factories may range from 1 to 300 $\mu\text{g}/\text{m}^3$, compared to normal atmospheric levels of 0.4–2.0 ng/m^3 (Burr and Sinks 1989; Haddad and Zikovsky 1985; Koponen et al. 1982; Lichtenstein et al. 1975). The maximum OSHA permissible level is 100 $\mu\text{g}/\text{m}^3$. The concentration of cobalt in the dust of an electric welding factory was 4.2 $\mu\text{g}/\text{g}$ compared to its normal dust level of 0.1–1.0 $\mu\text{g}/\text{g}$ (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 or lower, 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). An extensive survey of workers potentially exposed to cobalt in the Bergamo Province in northern Italy in 1991 identified 403 exposed workers in different production areas (Mosconi et al. 1994b). Significant cobalt exposure occurred especially for operators working in diamond abrasive production, particularly in mold filling and sintering units where occupational limits were regularly exceeded. Exposure in tool production, tool sharpening, and hard metal alloy filling is much more restrained.

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

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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 concentration of cobalt in air was 21.2 and 137.7 $\mu\text{g}/\text{m}^3$ (Permissible exposure limit [PEL]-TWA 100 $\mu\text{g}/\text{m}^3$) in work places with and without dust ventilation, respectively (Imbrogno and Alborghetti 1994).

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 old 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 ($8.18 \pm 2.73 \mu\text{g}/\text{L}$) and quality control workers ($7.39 \pm 1.26 \mu\text{g}/\text{L}$) than in the control population ($0.92 \pm 8.13 \mu\text{g}/\text{L}$). 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 ($\mu\text{g}/\text{dL}$), 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 $\mu\text{g}/\text{L}$ (range: 1– 51 $\mu\text{g}/\text{L}$) and 29 (3–159 $\mu\text{g}/\text{L}$), on Monday and Friday before the shift, respectively, and 85 $\mu\text{g}/\text{L}$ (6–505 $\mu\text{g}/\text{L}$) 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 $\mu\text{g}/\text{L}$ and the maximum was 86 $\mu\text{g}/\text{L}$. The average urinary cobalt level among workers using wet/mixed sharpening methods was 4 times higher than those using dry sharpening methods; 21.38 $\mu\text{g}/\text{L}$ as compared to 5 $\mu\text{g}/\text{L}$, respectively. 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 $\mu\text{g}/\text{L}$). 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 $\mu\text{g}/\text{m}^3$ (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

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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 $\mu\text{g}/\text{m}^3$ of cobalt, respectively (Stebbins et al. 1992). For the method collecting respirable particles, cobalt levels ranged from 2 to 28 $\mu\text{g}/\text{m}^3$. 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). 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). Similarly, 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).

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 $\mu\text{g}/\text{cm}^2$, 0.25–28 $\mu\text{g}/\text{cm}^2$,) 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). 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 154–1,328 μg on hands and 7.8 to 342 μg on necks (Day et al. 2009). 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 the 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 $\mu\text{g}/\text{cm}^2/\text{hr}$ on the thumb.

In addition to workers in the hard metal industry and other industries, the general population living near these industrial sites, hazardous waste sites, and agricultural areas may be exposed to high levels of cobalt in air and in soil. People living near industrial and hazardous waste sites or agricultural areas that use

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sewage sludge or cobalt containing fertilizers or other soil amendments may be exposed to cobalt by inhaling dust from contaminated sites or through dermal contact with cobalt-contaminated 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 mining and smelting facilities or metal shops where cobalt is used in grinding tools is a public health concern, especially for infants and children. Since cobalt can remain in surface soil long past when land use that caused the contamination has changed, people may not realize that they are living in areas where high levels of cobalt may occur in soil. Contaminated soils pose a particular hazard to children because of both hand-to-mouth behavior and intentional ingestion of soil that contain metals and other contaminants (Hamel et al. 1998). In the case of children playing in and around unrestricted landfill sites, exposure via dermal and ingestion routes is possible. In communities near industrial and hazardous waste sites, cobalt may have been tracked in from outdoors and contaminate carpeting. Cobalt-containing dust may be brought home in the clothing of parents working in industries where they are exposed to cobalt. Children may be exposed to this cobalt while crawling around or playing on contaminated carpeting. Exposure may also result from dermal contact with soil, or by inhaling dust and then swallowing it after mucociliary transport up out of the lungs.

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 0.59-14.85 ng/m³ (Han et al. 2020). Han et al. (2020) estimated that the cancer risk due to inhalation of cobalt was 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 Democratic Republic of Congo, mean urinary concentrations of cobalt were significantly higher in individuals living less than 3 kilometers 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 kilometers from mining and refining (Banza et al. 2008). 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. 2008). Cheyns et al. (2014) measured the concentrations of cobalt in urine samples and environmental media in communities close to metal mining

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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 two-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 $\mu\text{g}/\text{cm}^3$ in exposed technicians and 0.0017 $\mu\text{g}/\text{cm}^3$ in non-exposed technicians (Kettelarij et al. 2016). After 2 hours of work without hand washing, concentrations had increased to 0.15 $\mu\text{g}/\text{cm}^3$ for exposed individuals and 0.0026 $\mu\text{g}/\text{cm}^3$ for non-exposed individuals (Kettelarij et al. 2016). At the end of the day, the median concentrations had increased overall to 0.014 $\mu\text{g}/\text{cm}^3$ in exposed individuals and 0.0057 $\mu\text{g}/\text{cm}^3$ in non-exposed individuals (Kettelarij et al. 2016). Cobalt was found in all 10 air samples taken during this study at concentrations ranging from 0.22-155 $\mu\text{g}/\text{m}^3$ (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 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,

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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 and 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 (Zywiell et al. 2013). Transient hearing loss was reported in individuals undergoing cobalt therapy attempting to increase hematocrit (Bowie and Hurley 1975).

People who use cobalt supplements as a treatment for anemia and those who take large amounts of vitamin B₁₂ 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 to 5.1 µg/L (Tvermoes et al. 2013). Whole blood concentrations decreased to 1.1 µg/L two 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 UK Expert Group on Vitamins and Minerals (600-1400 µg/day) would result in mean whole blood concentrations of 5.0-12 µg/L and urinary concentrations of 57-130 µg/L after 30 days. After one 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). There is some evidence that cobalt chloride could be used as an alternative doping technique in athletes wanting to improve performance, and increased serum concentrations are occasionally measured in athletes (Lippi et al. 2006).

Cobalt has been detected in tobacco from U.S. cigarettes at mean values of 0.44 to 1.11 µg/g dry tobacco and in popular smokeless tobacco products at concentrations of 0.26±0.02 to 1.22±0.05 µg/g (Fresquez et

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al. 2013; Pappas et al. 2008). People who smoke cigarettes or use smokeless tobacco products may be at higher risk of cobalt exposure.