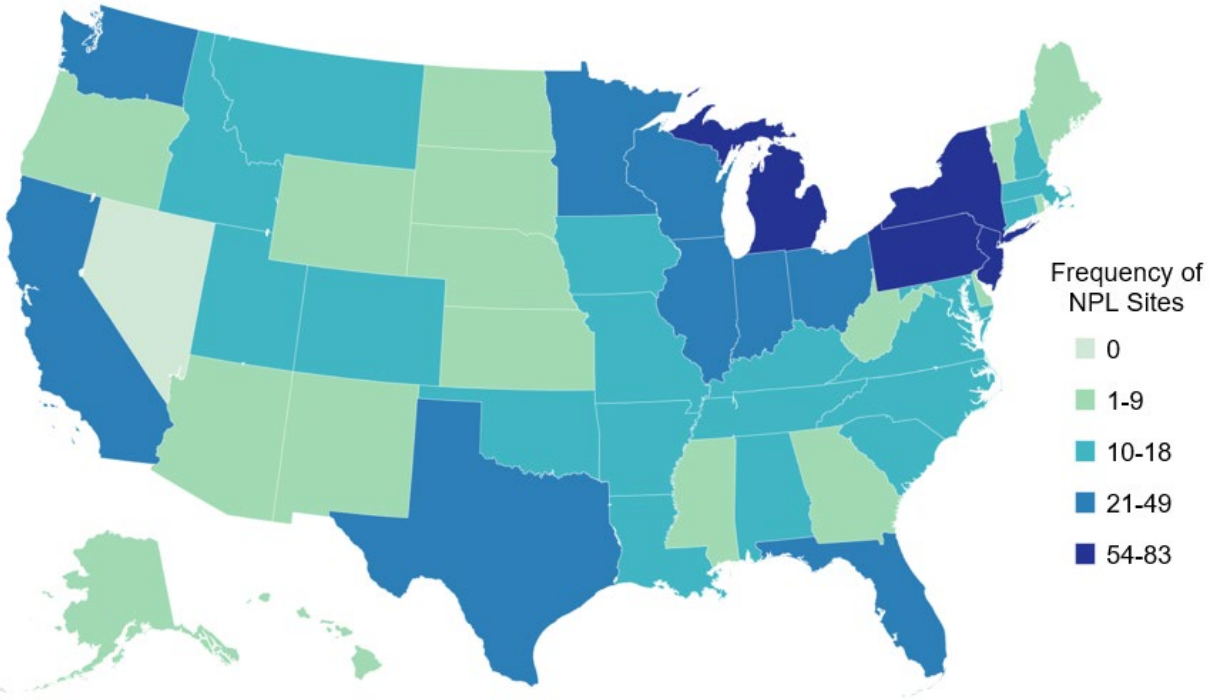
CHAPTER 5. POTENTIAL FOR HUMAN EXPOSURE

5.1 OVERVIEW

Nickel and nickel compounds have been identified in at least 867 of the 1,868 hazardous waste sites that have been proposed for inclusion on the EPA National Priorities List (NPL) (ATSDR 2022). However, the number of sites in which nickel and nickel compounds have been evaluated is not known. The number of sites in each state is shown in Figure 5-1. Of these sites, 862 are located within the United States, 1 is located in Guam, and 4 are located in Puerto Rico (not shown).

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



Source: ATSDR 2022

- Nickel is primarily used for production of stainless, alloy steels, nonferrous alloys, superalloys, and in electroplating.

- Nickel is an element and a component of the Earth's crust. It is ubiquitous in the environment. Nickel is released to the atmosphere or water from natural sources such as soil particles and anthropogenic sources such as oil combustion. Nickel is generally present at trace levels in air and water.

- Nickel typically exists in the environment as a hexahydrate, complexed to other species, or adsorbed to particulate matter. It is dispersed in the atmosphere by wind and removed by wet and

dry deposition. Nickel typically accumulates at the surface of soils due to deposition and is strongly adsorbed by soil. Nickel does not concentrate in the food chain. Accumulation in plants has been observed due to its necessity as an essential nutrient.

- The general population may be exposed to trace amounts of nickel through inhalation of ambient air and ingestion of food and drinking water. Small increases in dietary exposure may occur through use of stainless-steel cookware under certain conditions. Exposure may also occur from consumer goods, like toys and jewelry.

- Higher exposures may occur for workers and people who smoke tobacco or e-cigarettes. Occupational exposure via inhalation and dermal routes occurs in industries that work with nickel and its compounds such as electroplating. Dental technicians may be exposed to nickel in alloys used in the industry.

Nickel and its compounds are naturally present in the Earth's crust and can be found in many minerals. In 2023, nickel in the United States was produced from one mine in Michigan (USGS 2024). The United States imports more nickel than it produces or exports. Nickel is primarily used for stainless steels, batteries, alloy steels, nonferrous alloys and superalloys, and electroplating (IEA 2023; USGS 2024). Nickel compounds have applications in catalyst synthesis, electroplating, batteries, and pigments for ceramics (Antonsen and Meshri 2005; Lascelles et al. 2019; Tundermann et al. 2013). Nickel was identified as one of the Energy Critical Materials by the Department of Energy (DOE) in 2023 (DOE 2023). Nickel is also used as an alloy in medical and dental appliances and tools, for cast iron, for chemical uses, and to make U.S. coins (Berniyanti et al. 2020; Hariyani et al. 2015; Kulkami et al. 2016; USDT 2018).

Since nickel and its compounds are naturally occurring, they are released from natural sources such as windblown dust, volcanic ash, forest fires, meteoric dust, and sea salt spray. Anthropogenic sources of nickel include coal and oil combustion, and waste and sewage incineration (Cempel and Nikel 2006; Pacyna and Pacyna 2001). Most nickel from facilities required to report to the EPA’s Toxics Release Inventory (TRI) is released to the soil. Natural sources will also release nickel to the soil, such as weathering of ultramafic rocks (Li et al. 2020b).

Nickel is released to the atmosphere as particulate matter or adsorbed to particulate matter. It is dispersed by wind and removed by gravitational settling, dry deposition, washout by rain, and rainout (Schroeder et al. 1987). Adsorption of nickel onto suspended particles in water is one of the main removal mechanisms of nickel from the water column. Nickel typically accumulates at the surface of soils due to deposition and is strongly adsorbed by soil and accumulates and concentrates in various plant species. Nickel is an essential nutrient for plants; therefore, some uptake and accumulation is expected to occur (Brown et al.

1987; Correia et al. 2018; Wood et al. 2004). Nickel does not appear to accumulate in aquatic organisms or biomagnify in aquatic food webs (McGeer et al. 2003). Studies on voles and rabbits also do not indicate that nickel is biomagnified in the food chain (Alberici et al. 1989; Dressler et al. 1986).

Nickel is present in the air at concentrations typically <3 ng/m^3 (EPA 2024). Nickel concentrations may be higher in urban air and in air near industrial facilities. In New York City, concentrations are known to vary by season, likely due to increased fuel oil burning in the winter for space heating (Hsu et al. 2012; Peltier and Lippmann 2010; Rohr et al. 2014b). Indoor air concentrations are lower than outdoor air concentrations but are affected by outdoor sources and may also vary seasonally (Habre et al. 2014; Peltier and Lippmann 2010; Schachter et al. 2020). Dissolved nickel is present in natural waters at trace levels; 3–3.5 ppb in surface water and around 4–7 ppb in groundwater (WQP 2024). Nickel is naturally present in soil, sediment, and food. According to the U.S. FDA Total Diet Study, the average concentration of nickel in various U.S. foods ranges from 0.034 to 10.6 mg/kg (FDA 2023). Nickel is also present in cigarettes and smokeless tobacco products at concentrations ranging from 1.19 to 27.67 µg/g and in e-cigarette liquid at concentrations up to 22,600 µg/L (Aherrera et al. 2017; Arain et al. 2015; Badea et al. 2018; Hess et al. 2017; Mohammad et al. 2019).

The general population is primarily exposed to trace amounts of nickel in food and drinking water and in the ambient environment. The average daily dietary nickel intake for U.S. diets is <0.5–162 µg (Institute of Medicine 2001). Estimates from the European Union are 2.51–10.1 µg/kg body weight/day across different age groups (EFSA 2020). The general population may also be exposed to nickel from stainless steel cookware, jewelry, clothing buckles and fasteners, technology, and toys, which may leach from the products under certain conditions (Hedberg et al. 2014; Jensen et al. 2014; Kamerud et al. 2013; Thyssen and Maibach 2008; Tuchman et al. 2015; Uter and Wolter 2018).

Individuals who work in the mining of or the production of nickel and nickel products may be exposed to higher levels of nickel than the general population. Workers in primary nickel production, primary nickel user industries, manufacturing, nickel refining, and electroplating may be exposed to nickel via inhalation or dermal routes (Hughson et al. 2010; Julander et al. 2010; Vuskovic et al. 2013). Populations living near these industry sites or near disposal sites may also have increased exposures to nickel. Dental technicians are also likely to be exposed to higher levels of nickel than the general population, as are people who smoke cigarettes (Aherrera et al. 2017; Badea et al. 2018; Kettelarij et al. 2014, 2016; Pappas et al. 2008).

5.2 PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

5.2.1 Production

Nickel is the 5th most common element on Earth and 24th most abundant element in the Earth's crust, accounting for about 3% of the Earth's composition (Harasim and Filipek 2015; Iyaka 2011). Nickel is found in the minerals pentlandite, garnierite, millerite, niccolite, and ullmannite and in the ore types, sulphide and laterite (Harasim and Filipek 2015). Nickel ores are of two general types: magmatic sulfide ores, which are mined underground, and lateritic hydrous nickel silicates or garnierites, which are surface mined (Duke 1980a; Warner 1984).

The most important nickel sulfide-arsenide deposits are in hydrothermal veins associated with mafic (i.e., rich in magnesium and iron) and ultramafic igneous rock. These ores typically contain 1–3% nickel; pentlandite $(Ni,Fe)_9S_8$ is the principal ore (Kerfoot 2012). Pentlandite often occurs along with the iron mineral pyrrhotite and the copper mineral, chalcopyrite (Tundermann et al. 2013). The ore is concentrated by physical means (i.e., flotation and magnetic separation) after crushing.

The lateritic hydrous nickel silicate ores are formed by the weathering of rocks rich in iron and magnesium in humid tropical areas. The repeated processes of dissolution and precipitation lead to a uniform dispersal of the nickel that is not amenable to concentration by physical means; therefore, these ores are concentrated by chemical means such as leaching. Lateritic ores are less well defined than sulfide ores. The nickel content of lateritic ores is like that of sulfide ore and typically ranges from 1 to 3% nickel. The non-sulfur addition process involves the reduction, smelting, and refining of lateritic ores to a low nickel ferronickel-like product called nickel pig iron (NPI) in a method referred to as the rotary kiln-electric furnace (RKEF) process. The process usually involves ore drying, prereduction of the ore in a rotary kiln, final reduction, and smelting in an electric arc furnace, before refining steps. NPI is suitable for stainless steel production.

Sulfide ores are processed by sequential pyrometallurgical processes: roasting, smelting, and converting (Tundermann et al. 2013). During roasting, iron is oxidized, and the sulfur is removed as sulfur dioxide. The smelting stage occurs in reverberatory or blast furnaces, or by flash smelting. Iron oxide and other oxide compounds are removed in a slag and further reduction of the sulfur content occurs, yielding an impure copper-nickel-iron-sulfur matte. During converting, the molten matte is added with silica to air to remove the remaining iron and sulfur, to yield a sulfur-deficient copper-nickel matte (Tundermann et al.

2013). After physical separation of the copper and nickel sulfides, the nickel is refined electrochemically or by a carbonyl process. The treatment of the matte depends on the end use of the nickel. Alternatively, the sulfide can be roasted to form a nickel oxide sinter that is used directly in steel production (Tundermann et al. 2013).

Lateritic ore is processed by pyrometallurgical or hydrometallurgical processes. In the pyrometallurgical process, sulfur is generally added to the oxide ore during smelting, usually as gypsum or elemental sulfur, and an iron-nickel matte is produced (Tundermann et al. 2013). The smelting process that does not include adding sulfur produces a ferronickel alloy, containing ≤50% nickel, which can be used directly in steel production (Tundermann et al. 2013). Hydro-metallurgical techniques involve leaching with ammonia or sulfuric acid, after which the nickel is selectively precipitated (Duke 1980b; IARC 1990; Tien and Howson 1981; Warner 1984). Nickel precipitated by the acid-leaching process can be used for applications such as batteries (Tundermann et al. 2013). Alloys, such as stainless steels, are produced by melting primary metals and scrap in large arc furnaces and adjusting the carbon content and concentration of alloying metals to the desired levels.

There is an estimated 350 million tons of nickel resources available globally (USGS 2024). Approximately 54% of these resources is in laterites and 35% is in sulfide deposits, but nickel can also be found in manganese crusts and nodules on the ocean floor (USGS 2024). Nickel has also been found in meteorites, with the content ranging from 5 to 50% (Duke 1980a; Mastromatteo 1986). In 2023, all of the 16,000 tons of nickel produced in the United States occurred at the underground Eagle Mine in Michigan (USGS 2024). One company in Missouri recovered nickel from mine tailings, and nickel was also produced as a byproduct of smelting and refining ore in Montana (USGS 2024).

Simple nickel salts (nickel acetate, nickel nitrate, and nickel chloride) can be produced by the reaction of the organic acid and nickel carbonate, reaction of the acid with an aqueous nickel salt solution, or reaction of the acid with a fine nickel powder or black nickel oxide (Antonsen and Meshri 2005). Nickel carbonate can be produced by oxidation of nickel powder in ammonia and CO_2; the carbonate salt is formed as a precipitate after boiling off the ammonia (Antonsen and Meshri 2005). Double salts like nickel ammonium sulfate are produced by crystallizing the individual salts from aqueous solution (Antonsen and Meshri 2005). Nickel cyanide is produced from potassium cyanide and nickel sulfate (Antonsen and Meshri 2005). A sintered green nickel oxide is produced by smelting purified nickel matte at 1,000°C, and the powdered form is produced through desulfurization of the nickel matte. Green nickel oxide is also a product of thermal decomposition of some nickel salts (nickel carbonate and nickel nitrate)

(Antonsen and Meshri 2005). Black nickel oxide is produced from the calcination of nickel carbonate or nickel nitrate salts at 600°C. Nickel subsulfide occurs in the mineral, heazlewoodite (Antonsen and Meshri 2005). Nickel sulfamate is prepared from fine nickel powder or black nickel oxide with a hot sulfamic acid aqueous solution (Antonsen and Meshri 2005). Nickel sulfate can be prepared in a similar way with sulfuric acid, or from a gas-phase reaction of nickel carbonyl, sulfur dioxide, and oxygen at 100°C.

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

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

State[a]	Number of facilities	Minimum amount on site in pounds[b]	Maximum amount on site in pounds[b]	Activities and uses[c]
AL	72	0	10,000,000,000	1, 7, 8, 9, 11, 12, 13, 14
AR	42	0	999,999	2, 4, 7, 8, 11, 12, 13, 14
AZ	24	0	9,999,999	1, 5, 8, 11, 12, 14
CA	99	0	9,999,999	1, 2, 3, 5, 6, 7, 8, 9, 11, 12, 13, 14
CO	12	0	999,999	1, 2, 3, 4, 5, 7, 8, 11, 12, 14
CT	53	100	9,999,999	2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 14
DE	3	10,000	99,999	2, 3, 8
FL	28	100	999,999	1, 5, 7, 8, 9, 10, 12, 13, 14
GA	43	0	49,999,999	1, 2, 3, 5, 7, 8, 11, 12, 14
IA	70	100	9,999,999	1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
ID	9	0	999,999	1, 5, 8, 12, 14
IL	134	0	49,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14
IN	161	0	49,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
KS	49	0	9,999,999	7, 8, 9, 12, 14
KY	60	100	49,999,999	1, 2, 3, 4, 6, 7, 8, 9, 11, 12, 13, 14
LA	29	1,000	9,999,999	1, 2, 3, 5, 7, 8, 10, 11, 12, 13, 14
MA	36	1,000	999,999	8, 9, 11, 12, 14
MD	9	0	999,999	2, 3, 4, 8, 9, 12
ME	8	1,000	999,999	2, 3, 7, 8, 9, 11, 12
MI	112	0	9,999,999	1, 2, 3, 4, 5, 7, 8, 9, 11, 12, 14

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

State[a]	Number of facilities	Minimum amount on site in pounds[b]	Maximum amount on site in pounds[b]	Activities and uses[c]
MN	57	0	999,999	2, 7, 8, 9, 12, 13, 14
MO	58	0	9,999,999	1, 7, 8, 9, 10, 11, 12, 13, 14
MS	29	1,000	9,999,999	7, 8, 12
MT	1	10,000	99,999	7, 8, 11
NC	70	0	9,999,999	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 14
ND	6	1,000	99,999	8, 9, 10, 12
NE	23	1,000	999,999	1, 2, 3, 5, 8, 9, 10, 11, 14
NH	14	100	999,999	2, 3, 7, 8, 11
NJ	20	100	9,999,999	2, 3, 4, 7, 8, 9, 11, 12, 14
NM	2	10,000	999,999	2, 4, 9, 11, 12
NV	13	100	9,999,999	1, 2, 3, 4, 5, 7, 8, 9, 11, 12, 13, 14
NY	47	0	49,999,999	2, 3, 4, 7, 8, 9, 11, 12, 14
OH	219	0	49,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
OK	73	100	49,999,999	1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
OR	19	100	999,999	1, 2, 3, 4, 6, 7, 8, 9, 12, 14
PA	207	0	9,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
PR	3	10,000	9,999,999	7, 8, 11
RI	6	1,000	99,999	8, 9
SC	56	100	9,999,999	2, 3, 4, 6, 7, 8, 9, 11, 12, 14
SD	10	0	99,999	8, 14
TN	75	0	9,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14
TX	170	0	499,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
UT	15	1,000	999,999	7, 8
VA	28	1,000	999,999	1, 2, 3, 4, 5, 7, 8, 12, 14
VT	2	1,000	99,999	2, 3, 8, 9, 11, 14
WA	23	1,000	999,999	1, 2, 3, 4, 7, 8, 9, 10, 11, 12, 14
WI	177	0	9,999,999	1, 2, 3, 5, 7, 8, 9, 10, 11, 12, 14

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

State[a]	Number of facilities	Minimum amount on site in pounds[b]	Maximum amount on site in pounds[b]	Activities and uses[c]
WV	7	100	9,999,999	1, 2, 3, 5, 7, 8, 14
WY	2	1,000	99,999	2, 4, 9, 12

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

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

Source: TRI22 2024 (Data are from 2022)

Table 5-2. Facilities that Produce, Process, or Use Nickel Compounds[a]

State[b]	Number of facilities	Minimum amount on site in pounds[c]	Maximum amount on site in pounds[c]	Activities and uses[d]
AK	3	10,000	9,999,999	1, 5, 8, 12, 13, 14
AL	37	0	9,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
AR	15	1,000	999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
AZ	11	1,000	99,999	1, 2, 3, 5, 7, 8, 9, 11, 12, 13, 14
CA	43	0	9,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14
CO	12	0	999,999	1, 2, 4, 5, 6, 7, 8, 10, 12, 13, 14
CT	10	1,000	999,999	1, 3, 7, 8, 9, 10, 11, 12, 13
DC	1	10,000	99,999	1, 3, 11
DE	3	100	999,999	1, 2, 3, 8, 10, 13, 14
FL	18	0	9,999,999	1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
GA	22	100	999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
HI	1	0	99	1, 5
IA	8	1,000	999,999	1, 3, 4, 5, 7, 8, 9, 10, 11, 12
ID	7	0	999,999	1, 5, 7, 8, 11, 12, 13, 14
IL	61	0	999,999	1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14
IN	64	0	49,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
KS	11	1,000	999,999	1, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14

Table 5-2. Facilities that Produce, Process, or Use Nickel Compounds[a]

State[b]	Number of facilities	Minimum amount on site in pounds[c]	Maximum amount on site in pounds[c]	Activities and uses[d]
KY	32	1,000	49,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14
LA	38	0	49,999,999	1, 2, 3, 4, 5, 6, 8, 9, 10, 12, 13, 14
MA	5	1,000	999,999	1, 3, 4, 5, 6, 7, 8
MD	13	0	999,999	1, 3, 4, 5, 7, 9, 13, 14
ME	2	0	999	1, 5, 8, 12
MI	68	100	49,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
MN	21	0	99,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14
MO	20	0	999,999	1, 3, 4, 5, 6, 7, 8, 9, 12, 13, 14
MS	20	1,000	9,999,999	1, 2, 5, 7, 8, 10, 11, 12, 13, 14
MT	8	1,000	9,999,999	1, 3, 4, 5, 6, 10, 11, 12, 13, 14
NC	18	100	9,999,999	1, 2, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14
ND	4	1,000	999,999	1, 3, 5, 12, 13, 14
NE	9	0	999,999	1, 3, 4, 5, 6, 7, 8, 9, 12, 13
NH	4	1,000	99,999	8, 14
NJ	10	1,000	999,999	1, 2, 3, 4, 6, 7, 8, 9, 10, 14
NM	4	100	99,999	1, 3, 4, 5, 9, 10, 13, 14
NV	17	0	9,999,999	1, 2, 3, 4, 5, 7, 8, 9, 12, 13, 14
NY	14	0	999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 12, 13, 14
OH	76	0	49,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
OK	21	0	999,999	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14
OR	4	1,000	9,999,999	1, 2, 3, 5, 7, 8, 11
PA	75	0	499,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
PR	2	1,000	99,999	1, 3, 5, 6, 8, 12, 14
RI	4	1,000	9,999,999	7, 8, 10
SC	28	0	9,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12, 13, 14
TN	45	0	9,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
TX	101	0	999,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
UT	14	1,000	49,999,999	1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
VA	6	10,000	999,999	1, 5, 8, 12
VT	1	10,000	99,999	1, 2, 3, 5, 8, 9, 11
WA	11	100	9,999,999	1, 3, 5, 7, 8, 9, 10, 12, 13, 14

Table 5-2. Facilities that Produce, Process, or Use Nickel Compounds[a]

State[b]	Number of facilities	Minimum amount on site in pounds[c]	Maximum amount on site in pounds[c]	Activities and uses[d]
WI	31	0	999,999	1, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14
WV	13	1,000	49,999,999	1, 2, 3, 4, 5, 7, 8, 9, 12, 13, 14
WY	7	0	9,999,999	1, 3, 4, 5, 9, 10, 12, 13, 14

[a]Data are for any unique substance that contains nickel as part of that chemical's structure; specific nickel compounds are not specified by the TRI.
[b]Post office state abbreviations used.
[c]Amounts on site reported by facilities in each state.
[d]Activities/uses:

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

Source: TRI22 2024 (Data are from 2022)

5.2.2 Import/Export

According to USGS (2024), an estimated 1 metric ton of nickel ore and concentrates, 120,000 metric tons of primary nickel, and 39,000 metric tons of secondary nickel were imported into the United States in 2023. Between 2019 and 2022, annual imports ranged from 3 to 95 metric tons of ores and concentrates, 105,000–127,000 metric tons of primary nickel, and 31,800–37,700 of secondary nickel (USGS 2024). Between 2019 and 2022, Canada, Norway, Finland, and Russia supplied 46, 9, 7, and 7% of nickel, respectively (USGS 2024). Canada, Mexico, and the United Kingdom supplied 40, 26, and 9% of nickel-containing scrap, respectively (USGS 2024). The product class with the highest quantity of imports in 2018 was unwrought cathodes, pellets, briquets, and shot at 112,000 metric tons of contained nickel, followed by stainless steel scrap at 24,800 metric tons of contained nickel (USGS 2023).

Nickel exports of ores and concentrates in the United States ranged from 13,400 to 15,200 metric tons between 2019 and 2022; primary nickel exports ranged from 11,100 to 12,800 and secondary nickel exports ranged from 29,200 to 47,800 (USGS 2024). Exports in 2023 are estimated to be 10,000 metric tons of ores and concentrates, 11,000 metric tons of primary nickel, and 58,000 metric tons of secondary nickel (USGS 2024). In 2018, stainless steel scrap was the product class with the most exports at 49,000 metric tons of contained nickel (USGS 2023). Most exports of nickel in 2018 were to Canada (35,900 metric tons) followed by Taiwan (7,790 metric tons) and Mexico (4,280 metric tons) (USGS 2023).

5.2.3 Use

Nickel is useful in many applications due to its resistance to corrosion, strength, and ability to withstand extreme temperatures. Commercial forms of nickel and their uses are reported below in Table 5-3.

Table 5-3. Commercial Forms of Nickel and Their Uses

Type	Approximate nickel content (weight %)	Uses	Reference
Electrolytic (cathode)	>99.9	Alloy production, electroplating	Tundermann et al. 2013
Electrolytic rounds	>99.9	Electroplating	
Carbonyl pellets	>99.7	Alloy production, electroplating	
Briquettes	99.9	Alloy production	
Rondelles	99.3	Alloy production	
Powder	99.74	Sintered parts, battery electrodes	
Nickel oxide sinter	76.0	Steel and ferrous alloy production	
Ferronickel	20–50	Steel and ferrous alloy production	
Nickel acetate tetrahydrate ($Ni(CH_3COO)_2 \cdot 4\ H_2O$)	23.59	Catalyst intermediate, intermediate for other nickel compounds, dye mordant, sealer for anodized aluminum, electroplating	Antonsen and Meshri 2005
Nickel ammonium sulfate		Formerly in electroplating; Dye mordant	Antonsen and Meshri 2005; Lascelles et al. 2019
Basic nickel carbonate ($2\ NiCO_3 \cdot 3\ Ni(OH)_2 \cdot 4\ H_2O$)	49.94	Catalyst intermediate, colored glass preparation, pigment manufacture, neutralizing compound in electroplating solutions	Antonsen and Meshri 2005; Lascelles et al. 2019
Nickel chloride hexahydrate ($NiCl_2 \cdot 6\ H_2O$)	24.69	Electroplating, catalyst intermediate	Antonsen and Meshri 2005; Lascelles et al. 2019; Tundermann et al. 2013
Nickel cyanide	53.01	Used in Reppe process	Antonsen and Meshri 2005

Table 5-3. Commercial Forms of Nickel and Their Uses

Type	Approximate nickel content (weight %)	Uses	Reference
Nickel oxide	76–77 (black oxide); 78.5(green oxide)	Alloy steels and stainless steels (sinter oxide); ceramic industry for frit, ferrites, and inorganic colors (green and black oxide); catalysts, nickel salt production (black oxide)	Antonsen and Meshri 2005; Lascelles et al. 2019
Nickel nitrate hexahydrate ($Ni(NO_3)_2{\cdot}6\ H_2O$)	20.18	Electroplating, catalysts; intermediate in nickel-alkaline batteries	Antonsen and Meshri 2005; Lascelles et al. 2019; Tundermann et al. 2013
Nickel sulfamate	11 (aqueous solution)	Electrolyte in electroforming systems	Lascelles et al. 2019
Nickel sulfate tetrahydrate ($NiSO_4{\cdot}6\ H_2O$)	22.33	Electroplating, catalysts; lithium-ion batteries	Tundermann et al. 2013; Lascelles et al. 2019

In 2018, 159,000 of the 230,000 metric tons of nickel consumed in the United States was for stainless and heat-resistant steel (USGS 2023). In 2023, the estimated total apparent consumption of nickel in the United States was 190,000 metric tons (USGS 2024). Total apparent consumption ranged from 200,000 to 217,000 between 2019 and 2022 (USGS 2024). The primary uses of nickel in the United States are for stainless and alloy steels, nonferrous alloys and superalloys, and electroplating (USGS 2024). More than 85% of consumption in the United States is typically accounted for by stainless and alloy steel and nickel-containing alloys (USGS 2024). Nickel-containing alloys are often used in equipment and parts in chemical plants, petroleum refineries, jet engines, power generation facilities, and offshore installations due to nickel's ability to withstand corrosion and high temperatures (USGS 2012). Nickel alloys are used in dental appliances and tools (Berniyanti et al. 2020; Hariyani et al. 2015; Kulkami et al. 2016). Nickel alloys are commonly used in medical devices and implants including orthopedic implants and cardiovascular prosthesis (i.e., stents, pacemakers), and in permanent birth control implants (FDA 2020a; Saylor et al. 2018; Tramontana et al. 2020). Some batteries contain nickel, such as nickel-cadmium, nickel-metal hydride, and sodium nickel-chloride batteries, which are used in satellites, portable electronic equipment, and electric vehicles (Bukhari et al. 2015; Matheys et al. 2006). Nickel is also used in cast irons, for chemical uses, and as a catalyst (USGS 2023, 2024). Nickel is used in all U.S. coins but the penny (USDT 2018).

Nickel was on the 2023 DOE Critical Materials list of materials essential for energy technology development (DOE 2023). A growing sector of nickel demand is batteries. Nickel is used in the cathodes of lithium-ion batteries, such as the lithium-nickel-cobalt-aluminum and lithium-nickel-cobalt-manganese cathode formulations (USGS 2023). The Nickel Institute estimated that 39% of lithium-ion batteries contained nickel in 2016 and estimated that this would increase to 58% in 2025 (USGS 2023). The use of batteries in electric vehicles (EVs) is part of this increased demand. In 2022, 10% of global nickel demand was for EV batteries (IEA 2023).

5.2.4 Disposal

Little information concerning the disposal of nickel and its compounds is found in the literature. Much of the nickel used in metal products (e.g., stainless steel, nickel plate, various alloys) is recycled, which is evident from the fact that 57% of nickel consumption in 2023 was derived from secondary, purchased scrap (USGS 2024). The 2022 TRI reported that 80% of the 7,456,857 pounds of nickel and 88% of the 26,369,893 pounds of nickel compounds disposed of or otherwise released are released to land (TRI22 2024). Steel and other nickel-containing items discarded by households and commercial establishments are generally recycled, landfilled, or incinerated along with normal commercial and municipal trash.

Nickel (II) is poorly removed from wastewater in the activated sludge process because of its high solubility (Stephenson et al. 1987). Only 30–40% of nickel was removed in a pilot activated sludge plant. Nickel is removed from electroplating wastes by treatment with hydroxide, lime, and/or sulfide to precipitate the metal (Barakat 2011). Removal by adsorption onto activated carbon is also utilized (Barakat 2011).

Nickel and its compounds have been designated as toxic pollutants by EPA pursuant to Section 307(a)(1) of the Federal Water Pollution Control Act (EPA 2003). As such, permits are issued by the states under the National Pollutant Discharge Elimination System (NPDES) for discharges of nickel that meet the applicable requirements (EPA 2010).

5.3 RELEASES TO THE ENVIRONMENT

Tables 5-4 and 5-5 show the releases of nickel and nickel compounds, respectively, to the air, water, and soil from facilities required to report to the Toxics Release Inventory (TRI). The Toxics Release Inventory (TRI) data should be used with caution because only certain types of facilities are required to

report (EPA 2022a). This is not an exhaustive list. Manufacturing and processing facilities are required to report information to the TRI only if they employ ≥10 full-time employees; if their facility's North American Industry Classification System (NAICS) codes is covered under EPCRA Section 313 or is a federal facility; and if their facility manufactures (defined to include importing) or processes any TRI chemical in excess of 25,000 pounds, or otherwise uses any TRI chemical in excess of 10,000 pounds, in a calendar year (EPA 2022a).

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

		Reported amounts released in pounds per year[b]							
							Total release		
State[c]	RF[d]	Air[e]	Water[f]	UI[g]	Land[h]	Other[i]	On-site[j]	Off-site[k]	On- and off-site
AL	72	11,038	10,812	0	56,151	71,471	11,410	138,063	149,472
AZ	24	705	76	0	593,806	135	589,887	4,834	594,721
AR	41	2,626	16	0	1,163	1,490	3,016	2,279	5,295
CA	99	940	3,971	0	185,492	8,734	123,858	75,278	199,136
CO	12	43	50	0	118,594	11,455	92,044	38,098	130,142
CT	53	621	7,385	0	7,610	7,727	669	22,674	23,342
DE	3	5	0	0	698	146	5	844	849
FL	28	10,249	53	5,183	21,474	421	15,711	21,670	37,381
GA	43	1,167	51	0	24,936	44,688	22,697	48,146	70,843
ID	9	198	0	0	107,386	5,098	76,255	36,427	112,682
IL	134	4,470	1,344	2,310	57,720	14,233	5,817	74,259	80,076
IN	160	10,487	10,757	0	1,713,545	6,194	11,372	1,729,611	1,740,983
IA	68	4,029	705	0	35,205	12,020	22,273	29,686	51,959
KS	49	1,223	21	0	1,629	25,111	1,229	26,756	27,985
KY	60	6,230	307	0	752,821	1,618	6,248	754,728	760,976
LA	29	532	1,081	3,067	9,625	12	5,049	9,267	14,316
ME	8	249	34	0	1,580	3,647	264	5,246	5,510
MD	9	6	10	0	6	1,212	6	1,227	1,234
MA	36	413	932	0	52,547	31,123	1,201	83,815	85,015
MI	112	304,816	742	0	53,218	20,696	304,934	74,538	379,472
MN	57	1,861	30	0	15,690	13,016	1,862	28,736	30,597
MS	29	3,623	2,557	0	9,976	83,402	6,156	93,402	99,559
MO	58	951	541	0	103,871	106	96,229	9,240	105,469
MT	1	19	0	0	5	0	19	5	24
NE	23	731	2,468	0	15,986	3,289	731	21,744	22,475
NV	13	23	34	0	1,168,157	1,018	1,167,754	1,477	1,169,231
NH	14	46	22	0	6,608	4,059	47	10,688	10,734
NJ	20	684	98	0	116,105	2,194	691	118,389	119,080

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

		Reported amounts released in pounds per year[b]							
							Total release		
State[c]	RF[d]	Air[e]	Water[f]	UI[g]	Land[h]	Other[i]	On-site[j]	Off-site[k]	On- and off-site
NM	2	60	0	0	27,000	0	27,060	0	27,060
NY	47	893	1,751	0	12,474	7,151	1,038	21,230	22,268
NC	69	6,274	194	0	56,547	2,811	59,453	6,373	65,826
ND	6	252	8	0	5,119	0	265	5,114	5,380
OH	217	6,211	1,858	2,054	97,656	61,070	46,972	121,876	168,848
OK	73	1,277	67	0	52,439	1	1,305	52,480	53,786
OR	19	40,814	228	0	86,004	5,873	113,690	19,228	132,918
PA	207	12,963	1,920	0	70,299	56,006	13,875	127,313	141,189
RI	6	0	20	0	0	2,314	0	2,334	2,334
SC	56	809	370	0	33,377	16,230	1,892	48,893	50,785
SD	10	48	7	0	33	5,804	48	5,844	5,891
TN	75	11,379	117,393	0	164,468	64,383	11,508	346,115	357,623
TX	170	8,151	1,701	87,485	33,709	7,975	97,768	41,252	139,020
UT	15	322	14	0	201	0	324	213	537
VT	2	0	1	0	51	29,100	0	29,152	29,152
VA	28	479	682	0	20,624	1,172	1,010	21,947	22,957
WA	23	1,237	1,076	0	10,765	48,291	1,247	60,121	61,368
WV	6	8,748	292	0	0	7,189	8,758	7,471	16,229
WI	176	4,251	9,765	0	56,863	21,889	4,727	88,042	92,769
WY	2	21	1	0	32,337	0	32,359	0	32,359
PR	3	0	0	0	0	0	0	0	0
Total	2,476	472,173	181,445	100,099	5,991,567	711,573	2,990,732	4,466,125	7,456,857

[a]The TRI data should be used with caution since only certain types of facilities are required to report. This is not an exhaustive list. Data are rounded to nearest whole number. Data are for elemental nickel (CASRN 7440-02-0).
[b]Data in TRI are maximum amounts released by each facility.
[c]Post office state abbreviations are used.
[d]Number of reporting facilities.
[e]The sum of fugitive and point source releases are included in releases to air by a given facility.
[f]Surface water discharges, wastewater treatment (metals only), and publicly owned treatment works (POTWs) (metal and metal compounds).
[g]Class I wells, Class II-V wells, and underground injection.
[h]Resource Conservation and Recovery Act (RCRA) subtitle C landfills; other onsite landfills, land treatment, surface impoundments, other land disposal, other landfills.
[i]Storage only, solidification/stabilization (metals only), other off-site management, transfers to waste broker for disposal, unknown.
[j]The sum of all releases of the chemical to air, land, water, and underground injection wells.
[k]Total amount of chemical transferred off-site, including to POTWs.

RF = reporting facilities; UI = underground injection

Source: TRI22 2024 (Data are from 2022)

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

		Reported amounts released in pounds per year[b]							
							Total release		
State[c]	RF[d]	Air[e]	Water[f]	UI[g]	Land[h]	Other[i]	On-site[j]	Off-site[k]	On- and off-site
AL	37	3,713	5,715	0	600,299	20,896	374,222	256,401	630,623
AK	3	94	11	0	3,183,593	0	3,183,698	0	3,183,698
AZ	11	665	10	0	81,769	15,240	80,309	17,375	97,684
AR	15	140,172	413	0	503,512	2,970	606,034	41,034	647,068
CA	37	1,842	2,206	0	432,485	44,351	400,016	80,867	480,883
CO	12	4,767	211	0	182,341	0	157,416	29,903	187,319
CT	10	1,520	172	0	464	26,303	1,548	26,911	28,459
DE	3	127	366	0	0	1,506	493	1,506	1,998
DC	1	0	2	0	109	0	0	111	111
FL	18	3,904	4,643	0	166,197	6,824	81,613	99,956	181,569
GA	22	745	2,295	0	68,482	466,906	70,465	467,963	538,428
HI	1	15,000	1	0	21,200	0	15,001	21,200	36,201
ID	7	505	169	0	168,650	0	159,926	9,399	169,325
IL	56	10,536	21,619	280	597,894	157,658	464,085	323,902	787,987
IN	62	27,418	46,927	366	786,196	85,412	645,238	301,081	946,319
IA	7	424	151	0	9,935	0	568	9,941	10,510
KS	11	854	43,147	122	36,155	137,868	36,762	181,385	218,146
KY	32	4,371	9,911	0	447,216	162,593	324,639	299,452	624,090
LA	38	22,726	7,129	9,518	395,991	1,087	245,624	190,827	436,450
ME	2	200	212	0	1,640	0	2,052	0	2,052
MD	13	557	146	0	22,396	0	960	22,138	23,098
MA	5	1,133	32	0	4,184	15,296	1,133	19,511	20,644
MI	66	6,672	27,943	115,813	5,884,641	31,839	5,774,511	292,398	6,066,908
MN	21	856	625	0	56,717	23,904	28,630	53,472	82,102
MS	20	4,380	475	105,851	61,893	13,200	125,119	60,680	185,799
MO	20	891	407	0	98,524	5,501	64,970	40,352	105,323
MT	8	1,171	98	0	593,779	11	392,956	202,103	595,059
NE	9	1,176	1,262	0	68,559	2,061	56,410	16,648	73,058
NV	13	14,460	222	260	2,840,791	12	2,827,076	28,670	2,855,746
NH	4	0	0	0	4,058	0	0	4,058	4,058
NJ	10	256	38,529	0	13,529	8,209	641	59,883	60,524
NM	4	227	20	7	55,663	8,509	55,917	8,509	64,426
NY	14	624	679	5	10,125	16,023	625	26,831	27,456
NC	18	2,882	956	0	389,089	751	355,577	38,102	393,679
ND	3	819	1	244	71,958	0	46,214	26,808	73,022

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

		Reported amounts released in pounds per year[b]							
							Total release		
State[c]	RF[d]	Air[e]	Water[f]	UI[g]	Land[h]	Other[i]	On-site[j]	Off-site[k]	On- and off-site
OH	76	52,707	8,118	37,344	1,162,019	540,489	379,098	1,421,579	1,800,677
OK	20	1,218	126	1,826	298,871	0	275,341	26,700	302,041
OR	4	83	27	0	2,340	0	114	2,336	2,451
PA	75	13,669	2,531	0	793,506	114,452	444,577	479,581	924,158
RI	4	85	4	0	0	1,689	85	1,693	1,778
SC	28	4,107	1,677	0	213,624	43,899	165,044	98,263	263,308
TN	45	2,088	12,817	0	241,731	10,357	177,079	89,914	266,993
TX	101	23,645	17,092	106,757	1,309,571	70,893	569,155	958,803	1,527,958
UT	14	2,566	334	0	613,629	10	612,075	4,465	616,540
VT	1	0	1,547	0	770	15,007	0	17,324	17,324
VA	6	225	7,914	0	22,032	6,947	22,271	14,847	37,118
WA	11	2,835	1,082	0	32,554	16	7,042	29,445	36,487
WV	12	3,121	700	0	479,498	51	420,812	62,558	483,370
WI	31	541	1,302	2,131	69,913	12,683	3,186	83,384	86,569
WY	7	986	0	0	142,799	0	124,354	19,431	143,785
PR	2	230	26	0	19,257	0	230	19,283	19,513
Total	1,050	383,795	272,003	380,524	23,262,149	2,071,422	19,780,910	6,588,984	26,369,893

[a]The TRI data should be used with caution since only certain types of facilities are required to report. This is not an exhaustive list. Data are rounded to nearest whole number. Data are for any unique substance that contains nickel as part of that chemical's structure; specific nickel compounds are not specified by the TRI.
[b]Data in TRI are maximum amounts released by each facility.
[c]Post office state abbreviations are used.
[d]Number of reporting facilities.
[e]The sum of fugitive and point source releases are included in releases to air by a given facility.
[f]Surface water discharges, wastewater treatment (metals only), and publicly owned treatment works (POTWs) (metal and metal compounds).
[g]Class I wells, Class II-V wells, and underground injection.
[h]Resource Conservation and Recovery Act (RCRA) subtitle C landfills; other onsite landfills, land treatment, surface impoundments, other land disposal, other landfills.
[i]Storage only, solidification/stabilization (metals only), other off-site management, transfers to waste broker for disposal, unknown.
[j]The sum of all releases of the chemical to air, land, water, and underground injection wells.
[k]Total amount of chemical transferred off-site, including to POTWs.

RF = reporting facilities; UI = underground injection

Source: TRI22 2024 (Data are from 2022)

5.3.1 Air

Emissions also occur from industries that produce, process, and use nickel and its compounds. Estimated releases of 472,173 pounds (~214 metric tons) of nickel to the atmosphere from 2,476 domestic manufacturing and processing facilities in 2022 accounted for about 6.3% of the estimated total environmental releases from facilities required to report to the TRI (TRI22 2024). These releases are summarized in Table 5-4.

Estimated releases of 383,795 pounds (~174 metric tons) of nickel compounds to the atmosphere from 1,050 domestic manufacturing and processing facilities in 2022 accounted for about 1.5% of the estimated total environmental releases from facilities required to report to the TRI (TRI22 2024). These releases are summarized in Table 5-5.

Nickel is released to the air from both anthropogenic and geogenic sources. Most analytical methods for nickel in environmental samples do not distinguish between compounds of nickel or the nature of its binding to soil and particulate matter. It is generally difficult to determine with certainty what forms of nickel are released from natural and anthropogenic sources, what forms are deposited or occur in environmental samples, and to what forms of nickel people are exposed. The form of nickel has important consequences as far as its transport, transformation, and bioavailability are concerned.

Natural sources of nickel include windblown dust, volcanic ash, forest fires, meteoric dust, and sea salt spray. It is estimated that 30 million kg of nickel are emitted to the atmosphere annually from natural sources (Duce et al. 1991; Giusti et al. 1993). Between 30 and 50% of natural emissions are from windblown soil particles from eroded areas (Nieminen et al. 2007). Sokolov et al. (2023) reported atmospheric emissions of nickel from the Pechenganickel smelting facility located in Northern Russia and used these emissions data to model deposition to nearby soils, water bodies, and sediment. Atmospheric emissions rose from approximately 100 metric tons per year in the 1960s to a maximum of >500 tons per year by 1980 and decreased to <100 metric tons around 2020 before the plant was closed. A comprehensive review of atmospheric nickel releases from a wide variety of sources in Europe has been summarized in the European Union Risk Assessment Report (EU RAR) of nickel and nickel compounds (EC 2008).

EPA’s National Emission Inventory (NEI) database contains information regarding sources that emit criteria air pollutants (CAPs) and their precursors, and hazardous air pollutants (HAPs) for the 50 United

States, Washington DC, Puerto Rico, and the U.S. Virgin Islands. Emissions are estimated from multiple sources, including state and local environmental agencies; the TRI database; computer models for on- and off-road emissions; and databases related to EPA's Maximum Achievable Control Technology (MACT) programs to reduce emissions of HAPs. Nickel and nickel compound emissions estimated from the 2020 inventory are summarized in Table 5-6. Limited sectors were relevant for estimations of nickel oxide, nickel subsulfide, and nickel refinery dust emissions.

Table 5-6. National Emission Inventory (NEI) Total National Emissions for Nickel and Nickel Compounds Estimated by Sector 2020

Sector	Nickel emissions (pounds)	Nickel oxide emissions (pounds)	Nickel subsulfide emissions (pounds)	Nickel refinery dust emissions (pounds)
Industrial processes; NEC	109,409	14	24	–
Mobile; locomotives	87,367	–	–	–
Fuel combustion; electric generation; natural gas	86,871	–	–	–
Fuel combustion; commercial/ institutional; oil	46,984	–	–	–
Industrial processes; non-ferrous metals	41,483	5	-	0
Fuel combustion; electric generation; coal	40,376	–	–	–
Industrial processes; ferrous metals	38,799	2	–	–
Fuel combustion; electric generation; oil	36,039	–	–	–
Fuel combustion; industrial boilers, ICEs; oil	34,919	–	–	–
Industrial processes; petroleum refineries	29,416	–	26	–
Fuel combustion; industrial boilers, ICEs; natural gas	25,057	–	–	–
Mobile; on-road non-diesel light duty vehicles	24,955	–	–	–
Industrial processes; chemical manufacturing	24,764	26	–	1,581
Fuel combustion; industrial boilers, ICEs; coal	14,660	–	–	–
Fuel combustion; industrial boilers, ICEs; other	7,526	–	–	–
Mobile; non-road equipment; gasoline	7,314	–	–	–
Mobile; commercial marine vessels	7,204	–	–	–

Table 5-6. National Emission Inventory (NEI) Total National Emissions for Nickel and Nickel Compounds Estimated by Sector 2020

Sector	Nickel emissions (pounds)	Nickel oxide emissions (pounds)	Nickel subsulfide emissions (pounds)	Nickel refinery dust emissions (pounds)
Fuel combustion; industrial boilers, ICEs; biomass	3,375	–	–	–
Mobile; on-road diesel heavy duty vehicles	3,336	–	–	–
Solvent; industrial surface coating and solvent use	3,239	46	–	–
Industrial processes; pulp and paper	3,159	–	–	–
Industrial processes; cement manufacturing	2,670	–	–	–
Fuel combustion; commercial/ institutional; natural gas	2,472	–	–	–
Industrial processes; storage and transfer	2,050	91	0	0
Industrial processes; mining	1,350	–	–	–
Fuel combustion; residential; oil	1,183	–	–	–
Waste disposal	1,022	0	–	–
Mobile; on-road diesel light duty vehicles	1,006	–	–	–
Mobile; non-road equipment; diesel	915	–	–	–
Solvent; degreasing	805	–	–	–
Fuel combustion; electric generation; other	782	–	–	–
Fuel combustion; electric generation; biomass	446	–	–	–
Dust; construction dust	440	–	–	–
Industrial processes; oil and gas production	423	–	–	–
Mobile; on-road non-diesel heavy duty vehicles	369	–	–	–
Fuel combustion; commercial/ institutional; coal	300	–	–	–
Mobile; non-road equipment; other	243	–	–	–
Fuel combustion; commercial/ institutional; biomass	224	–	–	–
Fuel combustion; residential; wood	81	–	–	–
Fuel combustion; commercial/ institutional; other	47	–	–	–

Table 5-6. National Emission Inventory (NEI) Total National Emissions for Nickel and Nickel Compounds Estimated by Sector 2020

Sector	Nickel emissions (pounds)	Nickel oxide emissions (pounds)	Nickel subsulfide emissions (pounds)	Nickel refinery dust emissions (pounds)
Miscellaneous non-industrial NEC	13	–	–	–
Solvent; graphic arts	10	–	–	–
Bulk gasoline terminals	1	–	0	–
Fuel combustion; residential; other	0	–	–	–

Source: EPA 2020a

ICE = internal combustion engine; NEC = not elsewhere classified

Eagle Mine, in the upper peninsula of Michigan, is a nickel and copper mining site and the only active primary nickel mine in the United States. Estimated emissions, including fugitive emissions, from storage and transport on site were 2.275 pounds of nickel per year (Barr 2019). The nickel ore is sent to Humboldt Mill in Champion, Michigan, for processing. Estimated emissions from this site processes, including fugitive emissions, were 126.5 pounds of nickel per year (Barr 2023).

Nickel is present in fuel oil, natural gas, and coal. Outside of industrial processes, the other largest activities releasing nickel to the atmosphere is fuel combustion for motor vehicles or electricity generation (EPA 2020a). The nickel species present in particulate emissions from the stacks of eight residual fuel oil burning electric utility steam-generating units in New York, Hawaii, and Florida were characterized; nickel was present predominantly in the form of $NiSO_4 \cdot 6H_2O$, with lesser amounts of nickel oxides (Huggins et al. 2011). Nickel sulfide and nickel subsulfide were present at ≤3% total nickel in the particulate matter samples (Huggins et al. 2011). Nickel concentrations tend to increase with decreasing particle size (Galbreath and Zygarlicke 2004). Other studies found that only 17–22% of nickel emissions from coal-fired power plants were associated with particles of >2 μm, and that the mass median diameter (MMD) of nickel-containing particles from a plant with pollution control devices was 5.4 μm (Gladney et al. 1978; Lee et al. 1975). In one study, 40% of the nickel in coal fly ash was adsorbed on the surface of the particles rather than being embedded in the aluminosilicate matrix (Hansen and Fisher 1980). Surface-adsorbed nickel would be more bioavailable than embedded nickel.

Residual fuel oil combustion for residential space and water heating as a potential source of indoor air emissions has been well characterized (Habre et al. 2014; Hsu et al. 2012; Schachter et al. 2020). Nickel

has been measured in the vapor of e-cigarettes (Goniewicz et al. 2014; Pappas et al. 2020), which may also contribute to releases to indoor air.

Nickel emissions from municipal incinerators depend on the nickel content of the refuse and the design and operation of the incinerator. Emissions of 1,022 pounds of nickel were estimated from waste disposal in 2020 (EPA 2020a). From 2003 to 2010, the concentration of nickel in stack emissions from 10 municipal waste incinerators in the United Kingdom ranged from 0 to 177.50 µg/m^3, with a median of 6.80 µg/m^3 (Font et al. 2015).

de Foy et al. (2012) performed a detailed study of potential sources of nickel releases to the air in Milwaukee, Wisconsin in 2010. Most estimated emissions of nickel in Milwaukee were from point sources; point sources in Milwaukee and Waukesha counties contributed 2,184 pounds/year and regional point sources contributed 105,660 pounds/year of the total nickel emissions (117,195 pounds/year) in Milwaukee (de Foy et al. 2012). Emissions from Milwaukee ships accounted for 145 pounds/year of nickel emissions (de Foy et al. 2012). Local point sources that contributed to nickel emissions in Milwaukee and Waukesha included secondary metal production, primary metal production, fabricated metal products, organic solvent evaporation, electric generation, and metal production (de Foy et al. 2012). Local area sources included commercial marine vessels, industrial area sources, and gasoline highway vehicles (de Foy et al. 2012). The study authors of a long-term study of nickel in seven Korean cities between 1998 and 2010 concluded that the sources of nickel in urban environments could include non-road sources such as aircraft and maritime shipping ports, but these sources are more likely to affect local concentrations rather than long-term urban concentrations (Kim et al. 2014).

5.3.2 Water

Estimated releases of 181,445 pounds (~82 metric tons) of nickel to surface water from 2,476 domestic manufacturing and processing facilities in 2022 accounted for about 2.4% of the estimated total environmental releases from facilities required to report to the TRI (TRI22 2024). These releases are summarized in Table 5-4.

Estimated releases of 272,003 pounds (~123 metric tons) of nickel compounds to surface water from 1,050 domestic manufacturing and processing facilities in 2022 accounted for about 1.0% of the estimated total environmental releases from facilities required to report to the TRI (TRI22 2024). These releases are summarized in Table 5-5.

Nickel is a ubiquitous natural geologic constituent and is transported into streams and waterways in runoff from natural weathering or disturbed soil. Much of this nickel is associated with particulate matter. Nickel also enters bodies of water through atmospheric deposition.

Nickel emissions to water can result from industrial activities. Limited industrial effluent sampling in New Mexico of several sources between 2018 and 2019 reported a maximum of 25 µg/L nickel (dissolved fraction) at the outfall of an electricity generation site (WQP 2024). The maximum at a mining outfall was 20 µg/L nickel (dissolved fraction). Limited industrial effluent monitoring in Ohio reported a maximum of 90.8 µg/L nickel (total recoverable) at a truck, bus, and engine manufacturing site in 2018 (WQP 2024).

Recent emission estimates per sector in the United States were not located; however, robust estimates from the European Union may be comparable. In the European Union, the total emissions to surface water were 70,914 kg Ni/year from smelting/refining; 16,660 kg Ni/year from stainless steel production; 1,004 kg Ni/year from steel product manufacturing sites; 240 kg Ni/year from nickel alloy production; 34.5 kg Ni/year from steel production/foundries; 2,331 kg nickel/year from nickel chemical production companies; 290 kg Ni/year from nickel catalyst production; 1,370 kg Ni/year from plating; 13 kg nickel/year from metal product manufacturing; 463 kg Ni/year from battery production; 26 kg Ni/year from powder metallurgy production; and 5.8 kg Ni/year from recycling (EC 2008).

Nickel mining activities are expected to be another source of aquatic emissions. At Eagle Mine in the upper peninsula of Michigan, water is pumped underground for drilling, bolting, and dust suppression; this water is pumped back to the surface for storage and eventual treatment (Eagle Mine 2023). Water that has come into contact with the temporary development rock storage area is also pumped out and eventually treated. Nickel was present at 460–52,100 µg/L in water used for underground operations; 3,890–7,160 µg/L in water recovered after contact with development rock; and 22–214 µg/L in the contact water basin in 2022 (Eagle Mine 2023). Water is treated in a system that includes metals precipitation and sedimentation treatment, and final discharge is to a rapid infiltration system (MDEQ 2013). Available monitoring of the treated effluent in 2023 reported one measurement at 5.6 µg/L nickel; the remainder was below the limit of detection (2 µg/L) (CEMP 2023).

Domestic wastewater is another anthropogenic source of nickel in waterways. Maximum nickel concentrations in treated wastewater effluent were 22.9 µg/L total nickel and 6.4 µg/L dissolved nickel in

samples collected between 2018 and 2023 (WQP 2024). From a study of influent streams of a wastewater treatment plant in Stockholm, Sweden, it was determined that the waste streams from households (e.g., drinking water) and businesses (e.g., drinking water, car washes, chemical uses) accounted for 29% of nickel in influent streams (Sörme and Lagerkvist 2002), which is likely to be comparable to what occurs in the United States. Another 31% of the nickel in influent streams is added at the wastewater treatment plant through the addition of water treatment chemicals. Storm water accounts for between 1 and 5% of the nickel in influent streams. Concentrations in treated effluents were not reported. Nickel may be removed by chemical precipitation or coagulation treatment in publicly owned treatment works, which reduces nickel releases (EPA 1981). For example, improvements in sewage treatment facilities have attributed to a reduction in the flux of nickel in wastewater effluents into the Hudson River estuary, decreasing from 518 kg/day in 1974 to 43 kg/day in 1997 (Sañudo-Wilhelmy and Gill 1999).

Nickel is a common constituent of urban and stormwater runoff. A significant source in these scenarios is from cars. Nickel can be released from diesel fuel and gasoline, lubricating oil, metal plating, and wear of the bushing or brake lining (WSDOT 2006). Use of deicers and paving asphalt can also contribute to nickel runoff. Nickel was reported at a median of 9.0 µg/L in urban stormwater runoff (EPA 2007). Runoff from highways ranged from 0 to 53.3 µg/L and runoff from parking lots ranged from 2.1 to 18 µg/L (EPA 2007).

One potential source of chemical release at waste sites is landfill leachate. In a study that looked at leachate from three municipal landfills in New Brunswick, Canada, the results were conflicting (Cyr et al. 1987). Average nickel concentrations in the three leachates (control) were 28 (45) µg/L, 33 (not detectable) µg/L, and 41 (23) µg/L. Sediment at three sites below the leachate outfalls contained 11.9, 37.4, and 71.2 ppm of nickel (dry weight). Municipal solid waste landfills in the European Union had a maximum of 23.1 mg/L total nickel in leachate, with leachate means of different landfills ranging from 0.0035 to 1.25 mg/L total nickel (EC 2008).

5.3.3 Soil

Estimated releases of 5.99 million pounds (~2,700 metric tons) of nickel to soils from 2,476 domestic manufacturing and processing facilities in 2022, accounted for about 80% of the estimated total environmental releases from facilities required to report to the TRI (TRI22 2024). An additional 100,099 pounds (~45 metric tons), constituting about 1.3% of the total environmental emissions, were released via underground injection (TRI22 2024). These releases are summarized in Table 5-4.

Estimated releases of 23.2 million pounds (~10,500 metric tons) of nickel compounds to soils from 1,050 domestic manufacturing and processing facilities in 2012, accounted for about 88% of the estimated total environmental releases from facilities required to report to the TRI (TRI22 2024). An additional 380,524 pounds (~173 metric tons), constituting about 1.4% of the total environmental emissions, were released via underground injection (TRI22 2024). These releases are summarized in Table 5-5.

Nickel is naturally present in the Earth's crust, and natural sources/processes will also release nickel to the soil. Ultramafic rocks contain high concentrations of nickel, and weathering results in geogenic releases of nickel to the soil (Li et al. 2020b). The source of anthropogenic nickel will depend greatly on land use. The major sources of anthropogenic nickel release to soil are industrial waste materials, and to agricultural soils are lime, fertilizer, and sewage sludge (McIlveen and Negusanti 1994).

5.4 ENVIRONMENTAL FATE

5.4.1 Transport and Partitioning

Air. Nickel is released into the atmosphere in the form of particulate matter or adsorbed to particulate matter. It is dispersed by wind and removed by gravitational settling (sedimentation), dry deposition (inertial impaction characterized by a deposition velocity), washout by rain (attachment to droplets within clouds), and rainout (scrubbing action below clouds) (Schroeder et al. 1987). The removal rate and distance traveled from the source depends on source characteristics (e.g., stack height), particle size and density, and meteorological conditions.

Gravitational settling governs the removal of large particles (>5 μm), whereas smaller particles are removed by other forms of dry and wet deposition. The partitioning between dry and wet deposition depends on the intensity and duration of precipitation and particle size. The importance of wet deposition relative to dry deposition generally increases with decreasing particle size. Removal of coarse particles may occur in a matter of hours. Small particles within the size range of 0.3–0.5 μm may have an atmospheric half-life as long as 30 days and, therefore, have the potential to be transported over long distances (Schroeder et al. 1987). Evidence for the long-range transport of nickel is provided by the fact that emission sources in North America, Greenland, and Europe are responsible for elevated atmospheric nickel concentrations in the Norwegian Arctic during both the summer and winter (Pacyna and Ottar 1985). Sokolov et al. (2023) used emission data over a roughly 50-year period from a smelting facility in

Northern Russia to calculate atmospheric deposition rates in nearby soils, waters, and sediment. Results from the model indicated that the intensities of nickel accumulation in the soil and bottom sediments were 2.35 and 4.48 mg/(m^2 year) during the maximum deposition periods (1980–2005), whereas the model predicted a decrease in the intensity of accumulation in the bottom sediments (0.23 mg/(m^2 year)) and slow leaching from the soil (0.19 mg/(m^2 year)) after the plant was closed.

Available studies indicate that nickel is broadly distributed among aerosol size groups. It has been concluded, based on the chemical and physical properties of atmospheric particles, that the concentrations of nickel in large particles (>1 μm diameter) that are commonly associated with particulates derived from natural sources are less than concentrations in smaller particles (<1 μm diameter) that are typically derived from anthropogenic sources (Giusti et al. 1993; Scudlark et al. 1994; Stoessel and Michaelis 1986). However, experiments in Ontario showed that nickel is associated with relatively large particles, 5.6±2.4 μm (Chan et al. 1986). A 1970 National Air Surveillance Network study of the average nickel size distribution in six American cities indicated that the MMD is ≈1.0 μm in all six cities (Lee et al. 1972). Although the sampling procedure used in this study may have underestimated large particles (Davidson 1980), it represents one of the few studies involving the size distribution of nickel aerosols in U.S. cities. Combustion conditions can impact the speciation of nickel and size of the aerosol. In the presence of sulfur, the resulting aerosols are smaller (mean size of 34 nm); without sulfur, NiO forms as larger aerosols (mean size of 44 nm) (Wang and Biswas 2000).

Metal deposition is characterized by large temporal and spatial variability. Prehistoric periods of climate change and the industrial revolution's influence on nickel deposition has been demonstrated through analysis of the Finnish peat moss cores (Krachler et al. 2003; Rausch et al. 2005). In the Florida Atmospheric Mercury Study (FAMS) conducted during 1993–1994, bulk deposition rates for nickel varied between 1.700 and 4.130 mg/m^2/year, depending on local/regional anthropogenic activity (Landing et al. 1995). Wet and dry deposition of particulates emitted from the Claremont Incinerator in Claremont, New Hampshire, were measured within an area between 2 and 15 km from the incinerator. Wet deposition rates varied between 0.50 and 8.87 μg/m^2/day, with a mean value of 3.0 μg/m^2/day and depended on distance from the incinerator and frequency that the wind blew. The mean wet deposition rate of 3.0 μg/m^2/day was a factor of approximately 19 greater than the mean dry deposition rate of 0.16 μg/m^2/day, which had been calculated from values ranging from 0.067 to 0.29 μg/m^2/day (Feng et al. 2000).

Atmospheric deposition of nickel in coastal waters has been reported. Bulk and wet deposition of nickel into Massachusetts Bay was determined to be 7,200 and 3,000 μg/m^2/year (Golomb et al. 1997), respectively, whereas a lower wet deposition rate of 257 μg/ m^2/year was measured for nickel in Chesapeake Bay (Scudlark et al. 1994). Atmospheric input of nickel into the Great Lakes has been estimated to average 160–590 ng/m^2/year (Nriagu et al. 1996). Atmospheric deposition is the primary source of nickel to the open ocean, and events like Saharan dust events, which are large-scale depositions of soil dust from the Saharan Desert, are important influxes of nickel to surface seawater (Ebling et al. 2017). Wet and dry deposition of nickel into the world's oceans is estimated to be 8–11 and 14–17 gigagrams (10^9 grams) per year, respectively (Duce et al. 1991). For the coastal ocean and waterways, fluvial input plays a bigger role in providing nickel than atmospheric deposition. The nickel that is carried into oceans in both dissolved and particulate forms through riverine input is estimated at 1,411 gigagrams per year, which is a factor of approximately 50 greater than the sum of the wet and dry deposition of nickel of 22–28 gigagrams per year (Duce et al. 1991). In an example of nickel input into Chesapeake Bay, the fluvial input of nickel of 98,700 kg/year (0.0987 gigagrams/year) is 25 times greater than bulk deposition of nickel from the atmosphere (Scudlark et al. 1994). However, for the Great Lakes, the atmospheric input of nickel accounts for 60–80% of the total anthropogenic input of nickel into Lake Superior, and 20–70% of the total inputs into Lakes Erie and Ontario (Nriagu et al. 1996).

Water. The fate of heavy metals in aquatic systems depends on partitioning between soluble and particulate solid phases. Adsorption, precipitation, coprecipitation, competition, and complexation are processes that affect partitioning. These processes are influenced by pH, redox potential, ionic strength of the water, concentration of competing and complexing ions, and species and concentration of the metal (Doig and Liber 2007; Paquin et al. 2002; Santore et al. 2021). With respect to the complexation and adsorption of nickel, the quantity and quality of organic matter have been found to be particularly important parameters (Doig and Liber 2007). The humic acid fraction reduced dissolved nickel to a greater extent than the fulvic acid fraction when dissolved organic carbon (DOC) was comparable (Doig and Liber 2007). Sorptive removal of nickel follows kinetically controlled adsorption to settling organic particulate or transport to, and direct adsorption by, the settled organic particulate (Burton et al. 2019; Huntsman et al. 2019). Desorption from dissolved organic matter is impacted by the concentration of nickel, pH, and quality of organic matter (Wang et al. 2019). Nickel dissociated faster from the fulvic acid fraction than the humic acid fraction when pH was decreased (Wang et al. 2019). The presence of other metals such as Ca^{+2} and Mg^{+2} can result in greater dissociation of soluble nickel from DOC as well (Mandal et al. 2002).

Adsorption of nickel onto suspended particles in water is one of the main removal mechanisms of nickel from the water column. Much of the nickel released into waterways as runoff is associated with particulate matter; it is transported and settles out in areas of active sedimentation such as the mouth of a river. Additionally, when a river feeds into an estuary, the salinity changes may affect adsorptivity due to complexation and competition for binding sites (Bowman et al. 1981). During a 4-month study of Lake Onondaga in Syracuse, New York, 36% of the nickel in the lake was lost to sediment (Young et al. 1982). Seventy-five percent of the nickel load into the lake was soluble and remained in the lake. The soluble nickel is not likely to be as the Ni(II) ion but is expected to exist as a complex. For example, in an analysis of the speciation of nickel in wastewater effluents and runoff discharging into San Francisco Bay, it was found that approximately 20% of soluble nickel was complexed to moderately strong complexing agents, such as humic acid and biopolymers from activated sludges (Sedlak et al. 1997). However, a larger proportion of the nickel, 75% in wastewater effluent and 25% in runoff, is found strongly complexed, with stability constants that are similar to those found for synthetic chelating agents such as EDTA, DTPA, and phosphonates. Nickel is also strongly adsorbed at mineral surfaces such as oxides and hydrous oxides of iron, manganese, and aluminum (Evans et al. 1995; Rai and Zachara 1984). Such adsorption plays an important role in controlling the concentration of nickel in natural waters.

Sediment and Soil. Nickel in soil can accumulate from chemical weathering and migration of underlying sediments, atmospheric deposition of soil dust, or, more likely for surface soils, atmospheric deposition of anthropogenic particulate (Krachler et al. 2003). Nickel typically accumulates at the surface of soils due to deposition; however, evidence of mobility in subsurface soil prior to deposition has been reported (Krachler et al. 2003; Rausch et al. 2005). Soil properties such as texture, bulk density, pH, organic matter, the type and amount of clay minerals, and certain hydroxides, as well as the extent of groundwater flow, influence the retention and release of metals by soil (Hale et al. 2017; Richter and Theis 1980). Hsieh et al. (2019) concluded that nickel favored binding with high molecular weight soil humic substances extracted from agricultural soils.

Amorphous oxides of iron and manganese, and to a lesser extent clay minerals, are important adsorbents in soil. In alkaline soils, adsorption may be irreversible (Rai and Zachara 1984), which limits nickel's availability and mobility in these soils. For example, studies of nickel speciation in ferromanganese nodules from loess soils of the Mississippi Basin found higher partitioning of nickel in the soil nodules than in soil clay matrices (Manceau et al. 2003). This is due to the selective sequestration of nickel by finely divided iron and manganese oxides in goethite and lithiophorite minerals present in the soils. Cations such as Ca^{2+} and Mg^{2+} have been reported to reduce adsorption due to competition for binding

sites, whereas anions like sulfate reduce adsorption because of complexation. Nickel adsorption depends strongly on metal concentration and pH (Giusti et al. 1993).

Batch equilibrium studies were performed to assess the potential mobility of nickel in contaminated subsoil; nickel was more mobile in soils than lead, cadmium, and zinc (LaBauve et al. 1988). The retention of nickel in two of the test subsoils diminished in the presence of synthetic landfill leachate, possibly because of complex formation. In another study in which batch adsorption experiments were conducted with a mixture of cadmium, cobalt, nickel, and zinc, and 38 different agricultural soils, taken from three depths at 13 sites, the adsorption constants ranged from 10 to 1,000 L/kg (Anderson and Christensen 1988). Soil pH, and, to a lesser extent, clay content and the amount of hydrous iron and manganese oxides most influenced nickel sorption. Mobility in soil is reduced for insoluble species of nickel, and through the initial fast adsorption followed by slow sequestration of the soluble nickel species (Hale et al. 2017).

In 12 New Mexican soils from agricultural areas and potential chemical waste disposal sites, most soils had an extremely high affinity for nickel and once sorbed, nickel was difficult to desorb (Bowman et al. 1981). Sadiq and Enfield (1984b) observed nickel ferrite formation following adsorption. Bowman et al. (1981) found that when nickel levels were >10 ppm, adsorption decreased. High concentrations of chloride decreased adsorption, but not as much as did calcium ions, which indicates that calcium competition for sorbing sites is more important than chloride complexation for reducing adsorption.

The leachability of nickel from some soils does not necessarily correlate with the total concentration of nickel in the soil. In an extraction study of soils sampled from the mining and smelting regions of Sudbury, Ontario, the percentage of nickel that is most easily extractable (in acetic acid) varied between 12 and 31% of the total nickel content (220–455 mg/kg) among the different sampling sites (Adamo et al. 1996). The remaining nickel was found in less extractable forms: 6–11% was found to be associated with manganese oxides and easily reducible iron oxides, 6–20% either bound to readily oxidizable organics or sulfides, and the remainder (55–73%) was associated with sulfides as separate grains or inclusions, iron oxide phases, carbon particles, and silicate spheroids. Similarly, in soils that are naturally enriched in heavy metals sampled from the Port MacQuaire region in Australia, the amount of nickel that can be easily extracted from soil samples is only a small fraction of the total nickel content (Lottermoser 2002). Extraction of these soils with EDTA or acetic acid yielded leachable nickel that amounted to between <0.1–4.1 and <0.01%, respectively, of the total nickel concentrations in the soil samples. Use of stronger extraction methods, for example hydrochloric acid, yielded only leachable nickel in percentages (0.1–

2.4%) equivalent to those found for EDTA. The low amount of acetic acid extractable nickel indicates negligible leaching of this metal from these soils into groundwater and surface waters (Lottermoser 2002).

Amendment of soils with exogenous humic acid reduces mobility of dissolved nickel in soil and also increases the bioavailability of this nickel to plants. Halim et al. (2003) showed that humic acid in soils from nickel-humic acid complexes results in the removal of dissolved and exchangeable nickel from soil water. The extractability of nickel increased with the aging time of the organic material. The increased bioavailability of nickel bound to humic acid is temporary and is thought to occur mainly as the result of preventing nickel from undergoing a transformation into insoluble species in soil.

In order to evaluate the potential of elements to leach from land-spread sewage sludge, Gerritse et al. (1982) studied the adsorption of elements to sandy and sandy loam topsoils from water, salt solutions, and sludge solutions. They used metal levels that occurred in the solution phase of sewage sludge, 100–1,000 ppb in the case of nickel. The results indicated that nickel is fairly mobile in these soils; the adsorption constants were ≈10–100 in the sandy soil and a factor of ≈10 higher in the sandy loam soil. The presence of sludge increases the mobility of nickel, particularly in sandy and sandy loam soils, which may be because of complexation with dissolved organic compounds (Kaschl et al. 2002) or increased ionic strength (Gerritse et al. 1982). However, land application of nickel-contaminated sludge did not give rise to increased levels of nickel in groundwater (Demirjian et al. 1984). Higher doses and repeated application of nickel-containing sewage sludge did not result in a proportional increase in nickel mobility (Hargitai 1989).

As part of EPA's Nationwide Urban Runoff Program in Fresno, California, the soil water and groundwater at depths ≤26 m beneath five urban runoff retention/recharge basins were monitored during a 2-year study (Nightingale 1987). The results indicated that there were no significant downward movements of nickel with the recharge water.

The presence of iron-(di)sulfides in wetland sediments has been associated with increased mobilization of nickel into groundwater during periods of drought in Holland (Lucassen et al. 2002). Desiccation of sediments leads to oxidation of iron-(di)sulfides and subsequent acidification (H_2SO_4) of the sediments. When the S/(Ca+Mg) ratios in these sediments rise above 2/3, mobilization of heavy metals like nickel occurs, leading to groundwater concentrations of nickel that exceeded the Dutch signal level of 50 ppb for nickel in 50% of the monitoring locations. The presence of acid volatile sulfide, iron oxide, and

manganese oxide in sediment changes the speciation of nickel, which can impact mobility (Costello et al. 2016; Schlekat et al. 2016). Nickel competitively binds with iron or manganese monosulfides, precipitating out as nickel sulfide, reducing the metal's bioavailability and mobility (Schlekat et al. 2016). This reduction in aqueous availability is seen until nickel reaches 2–8 times higher concentrations than acid volatile sulfide concentrations.

Other Media. It has been reported that nickel is not accumulated in significant amounts by aquatic organisms (Birge and Black 1980; Zaroogian and Johnson 1984). The EPA considers bioconcentration factors (BCF) >1,000 to be of concern for bioaccumulation in fish (EPA 2020b). BCF values for nickel calculated in fish and other aquatic organisms are reported to be well below 1,000. The mean BCF for three carnivorous fish was 36. The concentrations of nickel in mussels and oysters treated with 5 µg nickel/kg of seawater for 12 weeks averaged 9.62 and 12.96 µg nickel/g, respectively, on a dry weight basis (Zaroogian and Johnson 1984). When these data are adjusted for controls and the nickel concentration in tissue is expressed on a wet weight basis, the BCF for the mussels and oysters is ≈100. After 2 weeks in flowing seawater, 58 and 38% of the tissue nickel was lost from the mussel and oyster, respectively. No significant loss of nickel occurred during the remainder of the 28-week depuration period. In the work of McGeer et al. (2003), BCFs for nickel in various aquatic organisms (e.g., algae, arthropods, mollusks, and fish) was assessed based on whole-body metal concentrations and exposure concentrations that were obtained from the literature. For exposure concentrations within the range of 5–50 µg/L nickel in water, mean BCF values of 106±53 (1 standard deviation) were obtained for all organisms. When the study authors also included data for exposure concentrations outside the range of 5–50 µg/L, a BCF value of 157±135 was obtained. The study authors noted that the BCF values were inversely correlated with the exposure concentrations, where the highest BCF values were obtained at the lowest exposure concentrations.

The most important water chemistry parameters that control uptake in aquatic organisms are water hardness and DOC (EPA 2022b). Increased water hardness (higher Ca^{+2} and Mg^{+2} concentrations) has been associated with decreased metal toxicity. Nickel uptake occurs through Ca^{+2} and Mg^{+2} uptake pathways and the presence of these cations in hard water competitively reduces uptake of nickel (Brix et al. 2017). Nickel binds with DOC in water, therefore reducing the bioavailable portion for uptake by aquatic species in high DOC waters (EPA 2022b). Water pH plays a species-dependent role in reducing toxicity, potentially due to different species' pH-driven mechanisms of nickel bioavailability (EPA 2022b).

In soil, bioavailability is impacted by the speciation of nickel deposited and aging of the soil. A review of soil toxicity studies investigated biogeochemical drivers of bioavailability (Hale et al. 2017). Soils with nickel chloride ($NiCl_2$), a soluble species, had higher bioavailability than soils with nickel oxide (NiO), an insoluble species released during refining activities. Soil aging results in the oxidation of insoluble nickel species to potentially other equally insoluble species (as was the case with NiO), or initial fast adsorption followed by slow sequestration of the soluble nickel species; ultimately, the soil amended with the soluble species still had higher bioavailability after aging (Hale et al. 2017). The presence of acid volatile sulfide, iron oxide, and manganese oxide in sediment changes the speciation of nickel as the sediment ages, which resulted in differences in bioavailability and toxicity during this process compared to steady toxicity levels seen in sediments without these redox reagents (Costello et al. 2016).

There was no evidence that nickel biomagnifies in aquatic food webs, while there is evidence to indicate that the nickel concentrations in organisms decrease with increasing trophic level (McGeer et al. 2003; Suedel et al. 1994). As part of the U.S. Geological Survey National Water-Quality Assessment (NAWQA) Program, there was no statistically significant correlation between nickel concentrations in bed-sediments collected from streams and rivers in both the Northern Rockies Intermontane Basin study area and the New Jersey study area, and nickel concentrations measured in liver and fillet samples taken from fish collected in the same study areas (USGS 2000b, 2000c).

Uptake and accumulation of nickel into various plant species is known to occur. For example, Peralta-Videa et al. (2002) reported the accumulation of nickel in alfalfa grown from soils contaminated with a mixture of four metals (e.g., Cd(II), Cu(II), Ni(II), and Zn(II)) at a loading of 50 mg/kg for each metal. Concentration ratios of nickel in plant versus soil (based on dry weights) ranged between 22 and 26 over a pH range of 4.5–7.1. As with most plant species that hyperaccumulate metals, the alfalfa actively removes and translocates heavy metals, like nickel, from the roots to the shoots. To assess the accumulation and bioavailability of nickel in rice, wheat, and soil, Li et al. (2020a) analyzed soil samples with elevated nickel concentrations due to natural sources. Li et al. (2020a) found that the mean nickel concentration in soils with naturally elevated levels in China was 85.2±24.2 mg/kg in wheat-growing soil and 75.9±21.1 mg/kg in rice-growing soil. In the crops, the mean nickel concentrations were 2.66±1.46 mg/kg in rice and 1.32±0.78 mg/kg in wheat, indicating that nickel bioavailability is higher in rice than in wheat (Li et al. 2020a).

The uptake of nickel into plants is modulated by the acidity (pH) of the soil. Smith (1994) showed that nickel concentrations in rye grass were reduced by a factor of 3 as the soil pH was raised from 4 to 7.

This is thought to be due to a decrease in bioavailability of nickel with increasing pH. The bioavailability of nickel to plants is also affected by soil type. Weng et al. (2004) found that the bioavailability of nickel to oat plants grown in soil rich in organic matter is half that of sandy or clay soils in the pH range of 4.4–7.0. These differences in bioavailability are attributed to a stronger binding of nickel to organic matter than to the silicates and iron hydroxides/oxides in clay and sand under the acidic conditions of the experiment. Nickel is an essential nutrient for some crops, and deficiency can result in growth deficiencies (Brown et al. 1987; Wood et al. 2004). Therefore, uptake and accumulation in plants is expected to occur to some degree. Studies in tomato plants showed increased nickel uptake with increased nickel soil concentration; the highest detections were in the root of the plant, followed by the leaves, stem, and fruit (Correia et al. 2018). The ratio between the concentration of nickel in the whole tomato plant and nickel in soil was between 0.26 and 0.56, indicating that tomatoes are moderate (ratios >0.1 and <1) accumulators of nickel (Correia et al. 2018). The highest reported BCF was approximately 0.36 in the roots (Correia et al. 2018).

Two studies concerning levels in voles and rabbits living on sludge-amended land did not indicate any accumulation of nickel in these herbivores or in the plants they fed upon (Alberici et al. 1989; Dressler et al. 1986). The lack of significant bioaccumulation of nickel in aquatic organisms, voles, and rabbits indicates that nickel is not biomagnified in the food chain.

5.4.2 Transformation and Degradation

Air. While most analytical methods provide information concerning the metal content rather than the specific compounds or species, some characterization of nickel in airborne particulate is available. In airborne dust collected near a metallurgical plant in Dortmund, Germany, nickel was identified at 48±18% in the oxidized (NiO) fraction, at 36±20% in the soluble fraction, at 11±15% in the metallic (Ni) fraction, and at 6±4% in the sulfidic (NiS) fraction (Fuichtjohann et al. 2001). In urban aerosols collected from Davie, Florida, nickel was present as 50% oxidized ($NiFe_2O_4$), 40% soluble ($NiSO_4 \cdot H_2O$) and 10% NiS (DOE 2003). The majority of nickel (78%) in the PM10 fraction (fraction absorbed to particulate matter ≤10 microns) was the soluble species. Combustion conditions can impact the speciation of nickel and size of the aerosol. In the presence of sulfur, the resulting aerosols contain a mix of $NiSO_4$ and NiO; without sulfur, NiO forms. Higher temperatures resulted in more NiO and less $NiSO_4$ formation (Wang and Biswas 2000). It is generally assumed that elements of anthropogenic origin, especially those emanating from combustion sources are present as the oxide, and nickel oxide has been identified in

industrial emissions (Schroeder et al. 1987). Windblown dust particles may contain nickel in mineral species, which often contain nickel as the sulfide.

Water. In natural waters, nickel primarily exists as the hexahydrate. While nickel forms strong, soluble complexes with OH^-, SO_4^{2-}, and HCO_3^-, these species are minor compared with hydrated Ni^{2+} in surface water and groundwater with pH <9 (Rai and Zachara 1984). Under anaerobic conditions, such as may exist in deep groundwater, nickel sulfide would reduce free aqueous nickel concentrations to low levels.

Precipitation can remove soluble nickel from water. In aerobic waters, nickel ferrite is the most stable compound (Rai and Zachara 1984). Nickel may also be removed by coprecipitation with hydrous iron and manganese oxides. Nickel removed by precipitation and coprecipitation settles into the sediment.

A metal's form in soil or sediment and its availability are determined by measuring the extractability of the metal with different solvents. Sediment samples from western Lake Ontario were analyzed in regard to the compositional associations of nickel by a series of sequential extractions (Poulton et al. 1988). The mean nickel percentages in the various fractions were as follows: exchangeable, 0.7±1.4; carbonate, 0.0; iron or manganese oxide-bound, 0.0; organic-bound, 7.4±4.1; and residual, 91.9±4.5. The nickel concentration in 450 uncontaminated estuarine and coastal marine sites in the southeastern United States covaried significantly with the aluminum concentration, suggesting that natural aluminosilicates are the dominant natural metal-bearing phase in some aquatic systems (Windom et al. 1989). In 13 random samples of bottom sediment from the highly industrialized Meuse River in The Netherlands, between 0 and 88% (median 33%) of the nickel was removable at low pH, showing the great variability of nickel to adsorb to sediments (Mouvet and Bourg 1983).

Nickel removed by coprecipitation can be remobilized by microbial action under anaerobic conditions (Francis and Dodge 1990). Remobilization results from enzymatic reductive dissolution of iron with subsequent release of coprecipitated metals. A lowering of pH as a result of enzymatic reactions may indirectly enhance the dissolution of nickel. Experiments using mixed precipitates with goethite (α-FeOOH) indicated that a *Clostridium* species released 55% of the coprecipitated nickel after 40 hours. Similarly, precipitated nickel sulfides in sediment can be mobilized through sulfur oxidation by *Thiobacilli* (Wood 1987). In this case, the oxidized sulfur may produce H_2SO_4 and decrease the pH.

Sediment and Soil. An analysis of the thermodynamic stability models of various nickel minerals and solution species indicates that nickel ferrite is the solid species that will most likely precipitate in soils

(Sadiq and Enfield 1984a). Experiments on 21 mineral soils supported its formation in soil suspensions following nickel adsorption (Sadiq and Enfield 1984b). The formation of nickel aluminate, phosphate, or silicate was not significant. Ni^{2+} and $Ni(OH)^{+}$ are major components of the soil solution in alkaline soils. In acid soils, the predominant solution species will probably be Ni^{2+}, $NiSO_4$, and $NiHPO_4$ (Sadiq and Enfield 1984a).

A large percentage of nickel in sewage sludges exists in a form that is easily released from the solid matrix (Rudd et al. 1988). Although the availability of nickel to plants grown in sludge-amended soil is correlated with soil-solution nickel, it is only significantly correlated with diethylenetriaminepentaacetic acid-extractable nickel (Adams and Kissel 1989).

5.5 LEVELS IN THE ENVIRONMENT

Reliable evaluation of the potential for human exposure to nickel depends, in part, on the reliability of supporting analytical data from environmental samples and biological specimens. Concentrations of nickel 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 nickel levels monitored or estimated in the environment, it should also be noted that the amount of chemical identified analytically is not necessarily equivalent to the amount that is bioavailable.

Table 5-7 shows the limit of detections typically achieved by analytical analysis in environmental media. An overview summary of the range of concentrations detected in environmental media is presented in Table 5-8.

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

Media	Detection limit	Reference
Animal tissue	0.05 µg/L	USGS 2006
Water	0.3 µg/L	USGS 1998
Air	0.18 ng/cm^2	EPA 1999
Soil and sediment	0.05 µg/L	USGS 2006
Urine	0.31 µg/L	CDC 2020
Food	6.38 µg/kg	FDA 2020b

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

Table 5-8. Summary of Environmental Levels of Nickel

Media	Low	High	For more information
Outdoor air (ng/m^3)	0.70	72.32	Section 5.5.1
Indoor air (ng/m^3)	2.79	23.7	Section 5.5.1
Surface water (ppb)	2.2	1,200	Section 5.5.2
Groundwater (ppb)	4.38	6,110	Section 5.5.2
Drinking water (ppb)	2	48	Section 5.5.2
Ocean water (ng/L)	111	3,000	Section 5.5.2
Food (ppb)	0	10,600	Section 5.5.4
Soil (ppm)	<0.5	2,870	Section 5.5.3

Presented in Table 5-9 is a summary of the range of concentrations detected in environmental media at NPL sites.

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

Medium	Median[a]	Geometric mean[a]	Geometric standard deviation[a]	Number of quantitative measurements	NPL sites
Water (ppb)	188	300	12.4	426	242
Soil (ppb)	71,700	90,100	10.2	414	224
Air (ppbv)	0.0833	1.47	156	13	10

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

5.5.1 Air

Table 5-10 shows the mean ambient air nickel concentrations measured by EPA, state, local, and tribal air pollution control agencies for the Air Quality System (AQS). Mean ambient total suspended particulate (TSP) air concentrations are typically <3 ng/m^3, with a maximum mean concentration of 18 ng/m^3 in the last 5 years according to these data. The potentially respirable fraction is reflected in the PM10 concentrations, where means were generally <1.5 ng/m^3, with a maximum mean of 9.9 ng/m^3 reported for this time period. Recent studies with data on outdoor air concentrations are presented in Table 5-11. These studies focused on urban areas and major cities. Outdoor air concentrations in urban areas are typically higher than most of the mean concentrations of nickel in ambient air measured for AQS, but below the maximum from the last five years. Very high nickel concentrations may be found near

industrial facilities; mean concentrations at the fence lines of four metal recycling facilities in Houston, Texas were as high as 769.8 ng/m^3, but decreased to levels similar to background concentrations at 600 m (Han et al. 2020).

Table 5-10. Percentile Distribution of Mean Nickel Concentrations Measured in Ambient Air at Locations Across the United States[a]

Year	Number of U.S. locations	Percentile				Maximum
		10th	50th	75th	95th	
Nickel total suspended particulates (ng/m^3)						
2018	43	0.87	2.12	3.27	5.88	62.4
2019	40	0.70	1.18	1.74	3.76	72.32
2020	37	0.70	1.45	2.23	3.68	26.8
2021	34	0.95	2.16	3.02	5.26	42.7
2022	43	0.73	1.46	2.13	3.75	28.9
2023[b]	29	0.73	1.37	1.96	4.46	16
Nickel PM10 (ng/m^3)						
2018	22	0.41	0.65	0.90	2.23	22.8
2019	19	0.40	0.67	0.90	2.72	41.3
2020	19	0.35	0.67	0.96	3.46	216
2021	17	0.47	0.77	1.06	2.13	34.7
2022	11	0.55	0.83	1.07	2.18	6.6
2023[b]	12	0.49	0.84	1.24	4.54	60.2

[a]At standard temperature and pressure conditions.
[b]As of October 26, 2023.

PM10 = fraction absorbed to particulate matter ≤10 microns.

Source: EPA 2024

Table 5-11. Outdoor Air Monitoring Data for Nickel

Location	Geographic type	Date(s)	Mean concentration	Notes	Reference
Seoul, Busan, Daegu, Incheon, Gwangju, Daejeon, and Ulsan, Korea	Urban	1998–2010	3.71–12.6 ng/m^3	Results from 42 monitoring stations; mean concentration is reported as a range of the lowest mean in Gwangju to the highest mean in Daegu	Kim et al. 2014

Table 5-11. Outdoor Air Monitoring Data for Nickel

Location	Geographic type	Date(s)	Mean concentration	Notes	Reference
Houston, Texas	Urban	September 2015–May 2017	14.24±7.98–769.8±668.6 ng/m^3	63 samples total from four metal recycling facilities; mean concentration is reported as a range of the concentrations at the facilities	Han et al. 2020
New York City, New York	Urban	May–February and June–September 2008; November 2008–April 2009; June–October 2009	8.8±7.4 ng/m^3	360 samples	Rohr et al. 2014a
New York, Kings, Queens, and Bronx Counties, New York	Urban	Winter 2007–2008; summer 2008	3.0±0.6–24.6±21.2 ng/m^3	13 locations were monitored; 157 filters were collected during the winter period and 129 were collected during the summer period	Peltier and Lippmann 2010
New York City, New York	Urban	February–May 2008; November 2008–April 2009; June–September 2008; June–October 2009	8.7±6.0 ng/m^3	121 samples	Habre et al. 2014
New York City, New York	Urban	February-April 1999; June–August 1999	21.3 ng/m^3	30% of samples were above the LOD; median concentration 19.2 ng/m^3; maximum concentration 94.3 ng/m^3	Sax et al. 2006
Los Angeles, California	Urban	February–March 2000; September–October 2000	6.71 ng/m^3	All samples were above the LOD; median concentration 4.78 ng/m^3; maximum concentration 29.7 ng/m^3	Sax et al. 2006
United Kingdom	Rural	2010	NR	Median concentration 0.52 ng/m^3; minimum 0.06 ng/m^3; maximum 11.2 ng/m^3; 579 samples	Font et al. 2015

LOD = limit of detection; NR = not reported

Many recent studies of outdoor air focus on New York City. Outdoor air concentrations in New York City range from 3.0 to 24.6 ng/m^3 (Habre et al. 2014; Peltier and Lippmann 2010; Rohr et al. 2014a; Sax et al. 2006). Nickel concentrations in outdoor air in New York City are higher than in outdoor air in Los Angeles and Seattle (Hsu et al. 2012; Sax et al. 2006). The source of nickel in outdoor air in New York City is primarily residual fuel oil combustion, which is used for space and water heating (Hsu et al. 2012; Peltier and Lippmann 2010; Rohr et al. 2014a). Peltier and Lippmann (2010) also attributed nickel air concentrations to shipping ports. Shipping ports and space heating also affect spatial and temporal differences in nickel air concentrations within New York City. Mean nickel concentrations in New York City were 5.5–24.6 ng/m^3 in winter samples and 3.0–15.1 ng/m^3 in summer samples (Peltier and Lippmann 2010). In the winter, fuel oil combustion typically increases for heating residential buildings (Schachter et al. 2020).

The results of studies which monitored indoor air concentrations of nickel are presented in Table 5-12. Many studies have collected data on indoor air pollution to study its effect on children with asthma, especially in New York City. Many studies find that concentrations are higher in winter than in summer (Habre et al. 2014; Peltier and Lippmann 2010; Schachter et al. 2020). Schachter et al. (2020) found that weekly concentrations of nickel in the summer and winter were 2.79 and 11.72 ng/m^3, respectively. Mean nickel concentrations in New York City were 5.5–24.6 ng/m^3 in winter samples and 3.0–15.1 ng/m^3 in summer samples (Peltier and Lippmann 2010). Seasonal differences in indoor air concentrations are likely due to reduced ventilation in the winter and increased fuel oil combustion for residential heating (Hsu et al. 2012; Schachter et al. 2020). Schachter et al. (2020) concluded that shipping ports were also a source of nickel in indoor air. Habre et al. (2014) concluded that the source of nickel in indoor air was of outdoor origin.

Table 5-12. Indoor Air Monitoring Data for Nickel

Location	Geographic type	Date(s)	Mean concentration	Notes	Reference
New York, New York	Urban	February–May 2008; November 2008-April 2009; June–September 2008; June–October 2009	7.2±10.1 ng/m^3	121 samples	Habre et al. 2014

Table 5-12. Indoor Air Monitoring Data for Nickel

Location	Geographic type	Date(s)	Mean concentration	Notes	Reference
New York, New York	Urban	February–April 1999; June–August 1999	23.7 ng/m^3	48% of samples were above the LOD; median concentration 15.7 ng/m^3; maximum concentration 348 ng/m^3	Sax et al. 2006
Los Angeles, California	Urban	February–March 2000; September–October 2000	6.56 ng/m^3	All samples were above the LOD; median concentration 4.17 ng/m^3; maximum concentration 42.5 ng/m^3	Sax et al. 2006
New York City, New York	Urban	Summers and winters of 2008 and 2009	2.79±1.66–11.72±13.3 ng/m^3	57 samples in summer and 56 samples in winter	Schachter et al. 2020

LOD = limit of detection

Sax et al. (2006) also measured the mean nickel concentration of personal air of teenagers using a sampler in a backpack. The mean concentration was 28.7±52.8 ng/m^3 for New York City teenagers (Sax et al. 2006). In south central Los Angeles, mean nickel concentrations in personal air (28.7±52.8 ng/m^3) were similar to samples in New York City, even though mean concentrations were lower in indoor and outdoor air samples in Los Angeles (Sax et al. 2006).

5.5.2 Water

Nickel is ubiquitous in the environment and is commonly detected in surface and groundwater, precipitation, and seawater. Nickel has been detected in rain and snow as a result of atmospheric washing out of particulates containing nickel. The concentration of nickel in precipitation is influenced by the back-trajectory of the air masses in which the precipitation originates. Correlation with other trace metals can help elucidate the source of the emission (Rivera-Rivera et al. 2020). Rainwater samples were collected in Mexico between 2016 and 2017. Nickel was detected at averages of 0.012 mg/L in rural area samples and 0.033 mg/L in industrial area samples (Rivera-Rivera et al. 2020). Mean concentrations of

nickel in precipitation collected near a large municipal incinerator in Claremont, New Hampshire, were 0.69 µg/L in rainwater and 0.62 µg/L in snow (Feng et al. 2000).

The distribution of nickel in the marine water column has been well characterized by GEOTRACES studies. Higher levels of nickel are found in deep seawater than in surface water: average surface water nickel concentrations in the equatorial Atlantic Ocean were 111 and 122 ng/L and the highest average was found in Antarctic bottom water at 443 ng/L (Middag et al. 2020). Nickel concentrations in South San Francisco Bay were about 3,000 ng/L, with one-third to one-half of the nickel complexed to a class of strong organic ligands (Donat et al. 1994).

The EPA maintains a Water Quality Portal (WQP) database which aggregates air monitoring data from the National Water Information System (NWIS) and STORage and RETrieval (STORET) system. A summary of the data for ambient surface and groundwater from recent years are reported in Table 5-13 (WQP 2024). Data are reported as the dissolved fraction to reflect the potentially bioavailable fraction. Nickel is ubiquitous in the environment and was detected fairly consistently at averages around 3–3.5 ppb in surface water and at averages around 4–7 ppb in groundwater. The maximum of 6,110 µg/L observed in 2021 was recorded in Utah during drought conditions which may have impacted the results. This value is an order of magnitude higher than other measurements from that location and may be an outlier.

Table 5-13. Summary of Concentrations of Dissolved Nickel (ppb) Measured in Surface Water and Groundwater Across the United States

Year	Average	Maximum	Number of samples	Percent detected
Surface water				
2018	4.69	450	6,176	47%
2019	2.89	251	6,628	45%
2020	3.16	357	4,736	48%
2021	3.60	506	6,397	45%
2022	3.49	1,200	6,612	46%
2023	2.96	440	4,078	55%
Groundwater				
2018	6.13	262	1,472	55%
2019	6.80	206	1,353	59%
2020	5.92	443	1,074	54%
2021	18.2	6,110	1,062	58%

Table 5-13. Summary of Concentrations of Dissolved Nickel (ppb) Measured in Surface Water and Groundwater Across the United States

Year	Average	Maximum	Number of samples	Percent detected
2022	7.59	579	1,135	61%
2023	4.38	400	602	58%

Source: WQP 2024

Nickel in surface water can be geologically influenced. Surface water samples were collected between 2013 and 2015 in northern Minnesota to determine the potential influence of underlying nickel-rich mineral deposits in the bedrock (USGS 2020). Measured median values were 3.4 µg/L (total) and 3.2 µg/L (dissolved) in Filson Creek; 2.3 µg/L (total) and 2.2 µg/L (dissolved) in Keeley Creek; and 1.1 µg/L (total and dissolved) in the St. Louis River. The Filson Creek and Keeley Creek watersheds contain exposed Cu-Ni-sulfide mineralization, resulting in higher nickel concentrations near these areas; mineralization impacts were not observed for the St. Louis River due to thick glacial sediments covering the bedrock (USGS 2020).

For the USGS National Water-Quality Assessment Program, a comprehensive study of trace elements in groundwater across the United States was conducted from 1992 to 2003. In this study, the USGS collected data from 5,183 monitoring and drinking-water wells representing more than 40 principal and other aquifers in humid and dry regions and in various land-use settings (USGS 2011). Very few samples (0.23%) exceeded the human-health benchmark value of 100 µg/L. The median nickel concentration was 1.1 µg/L and the maximum was 670 µg/L (USGS 2011). Dry regions had significantly more detections (62%) than humid regions (54%) greater than the reporting level (1 µg/L). In dry regions, the percentage of detections >1 µg/L were the same for agricultural and urban land use wells (86%). In humid regions, percent detections urban land-use wells (78%) were significantly higher than in agricultural land-use wells (72%) (USGS 2011).

In a comprehensive survey of U.S. groundwater conducted between 1992 and 2003 by the USGS, 46% of drinking water wells in dry regions and 42% of drinking water wells in humid regions had nickel greater than the 1 µg/L reporting limit (USGS 2011). Nickel was detected in two bottled water samples at 2 and 7.4 ppb collected for the FDA's Total Diet Study between 2018 and 2020 (FDA 2023c). Drinking water sampled for the European Union diet study contained 2–3 ppb (EFSA 2020).

Elevated nickel levels may exist in drinking water because of the corrosion of nickel-containing alloys used as valves and other components in the water distribution system as well as from nickel-plated or chromium-nickel-plated faucets. In a Seattle study, mean and maximum nickel levels in standing water were 7.0 and 43 µg/L, respectively, compared with 2.0 and 28 µg/L in running water (Ohanian 1986). A similar result was observed in a comparison of the mean (±1 standard deviation) and 90th percentile concentrations of nickel measured during the NHEXAS EPA Region 5 study in standing tap water (9.2 [±21] and 16 µg/L) and in tap water sampled after the water line had been flushed for 3 minutes (5.3 [±4.4] and 11 µg/L) (Thomas et al. 1999). Even if an individual was to consume only first-draw water (containing nickel at the maximum concentration [48 µg/L] obtained from the Seattle study) as their sole source of drinking water, their daily intake of 96 µg/day is still less than the lifetime daily limit of 1,400 µg/day set by EPA, assuming a drinking water equivalent level (DWEL) of 700 µg/L and a consumption of 2 L/day (EPA 2000). Although leaching of metals from pipes generally increases with decreasing pH, none of the nickel studies reported the pH of the tap water. First water drawn from hot water taps plated with nickel may contain concentrations as high as 1–1.3 mg/L (Barceloux 1999).

Nickel concentrations were measured as part of a study of heavy metal content in streams and creeks located in the Black Hills of South Dakota that are impacted by abandoned or active mining operations (May et al. 2001). The concentrations of nickel in these surface waters generally ranged between 1.3 and 7.6 µg/L and were typically highest near where they received drainage water from abandoned or active mining operations. At one location, nickel concentrations as high as 20 µg/L were determined and were attributed to effluent and entrained streambed tailings from previous mining activities. The concentrations of nickel in water did not correlate with the concentrations of nickel in the underlying sediments. At the Bonita Peak Mining District Superfund Site, dissolved nickel was detected at an average of 27.1 µg/L (maximum: 820 µg/L) in groundwater in 2021 and at annual averages of 11.7–15.8 µg/L between 2018 and 2012 (overall maximum: 274 µg/L) (WQP 2024). In a monitoring study of the Upper Columbia River in Washington state, which is impacted by smelter slag pollution, medians were 0.6 µg/L (range: 0.6–17 µg/L, detected in 27% of samples) in surface water; 0.6 µg/L (range: 0.4–1 µg/L, detected in 39% of samples) in shallow pore-water; and 0.6 µg/L (range: 0.5–1 µg/L, detected in 57% of samples) (USGS 2016). At Eagle Mine, the only active primary nickel mine in the United States, groundwater monitoring wells reported one sample with 29.2 µg/L nickel; the remaining samples in 2023 were non-detects (<25.0 µg/L) (CEMP 2023). Nickel was not detected (<1.0 µg/L) in surface water near the mine in 2023. Nickel was not detected (<20.0 µg/L) in groundwater at the processing mill, and maximum surface water detections were 8.8 µg/L in 2023 (CEMP 2023).

5.5.3 Sediment and Soil

Nickel is the 24th most abundant element in the Earth's crust, accounting for about 3% of the Earth's composition (Iyaka 2011). The level of nickel in soil may vary widely and is dependent on the concentration in parent rocks, soil-forming process, and pollution; a range of nickel in U.S. soil has been reported as <0.5–1,890 ppm (USGS 2012). Enrichment factors, the ratio of the measured soil concentration to the regional standard geochemical background concentration, can be calculated to elucidate anthropogenic influence (USGS 2021).

Sediment is an important sink for nickel in water. Nickel content of sediments is expected to be high near sources of nickel emissions. For example, nickel carried into creeks and streams from drainage and runoff originating from active or abandoned mining operations in the Black Hills of South Dakota can lead to increased concentrations of this metal in sediments (May et al. 2001). Soil concentrations are also expected to be higher near emission sources and to decrease further from sources (Suh et al. 2019). Table 5-14 shows the results of several studies measuring concentrations of nickel in soil and sediment.

Table 5-14. Concentrations of Nickel in Soil and Sediment

Location	Concentration	Notes	Reference
U.S. neighborhood near a metal forge			Suh et al. 2019
Baghouse dust		2 samples; source material from alloy grinding operations	
Concentration	45,000 mg/kg		
Surface dust		6 samples from immediately outside of the facility	
Range	299–24,258 mg/kg		
Soil		8 samples from adjacent to and across the street from facility	
Range	32.1–185 mg/kg		
Background soil		5 samples from 1 mile from facility	
Range	19.8–63.8 mg/kg		
Conterminous United States			USGS 2013
Surface soil (0–5 cm)			
Range	<0.5–1,890 mg/kg	4,841 samples	
Mean	17.7±45.2mg/kg		
Soil A horizon			
Range	<0.5–2,310 mg/kg	4,813 samples	
Mean	18.5±54.4 mg/kg		
Soil C horizon			
Range	<0.5–2,870 mg/kg	4,780 samples	
Mean	22.6±68.8 mg/kg		

Table 5-14. Concentrations of Nickel in Soil and Sediment

Location	Concentration	Notes	Reference
United States			WQP 2024
Soil			
2018			
Maximum	27.8 mg/kg	Detected in 100% of 94 samples	
Mean	7.29 mg/kg		
2019			
Maximum	180 mg/kg	Detected in 100% of 122 samples	
Mean	13.2 mg/kg		
2020			
Maximum	21,000 mg/kg	Detected in 85% of 39 samples;	
Mean	3,040 mg/kg	maximum reported from South Dakota,	
2021		possibly due to natural enrichment	
Maximum	30 mg/kg	Detected in 100% of 10 samples	
Mean	28.2 mg/kg		
2022			
Maximum	42 mg/kg	Detected in 100% of 15 samples	
Mean	17.2 mg/kg		
2023			
Range	26 mg/kg	Detected in 10% of 7 samples	
Mean	19 mg/kg		
Bonita Peak Mining Superfund Site, Colorado			WQP 20224
Soil			
2018			
Maximum	66.8 mg/kg	Detected in 99% of 97 samples	
Mean	4.3 mg/kg		
2021			
Maximum	131 mg/kg	Detected in 81% of 186 samples	
Mean	6.7 mg/kg		
United States			WQP 2024
Sediment			
2018			
Maximum	306 mg/kg	Detected in 80% of 1,467 samples	
Mean	17 mg/kg		
2019			
Maximum	169 mg/kg	Detected in 73% of 1,144 samples	
Mean	21.7 mg/kg		
2020			
Maximum	390 mg/kg	Detected in 87% of 2,197 samples	
Mean	21.6 mg/kg		
2021			
Maximum	1,170 mg/kg	Detected in 79% of 1,134 samples	
Mean	19.4 mg/kg		
2022			
Maximum	8,960 mg/kg	Detected in 65% of 500 samples	
Mean	53.5 mg/kg		
2023			
Maximum	319 mg/kg	Detected in 93% of 154 samples	
Mean	12.3 mg/kg		

Table 5-14. Concentrations of Nickel in Soil and Sediment

Location	Concentration	Notes	Reference
Raritan River Basin, Passaic River Basin, Rahway River Basin, and Great Egg Harbor River Basin, New Jersey		Estimated baseline nickel: 3 µg/g (coastal plain sites), 20 µg/g (non-coastal plain sites)	USGS 2000b
Stream and riverbed-sediment		Concentrations significantly related to urban industrial/commercial land use and population density	
Range	18–43 µg/g		
Northern Rockies Intermontane Basin			USGS 2000a
Stream and riverbed-sediment		0–2-cm depth; 16 samples; basin impacted by mining activities	
Median	18 µg/g		
Range	12–24 µg/g		
United States		541 samples from 20 study areas of the National Water-Quality Assessment Program	Rice 1999
Streambed sediment			
Minimum	6 µg/g		
25th percentile	20 µg/g		
50th percentile	27 µg/g		
75th percentile	36 µg/g		
Maximum	530 µg/g		
Black Hills, South Dakota		Sampling locations were near mining operations	May et al. 2001
Sediment			
Range	10–64 µg/g		
Upper Columbia River, Washington		Area impacted by mining slag	USGS 2017
Sediment (total)			
Range	1.7–39.3 mg/kg	Total nickel	
Median	17.7 mg/kg		
Sediment (SEM)			
Range	0.293–8.63 mg/kg	Simultaneously-extracted metals, represents to bioavailable fraction.	
Median	3.2 mg/kg		
Bonita Peak Mining Superfund Site, Colorado			WQP 2024
Sediment			
2018			
Maximum	40.600 mg/kg	Detected in 100% of 122 samples	
Mean	7.148 mg/kg		

Table 5-14. Concentrations of Nickel in Soil and Sediment

Location	Concentration	Notes	Reference
Midnite Mine Superfund Site, Washington			WQP 2024
Sediment			
2018			
Maximum	472 mg/kg	Detected in 90% of 10 samples	
Mean	84.9 mg/kg		
2019			
Maximum	297 mg/kg	Detected in 90% of 10 samples	
Mean	47.2 mg/kg		
2020			
Maximum	100 mg/kg	Detected in 100% of 10 samples	
Mean	21.7 mg/kg		
2021			
Maximum	566 mg/kg	Detected in 100% of 10 samples.	
Mean	74.6 mg/kg		
2022			
Maximum	428 mg/kg	Detected in 100% of 10 samples	
Mean	75.8 mg/kg		

SEM = standard error of the mean

5.5.4 Other Media

Tables 5-15 and 5-16 and present the results of the FDA's Total Diet Study from 2018 through 2020 (FDA 2023c) for general food items and for baby food items. The Total Diet Study is conducted through Market Based Surveys in each of four geographic regions of the United States (north central, west, south, and northeast) during which foods purchased in each region for different are tested for elements, pesticides, and radionuclides. Products with the highest nickel concentrations included dairy products like cream cheese and milk; vegetables like peas and pickles; pie crust; veggie burgers; and popsicles (FDA 2023c). The European Union diet study reported the highest mean nickel concentrations in cocoa products, herbs and spices, tea leaves, and seaweed (EFSA 2020).

Table 5-15. Nickel Detections in Food from the U.S. Food and Drug Administration (FDA) Total Diet Study (TDS), 2018–2020

TDS food name	Number of analyses	Number of detects	Median (µg/kg)	Range (µg/kg)
Cream cheese	1	1	10,600	–
Peas, green, frozen, boiled	3	3	4,400	4,200–6,200
Pickles, dill, cucumber	22	22	3,800	2,800–5,000
Pie crust	1	1	3,200	–
Veggie burger	3	3	2,400	2,000–3,200

Table 5-15. Nickel Detections in Food from the U.S. Food and Drug Administration (FDA) Total Diet Study (TDS), 2018–2020

TDS food name	Number of analyses	Number of detects	Median (µg/kg)	Range (µg/kg)
Yogurt, lowfat, vanilla	7	7	2,000	1,600–2,700
Popsicle, fruit-flavored	3	3	1,600	1,300–2,000
Eggplant, fresh, peeled, boiled	3	3	1,100	1,000–1,100
Milk, reduced fat, fluid	3	3	1,000	830–1,000
Milk, chocolate, reduced fat, fluid	3	3	960	930–1,300
Beer	3	3	920	910–1,000
Milk, skim, fluid	2	2	920	910–930
Quinoa, cooked	7	7	870	700–1,200
Coffee, brewed from ground	3	3	810	640–860
Juice, lemon	3	3	670	510–-810
Pork sausage (link/patty), pan-cooked	3	3	660	620–680
Pork chop, pan-cooked with oil	3	3	650	530–800
Juice, tomato-vegetable	1	1	650	–
Almonds, shelled	8	8	590	510–800
Mixed vegetables, frozen, boiled	3	3	580	490–660
Cauliflower, fresh/frozen, boiled	3	3	540	470–570
Luncheon meat, bologna	27	27	530	380–680
Fish sticks or patty, frozen, oven-cooked	3	3	520	510–570
Eggs, hard-boiled	3	3	460	450–890
Pork and beans, canned	3	3	450	420–480
Lima beans, immature, frozen, boiled	3	3	440	400–550
Beans, black, canned, drained solids	3	3	440	350–630
Avocado, raw	27	27	390	220–500
Beans, kidney, canned, drained solids	5	5	360	260–420
Muffin, blueberry	3	3	360	360–390
Blueberries, raw	3	3	330	250–480
Granola bar	1	1	330	–
Breakfast tart/toaster pastry	8	8	325	89–600
Beans, pinto, canned, drained solids	3	3	310	310–380
Beans, white, canned, drained solids	3	3	300	200–360
Bread, white, enriched, pre-sliced	3	3	260	260–310
Crackers, cheese	1	1	250	–
Broth, chicken, cartoned	1	1	250	–
Crackers, saltine	3	3	240	220-290
Bagel, plain, toasted	3	3	230	200–270
Soup, broccoli cheese, canned, condensed, prepared with water	3	3	230	200–230
Chips, tortilla	3	3	220	140–230

Table 5-15. Nickel Detections in Food from the U.S. Food and Drug Administration (FDA) Total Diet Study (TDS), 2018–2020

TDS food name	Number of analyses	Number of detects	Median (µg/kg)	Range (µg/kg)
Soup, clam chowder, New England, canned, ready to serve	8	8	215	190–250
Soup, cream of mushroom, canned, condensed, prepared with water	3	3	210	120–220
Soup, cream of potato, canned, condensed, prepared with water	2	2	210	180–240
Macaroni and cheese, prepared from boxed mix	27	27	200	120–280
Soup, vegetable beef, canned, ready to serve	5	5	190	150–390
Cinnamon roll, iced	27	27	180	66–580
Peach, raw/frozen	27	27	180	140–250
Pasta, rice noodles, cooked	5	5	180	–
Soup, vegetable, canned, ready to serve	1	1	180	180–180
Cereal, shredded wheat, frosted	3	3	170	150–210
Apple, red, with peel, raw	3	3	170	140–180
Fruit cocktail, canned in light syrup, solids and liquids	8	8	155	94–190
Pasta, whole wheat, cooked	5	5	150	120–200
Pudding, ready-to-eat, chocolate	3	3	150	100–190
Syrup, pancake	27	27	140	50–280
Raisins	8	8	140	90–150
Beans, garbanzo (chickpeas), canned, drained solids	5	5	140	60–180
Grapefruit, raw	3	3	140	130–150
Lentils, dry, cooked	3	3	140	130–290
Luncheon meat, turkey	3	2	140	0–160
Green beans, canned, drained solids	8	8	135	100–180
Brussels sprouts, fresh/frozen, boiled	27	27	130	69–290
Turkey, ground, pan-cooked	27	25	130	0–240
Cookies, chocolate chip	3	3	130	120–200
Cookies, sugar	3	3	130	63–150
Frankfurter (all beef/beef and pork), boiled	3	3	130	130–140
Cucumber, peeled, raw	22	22	120	71–250
Tofu, firm, plain, drained solids	9	9	120	94–140
Lettuce, iceberg, raw	8	8	120	58–200
Doughnut, cake-type, plain	3	3	120	63–160
Luncheon meat, ham	3	3	120	89–130
Chips, potato	27	26	110	0–190
Mushrooms, canned, drained solids	3	3	110	89–140

Table 5-15. Nickel Detections in Food from the U.S. Food and Drug Administration (FDA) Total Diet Study (TDS), 2018–2020

TDS food name	Number of analyses	Number of detects	Median (µg/kg)	Range (µg/kg)
Potato, peeled, boiled	3	3	110	94–180
Potato, with peel, baked	3	3	110	98–130
Chili con carne with beans, canned	3	3	110	93–150
Soup, tomato, canned, condensed, prepared with water	27	23	100	0–740
Mayonnaise	8	8	96.5	67–180
Cream, half and half	8	8	91	58–130
Sugar, white, granulated	27	17	90	0–250
Beef steak, loin/sirloin, oven-roasted	3	3	90	78-91
Cake, white with white icing	3	3	88	73–110
Margarine, salted	27	26	85	0–180
Butter, salted	27	27	84	69–140
Cookies, sandwich, with creme filling	27	27	81	56–150
Broccoli, fresh/frozen, boiled	3	3	81	51–83
Pie, apple, fresh/frozen	27	27	80	54–180
Powder, protein	27	27	79	55–160
Pie, pumpkin, fresh/frozen	27	26	79	0–120
Carbonated beverage, cola, regular	3	2	76	0–170
Sorbet, fruit-flavored	27	20	75	0–270
Chicken potpie, frozen, heated	27	26	72	0–140
Gelatin dessert, strawberry	27	24	72	0–220
Cheese, American, processed	3	3	72	65–79
Potatoes, French fries, fast-food	8	8	69	42–130
Cornbread, homemade	3	3	69	63–79
Soup, chicken noodle, canned, condensed, prepared with water	27	26	67	0–140
Pepper, bell, green, raw	27	22	67	0–310
BF, pasta, tomato and beef	3	2	67	0–67
Banana, raw	27	23	64	0–110
Pear, with peel, raw	8	7	61.5	0–91
Alcohol, distilled, whiskey/scotch	6	4	60.5	0–300
Yogurt, lowfat, fruit-flavored	3	2	60	0–120
Cheese, Swiss	3	3	59	48–75
Fruit drink (5–25% juice), canned or bottled	3	3	59	56–64
Celery, raw	27	19	58	0–170
Chicken nuggets, fast-food	3	3	58	42–68
Watermelon, raw/frozen	3	2	58	0–66
English muffin, plain, toasted	27	20	57	0–110

Table 5-15. Nickel Detections in Food from the U.S. Food and Drug Administration (FDA) Total Diet Study (TDS), 2018–2020

TDS food name	Number of analyses	Number of detects	Median (µg/kg)	Range (µg/kg)
Corn, canned, drained solids	27	18	56	0–140
Crackers, butter-type	27	20	55	0–130
Squash, winter, fresh/frozen, boiled	27	20	54	0–90
Juice, grape, bottled	27	18	52	0–100
Cereal, granola	27	17	52	0–420
Alcohol, distilled, vodka	3	3	47	42–73
Biscuits, fast-food	3	2	47	0–58
Pretzels, hard, salted	3	2	43	0–46
Syrup, chocolate-flavored	3	3	35	22–40
Jelly, grape	3	3	34	33–71
Cake, chocolate with chocolate icing	27	13	0	0–450
Pineapple, raw/frozen	27	13	0	0–480
Tomato, raw	27	13	0	0–400
Juice, orange, bottled/cartoned	27	12	0	0–170
Cheese, Monterey jack	27	12	0	0–150
Milk shake, vanilla, fast-food	27	11	0	0–580
Ketchup, tomato	27	10	0	0–130
Corn, frozen, boiled	27	9	0	0–85
Water, bottled, mineral/spring	27	8	0	0–76
Honey	27	8	0	0–72
Oil, olive	27	7	0	0–79
Onion, mature, raw	27	7	0	0–91
Spaghetti, enriched, boiled	22	6	0	0–76
Brown gravy, canned or bottled	27	6	0	0–87
Salad dressing, Italian, regular	27	6	0	0–140
Sweet potato, baked, peel removed	27	6	0	0–100
Shrimp, pre-cooked, shells removed, no tails	27	6	0	0–71
Salsa, tomato, bottled	27	5	0	0–160
Green beans, fresh/frozen, boiled	27	5	0	0–91
Pork bacon, oven-cooked	27	5	0	0–120
Salami, dry/hard	27	4	0	0–72
Juice, apple, bottled	27	4	0	0–79
Tea, brewed from tea bag	21	4	0	0–360
Chicken thigh, oven-roasted, skin removed	27	3	0	0–290
Beans, refried, canned	27	3	0	0–90
Tortilla, flour	27	3	0	0–99
Cocoa powder	8	2	0	0–44

Table 5-15. Nickel Detections in Food from the U.S. Food and Drug Administration (FDA) Total Diet Study (TDS), 2018–2020

TDS food name	Number of analyses	Number of detects	Median (µg/kg)	Range (µg/kg)
Cereal, oat ring	27	2	0	0–7.4
Ice cream, chocolate	27	2	0	0–76
Beverage, coconut water	8	2	0	0–86
Beef, ground, pan-cooked	27	2	0	0–78
Cantaloupe, raw/frozen	27	2	0	0–120
Fruit drink, from powder	27	2	0	0–110
Chicken leg, fried with skin, fast-food	27	1	–	0–40
Tuna, canned in water, drained solids	27	1	–	0–43
Peanut butter, creamy	3	1	–	0–51
Soup, ramen noodles, prepared with water	3	1	–	0–55
Cod, baked	3	1	–	0–20
Bread, white roll/bun (hamburger/hotdog)	3	1	–	0–62
Grapes, seedless, red/green, raw	27	1	–	0–88
Kale, fresh, pan-cooked	3	1	–	0–56
Meal replacement, liquid ready-to-drink, vanilla	27	1	–	0–54
Cereal, oat ring, honey	27	1	–	0–48
Sauce, soy	3	1	–	0–65
Sauce, tomato, pasta	8	1	–	0–53
Sour cream	27	1	–	0–58
Ham, cured (not canned), baked	27	1	–	0–64
Rice, white, enriched, cooked	3	1	–	0–20
Strawberry, raw/frozen	27	1	–	0–46
Collards, fresh/frozen, boiled	27	1	–	0–80
Asparagus, fresh/frozen, boiled	3	1	–	0–22
Salmon, steaks/fillets, baked	3	0	–	–
Baking powder	13	0	–	–
Cottage cheese, creamed, reduced fat	27	0	–	–
Chicken breast, fried with skin, fast-food	27	0	–	–
Catfish, pan-cooked with oil	27	0	–	–
Peanuts, dry roasted, salted	3	0	–	–
Seeds, sunflower, shelled, salted, roasted	27	0	–	–
Pancakes, frozen, heated	27	0	–	–
Fruit juice blend (100% juice), canned/ bottled	3	0	–	–
Juice, cranberry cocktail, bottled	27	0	–	–
Carrot, baby, raw	3	0	–	–
Lettuce, leaf, raw	3	0	–	–

Table 5-15. Nickel Detections in Food from the U.S. Food and Drug Administration (FDA) Total Diet Study (TDS), 2018–2020

TDS food name	Number of analyses	Number of detects	Median (µg/kg)	Range (µg/kg)
Oatmeal, plain, quick, cooked	1	0	–	–
Candy bar, chocolate, nougat, with nuts	3	0	–	–
Popcorn, microwave, butter-flavored	27	0	–	–
Oil, vegetable	3	0	–	–
Bread, whole wheat, pre-sliced	3	0	–	–
Tilapia, baked	3	0	–	–
Cheese, mozzarella	27	0	–	–
Cereal, corn flakes	3	0	–	–
Brownie	3	0	–	–
Cereal, crisped rice	3	0	–	–
Mustard, yellow, plain	3	0	–	–
Tortilla, corn	3	0	–	–
Walnuts, shelled	3	0	–	–
Rice, brown, cooked	3	0	–	–
Pizza, cheese, fast-food	3	0	–	–
Sauce, barbecue	3	0	–	–
Cabbage, raw	27	0	–	–
Zucchini, fresh/frozen, boiled	3	0	–	–
Cereal, bran with raisins	3	0	–	–
Spinach, raw	3	0	–	–
Yogurt, frozen, vanilla	3	0	–	–
Eggplant, baked with peel	3	0	–	–
Candy bar, milk chocolate, plain	27	0	–	–
Mango, raw/frozen	3	0	–	–
Garlic, raw	3	0	–	–
Cashews, salted	3	0	–	–
Olives, black, pitted	3	0	–	–
Wine, red	3	0	–	–
Crackers, graham	3	0	–	–
Wine, white	3	0	–	–
Beverage, almond (non-dairy)	8	0	–	–
Beverage, energy	8	0	–	–
Beverage, soy (non-dairy)	3	0	–	–
Beverage, sports	27	0	–	–
Carbonated beverage, lemon-lime, regular	3	0	–	–
Candies, fruit snacks	3	0	–	–
Carbonated beverage, cola, diet	26	0	–	–

Table 5-15. Nickel Detections in Food from the U.S. Food and Drug Administration (FDA) Total Diet Study (TDS), 2018–2020

TDS food name	Number of analyses	Number of detects	Median (µg/kg)	Range (µg/kg)
Cereal, whole wheat, cooked	27	0	–	–
Juice, pineapple, canned	3	0	–	–
Salad dressing, ranch, low-calorie	3	0	–	–
Salad dressing, ranch, regular	3	0	–	–
Sauce, tomato, canned	3	0	–	–
Milk, whole, fluid	3	0	–	–
Cheese, cheddar (sharp/mild)	27	0	–	–
Lamb chop, pan-cooked with oil	27	0	–	–
Turkey breast, oven-roasted	3	0	–	–
Cream of wheat (farina), enriched, cooked	3	0	–	–
Corn/hominy grits, enriched, cooked	3	0	–	–
Noodles, egg, enriched, boiled	3	0	–	–
Orange, raw	27	0	–	–
Applesauce, bottled	6	0	–	–
Juice, grapefruit, bottled/cartoned	27	0	–	–
Cream substitute, non-dairy, liquid	27	0	–	–
Chicken breast, oven-roasted, skin removed	3	0	–	–
Mushrooms, raw	3	0	–	–
Ice cream, vanilla	3	0	–	–
Candy, hard	3	0	–	–
Breadcrumbs	3	0	–	–
Flour, white, all-purpose	3	0	–	–
Salt, sea	1	0	–	–
Salt, iodized	1	0	–	–

Source: FDA 2023c

Table 5-16. Nickel Detections in Baby Food from the U.S. Food and Drug Administration (FDA) Total Diet Study (TDS), 2019–2020

TDS food name	Number of analyses	Number of detects	Median (µg/kg)	Range (µg/kg)
Beef and broth/gravy	27	24	72	0–220
Vegetables and beef	8	8	70.5	59–140
Chicken noodle dinner	3	3	69	63–79
Vegetables and chicken	8	8	69	42–130
Green beans	27	26	67	0–140
Turkey and rice	3	3	67	64–69

Table 5-16. Nickel Detections in Baby Food from the U.S. Food and Drug Administration (FDA) Total Diet Study (TDS), 2019–2020

TDS food name	Number of analyses	Number of detects	Median (µg/kg)	Range (µg/kg)
Pasta, tomato and beef	3	2	67	0–67
Carrots	27	22	67	0–310
Mixed vegetables	3	3	65	47–69
Peas	27	23	64	0–110
Sweet potatoes	3	2	64	0–87
Applesauce	3	3	63	60–69
Peaches	27	27	62	39–120
Pears	8	7	61.5	0–91
Juice, apple	6	4	60.5	0–300
Bananas	3	2	23	0–25
Teething biscuits	14	7	21	0–85
Cereal, oatmeal, dry	8	0	–	–
Cereal, mixed, dry	5	2	0	0–47
Finger foods, puffed snack	27	13	0	0–450
Peas, green beans, and avocado, pouch	3	0	–	–
Cereal, oatmeal, dry, prepared with water	3	0	–	–
Squash	3	0	–	–
Peas and spinach, glass jar	3	0	–	–
Prunes	6	2	0	0–100
Infant formula, soy-based, powdered	2	0	–	–
Sweet potato, apple, and spinach, pouch	3	0	–	–
Apple and sweet potato with cinnamon, pouch	3	0	–	–
Organic pears and spinach, pouch	3	0	–	–
Banana and blueberry, pouch	3	0	–	–
Pumpkin, banana, papaya, and cardamom, bowl	8	0	–	–
Cereal, rice, dry	5	2	0	0–60
Macaroni and cheese with vegetables	27	10	0	0–130
Turkey, quinoa, apple, and sweet potato, pouch	3	1	–	0–88
Cereal, mixed, dry, prepared with water	27	1	–	0–88
Pear, blueberry, apple, and avocado, pouch	3	0	–	–
Apple, spinach, and avocado, bowl/pouch	3	1	–	0–110
Pear, mango, avocado, pouch	1	0	–	–

Table 5-16. Nickel Detections in Baby Food from the U.S. Food and Drug Administration (FDA) Total Diet Study (TDS), 2019–2020

TDS food name	Number of analyses	Number of detects	Median (µg/kg)	Range (µg/kg)
Mango, yellow zucchini, corn, and turmeric, pouch	8	1	0	0–43
Organic yogurt, apple, pumpkin, cinnamon, and quinoa, pouch	3	0	–	–
Ravioli, cheese-filled, with tomato sauce	3	0	–	–
Mango, pouch	3	0	–	–
Mango, glass jar	3	0	–	–
Banana, blackberry, and blueberry, plastic jar	3	0	–	–
Sweet potato, apple, and corn, pouch	3	0	–	–
Vegetables and turkey	27	1	–	0–80
Juice, pear	27	2	0	0–120
Infant formula, milk-based, powdered	5	1	–	0–44
Cereal, rice, dry, prepared with water	3	0	–	–
Turkey and broth/gravy	27	0	–	–
Juice, grape	27	4	0	0–79
Fruit yogurt dessert	27	0	–	–
Apples with berries	27	13	0	0–400
Apples with fruit other than berries	27	7	0	0–91
Infant formula, milk-based, powdered, prepared with water	26	0	–	–
Infant formula, soy-based, powdered, prepared with water	21	4	0	0–360
Water, baby, bottled	3	0	–	–
Banana and strawberry, glass jar	3	0	–	–
Banana, apple, and pear, plastic jar	3	0	–	–
Apple, sweet potato, and pineapple, pouch	3	1	0	0–67
Mango, carrot, and turmeric, bowl	8	2	0	0–100
Juice, mixed fruit	1	0	–	–
Yogurt, peach pear	1	0	–	–

Source: FDA 2023c

Cabrera-Vique et al. (2011) analyzed 170 samples of food from 43 convenience stores and fast-food restaurants in Spain. Nickel concentrations ranged from 18.5 to 95.0 ng/g, and the highest concentrations were in egg-based food, pork-based foods, and sauces (Cabrera-Vique et al. 2011). Foods that contained spices and herbs, whole cereals, dry fruits, cheese, and mushrooms tended to have higher nickel

concentrations (Cabrera-Vique et al. 2011). The concentrations of nickel in drinks (48.4–319 µg/kg), legumes (149–744 µg/kg), breakfast cereals (413–485 µg/kg), soy-based foods (281–2,389 µg/kg), dried fruits (184–1,085 µg/kg), nuts (1,061–2,649 µg/kg), and chocolate (4,114–4,785 µg/kg) were measured in Belgium (Babaahmadifooladi et al. 2021). Based on these concentrations, the mean daily exposure to nickel through the consumption of different foods ranged from 0.31 to 4.70 µg/kg body weight/day in individuals aged 3–9 years, 0.13–2.00 in individuals aged 10–17 years µg/kg body weight/day, and 0.09–1.20 µg/kg body weight/day in individuals aged 18–64 years (Babaahmadifooladi et al. 2021). The exposure decreased when considering the bioaccessible fraction and dialyzable fraction (Babaahmadifooladi et al. 2021).

Many studies have measured nickel levels in cigarettes, smokeless tobacco products, and e-cigarettes. These studies are shown in Table 5-17. According to these studies, the mean concentration of nickel ranges from 2.1 to 3.9 µg/g in traditional cigarettes, 1.19–16.8 µg/g in smokeless tobacco products, and below detection to 22,600 µg/L in e-cigarette liquid. The age of e-cigarette devices may affect the metal concentrations in the liquid (Gray et al. 2019).

Table 5-17. Concentrations of Nickel in Cigarettes, Electronic Cigarettes, and Smokeless Tobacco Products

Product	Concentration	Notes	Source
Cigarettes			
	2.1±0.1 to 3.9±0.5 µg/g	Range of means of 50 cigarette brands purchased in Atlanta, Georgia in 2011	Fresquez et al. 2013
	2.21±0.54 µg/g	Mean of cigarettes supplied by participants in the International Tobacco Control United States Survey; range of samples was 0.60–4.40 µg/g	Caruso et al. 2013
Smokeless tobacco			
Moist snuff	2.28±0.36 µg/g	Mean 17 brands purchased in Atlanta, Georgia; means of each brand ranged from 1.39±0.11 to 2.73±0.06 µg/g	Pappas et al. 2008
Moist snuff	8.03±0.38 to 13.5±0.61 µg/g	Range of means of 23 brands purchased in Pakistan	Arain et al. 2015
Iqmik tobacco[a]	2.32±1.63 µg/g	Mean of 17 samples	Pappas et al. 2008
Dokha	25.58±2.50 µg/g	Mean of 13 products from stores in the UAE; mean of each product ranged from 17.5±2.5 to 35±2.5 µg/g	Mohammad et al. 2019
Shisha	27.67±5.31 µg/g	Mean of three products from stores in the UAE; mean of each product	Mohammad et al. 2019

Table 5-17. Concentrations of Nickel in Cigarettes, Electronic Cigarettes, and Smokeless Tobacco Products

Product	Concentration	Notes	Source
		ranged from 20±3.33 to 36.6±7.4 µg/g	
Mainpuri	10.6±0.34–16.8±0.46 µg/g	Range of means of 12 brands purchased in Pakistan	Arain et al. 2013, 2015
Gutkha	1.19±0.13–2.43±0.17 µg/g	Range of means 11 brands purchased in Pakistan	Arain et al. 2015
Electronic cigarettes			
Liquid	<LRL[b]–4.04 µg/g	Range of means of liquids from refill bottles, pods, cartridges, and single-use devices from vendors in Atlanta, Georgia or online	Gray et al. 2019
Liquid	58.7±22.4–22,600±24,400 µg/L	Range of means of five commercial brands in the United States; range across the 48 samples was 13.7–72,700 µg/L; medians for each brand ranged from 58.1 to 15,400 µg/L	Hess et al. 2017
Aerosols	490–190,000 nickel-containing particles per 10 puffs	Five brands were studied; two brands were not able to give accurate particle counts; mean particle size ranged from 55±17 to 138±23	Pappas et al. 2020
Vapor	0.11±0.06–0.29±0.08 µg per cigarette (150 puffs)	Range of means of 11 popular brands in Poland and 1 in Great Britain purchased online	Goniewicz et al. 2014

[a]*Iqmik* is a smokeless tobacco product that is popular among Alaska Natives.
[b]LRL = 0.032 µg/g.

LRL = lowest reportable level; UAE = United Arab Emirates

Nickel in fish and shellfish caught in Alaska ranged from non-detects to 0.85 mg/kg wet weight (Alaska Department of Environmental Conservation 2021). Mean concentrations were up to 0.71 mg/kg wet weight in marine fish, 0.64 mg/kg wet weight in salmonids, 0.69 mg/kg wet weight in marine forage fish, 0.494 mg/kg wet weight in marine invertebrates, and 0.85 mg/kg wet weight in freshwater fish (Alaska Department of Environmental Conservation 2021). A summary of recent biota monitoring data from the WQP are presented in Table 5-18. The *Bivalvia* and *Polychaeta* samples collected in 2021 with maximum values an order of magnitude higher than typically reported for other species were collected from an oceanic dredge near the Virginia Beach, Virginia coastline (WQP 2024).

Table 5-18. Summary of Nickel (µg/kg) Measured in Biota Samples Across the United States

Year	Species	Mean	Maximum	Number of samples	Percent detected
2018		433	4,650	250	8.0%
	Ictalurus punctatus	2,410	4,650	27	7.4%
	Lepomis megalotis	467	1,240	3	100%
	Ameiurus natalis	367	611	3	67%
	Micropterus dolomieu	260	260	6	17%
	Pomoxis nigromaculatus	243	243	7	14%
	Species with the five highest average detections reported; also detected in *Micropterus salmoides*, *Morone saxatilis*, *Cyprinus carpio*, and *Oncorhynchus mykiss*				
2019		315	2,800	266	21%
	Polychaeta	1,660	2,800	3	100%
	Salvelinus confluentus	1,170	1,170	8	13%
	Amia calva	685	720	7	29%
	Bivalvia	680	1,400	3	100%
	Richardsonius balteatus	588	1,540	16	25%
	Species with the five highest average detections reported; also detected in *Ictalurus furcatus, Hybognathus nuchalis, Lepomis cyanellus, Ptychocheilus oregonensis, A. natalis, Lepomis macrochirus, M. salmoides, Catostomus commersonii, Oncorhynchus nerka, Semotilus atromaculatus, C. carpio, Mylocheilus caurinus, Catostomus macrocheilus*, and *L. megalotis*				
2020		733	24,000	248	54%
	Taxon unknown	7,090	24,000	13	85%
	O. mykiss	510	3,010	13	54%
	Micropterus punctulatus	326	393	9	33%
	Pylodictis olivaris	287	373	7	29%
	M. salmoides	206	378	20	75%
	Species with the five highest average detections reported; also detected in *I. punctatus, Sciaenops ocellatus, P. nigromaculatus, Esox niger, I. furcatus, M. saxatilis, Lepomis microlophus, A. calva, L. macrochirus, Oncorhynchus clarkia, Morone chrysops, Catostomus Catostomus, C. macrocheilus, M. caurinus*, and *P. oregonensis*				
2021		1,300	17,300	145	91%
	Bivalvia	7,610	17,300	8	100%
	Polychaeta	7,445	14,500	8	100%
	Taxon unknown	–	4,800	1	100%
	P. olivaris	–	2,000	1	100%
	Sander vitreus	–	2,000	1	100%
	Species with the five highest average detections reported; also detected in *Vertebrata, A. calva, I. furcatus, M. salmoides, L. microlophus, I. punctatus, P. nigromaculatus, M. saxatilis,*				

Table 5-18. Summary of Nickel (µg/kg) Measured in Biota Samples Across the United States

Year	Species	Mean	Maximum	Number of samples	Percent detected
	L. macrochirus, Lepomis auratus, E. niger, M. punctulatus, Coregonus clupeaformis, A. natalis, M. dolomieu, and *C. commersonii*				
2022		952	4,610	52	88%
	C. commersonii x Catostomus latipinnis	1,820	2,310	2	100%
	Salmo trutta	1,680	2,660	2	100%
	C. latipinnis	1,490	4,610	9	100%
	Pantosteus discobolus	1,270	2,090	7	100%
	C. commersonii x Catostomus discobolus	–	1,260	1	100%
	Species with the five highest average detections reported; also detected in *C. commersonii, O. mykiss, M. salmoides, I. punctatus, M. dolomieu, L. microlophus, P. nigromaculatus,* and *A. calva*				
2023		515	1,080	8	100%
	P. discobolus	766	1,080	4	100%
	C. commersonii	–	510	1	100%
	S. trutta	213	311	2	100%
	O. mykiss	–	122	1	100%

Source: WQP 2024

Nickel was measured in cement dust from the United States at an average concentration of 47.45±3.21 µg/g (Ogunbileje et al. 2013).

5.6 GENERAL POPULATION EXPOSURE

Nickel occurs naturally in the Earth's crust, and the general population will be exposed to low levels of nickel in ambient air, water, and food.

Table 5-19 presents the geometric mean and selected percentiles of urinary nickel in the United States population from the 2017–2018 cycle of the NHANES. In the total population, the geometric mean concentration of urinary nickel is 1.11 µg/L (1.22 µg/g creatinine).

Table 5-19. Geometric Mean and Selected Percentiles of Urinary Nickel for the U.S. Population from the National Health and Nutrition Examination Survey (NHANES)

	Survey years	Geometric mean (95% CI)	Selected percentiles				Sample size
			50th	75th	90th	95th	
Urinary nickel (µg/L)							
Total	2017–2018	1.11 (1.03–1.20)	1.16	1.95	3.03	4.23	2,791
Age group							
3–5 years	2017–2018	1.36 (1.17–1.56)		1.50	2.55	4.19 5.59	399
6–11 years	2017–2018	1.55 (1.37–1.76)		1.70	2.54	4.23 5.02	328
12–19 years	2017–2018	1.30 (1.20–1.40)	1.30	2.30	3.57	4.17	362
≥20 years	2017–2018	1.04 (0.953–1.14)	1.07	1.75	2.82	3.95	1,702
Sex							
Males	2017–2018	1.14 (1.04–1.25)	1.19	1.89	3.00	4.31	1,376
Females	2017–2018	1.09 (0.97–1.22)	1.12	2.00	3.08	4.15	1,415
Race/ethnicity							
Mexican American	2017–2018	1.15 (1.05–1.26)	1.17	2.08	3.06	3.85	434
Non-Hispanic White	2017–2018	1.07 (0.95–1.20)	1.09	1.76	2.98	4.18	908
Non-Hispanic Black	2017–2018	1.34 (1.26–1.43)	1.37	2.22	3.44	4.64	637
All Hispanic	2017–2018	1.13 (1.02–1.24)	1.14		2.01	3.02 3.98	675
Non-Hispanic Asian	2017–2018	1.14 (0.949–1.38)	1.22	1.97	3.39	4.56	362
Urinary nickel (creatinine corrected) (µg/g creatinine)							
Total	2017–2018	1.22 (1.15–1.30)			1.20	1.88 2.87 3.84	2,789
Age group							
3-5 years	2017–2018	2.81 (2.58–3.07)			2.71	4.07 6.29 7.79	399
6-11 years	2017–2018	2.17 (1.99–2.36)			2.03	3.15 4.81 6.08	327
12–19 years	2017–2018	1.17 (1.07–1.28)			1.17	1.75 2.73 3.03	362
≥20 years	2017–2018	1.11 (1.04–1.19)			1.10	1.69 2.53 3.23	1,701
Sex							
Males	2017–2018	1.06 (0.991–1.14)			1.04	1.60 2.61 3.59	1,375
Females	2017–2018	1.40 (1.30–1.51)			1.38	2.17 3.08 4.04	1,414
Race/ethnicity							
Mexican American	2017–2018	1.24 (1.16–1.33)			1.16	1.91 2.75 3.65	432

Table 5-19. Geometric Mean and Selected Percentiles of Urinary Nickel for the U.S. Population from the National Health and Nutrition Examination Survey (NHANES)

	Survey years	Geometric mean (95% CI)	Selected percentiles				Sample size
			50th	75th	90th	95th	
Non-Hispanic White	2017–2018	1.25 (1.14–1.37)	1.22	1.94	2.90	3.84	908
Non-Hispanic Black	2017–2018	1.01 (0.937–1.09)	0.979	1.65	2.53	3.05	637
All Hispanic	2017–2018	1.22 (1.14–1.30)	1.14	1.80	2.73	3.78	673
Non-Hispanic Asian	2017–2018	1.50 (1.25–1.80)	1.57	2.41	3.66	5.51	362

CI = confidence interval

Source: CDC 2024

Since nickel is present in many foods, the general population is expected to be exposed to nickel via consumption of common food products; measurements of nickel in U.S. foods are available (see Table 5-15). The Tolerable Upper Intake Level for nickel by life stage group is shown in Table 5-20. More recently, the European Food Safety Authority (EFSA) derived a tolerable daily intake of 13 µg/kg body weight/day (EFSA 2020).

Table 5-20. Tolerable Upper Intake Levels for Nickel

Life stage group	UL (µg/day)
0–12 months old	ND[a]
1–3 years old	200
4–8 years old	300
9–13 years old	600
14–18 years old	1,000
≥19 years old	1,000
Pregnant females, 14–18 years old	1,000
Pregnant females, 19–50 years old	1,000
Lactating females, 14–18 years old	1,000
Lactating females, 19–50 years old	1,000

[a]Data are insufficient to determine a UL.

ND = not determined; UL = Tolerable Upper Intake Level

Source: Institute of Medicine 2001

Daily nickel intake calculations using the most recent Total Diet Study results (reported in Tables 5-15 and 5-16) were not available. Using data for the 1991–1997 Total Diet Study and the 1988–1994 NHANES, the Institute of Medicine (2001) estimated that the nickel intake from food for the general population is <0.5 mg/day and that supplements provide 9.6–15 µg/day. In one total dietary study (Institute of Medicine 2001), the mean daily dietary intake of nickel ranged from 101 to 162 µg/day for individuals >18 years of age, with males ranging from 136 to 140 µg/day and females ranging from 107 to 109 µg/day. Pregnant females averaged a daily dietary intake of 121 µg/day, whereas lactating females averaged 162 µg/day.

More recent dietary intake estimates are available from data outside of the United States, which are presented in Table 5-21. EFSA published daily intake estimates as part of their comprehensive risk assessment of nickel in food and drinking water (EFSA 2020). These estimates considered multiple market studies and dietary surveys within the European Union and are expected to be comparable to dietary exposure in the United States. Dietary exposure estimates based on consumption of cucumbers and bell peppers in Iran are expected to be comparable to expected exposures in the United States based on similar nickel contents of the produce. The mean concentrations of nickel measured in cucumbers and bell peppers in Iran were 0.18 and 0.08 µg/g, respectively (Khoshgoftarmanesh et al. 2009), which are comparable to those for cucumbers (120 µg/kg or 0.120 µg/g) and raw sweet green peppers (67 µg/kg or 0.067 µg/g) in the U.S. Total Diet Study (FDA 2023c). Nickel intake was estimated from measured concentrations in products from the Belgian marked; the potential exposure decreased when considering the bioaccessible fraction and dialyzable fraction (Babaahmadifooladi et al. 2021). A study of exposure to nickel via food consumption in Greece found that median hair nickel concentrations were significantly higher in females (0.08 µg/g) than in males (<0.05 µg/g) (Sazakli and Leotsinidis 2017). Foods that affected hair nickel levels were meat, yogurt, fast food, rice and pasta, coffee, and pre-treated meat (Sazakli and Leotsinidis 2017).

Table 5-21. Nickel Dietary Intake Estimates from Outside of the United States

Life stage group	Dietary exposure (µg/kg body weight/day)	Notes	Reference
<12 months old	4.40–6.14	Median lower bound and upper bound; based on data from the European market	EFSA 2020
≥12–<36 months old	8.52–10.1		
≥36 months–<10 years old	7.05–8.16		
≥10–<18 years old	3.58–4.27		
≥18–<65 years old	2.90–3.41		

Table 5-21. Nickel Dietary Intake Estimates from Outside of the United States

Life stage group	Dietary exposure (µg/kg body weight/day)	Notes	Reference
≥65–<75 years old	2.51–2.99		
≥75 years old	3.05–3.55		
Children	0.06–0.17	Based on intake from cucumbers and bell peppers in Iran; 0.07–0.24 µg/kg body weight/day average exposure	Khoshgoftarmanesh et al. 2009
≥55 years old	0.03–0.19		
3–9 years old	0.31–4.70	Based on drinks, legumes, breakfast cereals, soy-based foods, dried fruits, nuts, and chocolate from the Belgian market	Babaahmadifooladi et al. 2021
10–17 years old	0.13–2.00		
18–64 years old	0.09–1.20		
Not specified	12.2±8.41	Exposure from rice grown in soil naturally enriched in nickel	Li et al. 2020a
Not specified	0.84±0.40	Exposure from wheat grown in soil naturally enriched in nickel	

There is evidence that stainless steel pots and utensils may release nickel into acid solution (IARC 1990). Six stainless steel pots of different origins were tested to see whether they would release nickel by boiling 350 mL of 5% acetic acid in them for 5 minutes (Kuligowski and Halperin 1992). The resulting concentrations of nickel ranged from 0.01 to 0.21 ppm. Cooking acidic fruits in new stainless-steel pans resulted in an increase of nickel that was about one-fifth the average daily nickel intake (Flint and Packirisamy 1995). Further use of the pans did not result in any release of nickel into the food. One study found that nickel was released into food from 18/10 (grade 316) stainless steel pots while cooking (Guarneri et al. 2017). The amount of nickel released was higher in unused pots than used pots, increased with cooking time, and varied by manufacturer (Guarneri et al. 2017). Another study found that nickel leaching did not correlate with the nickel content of the stainless steel, but reduced leaching was observed when there was an increased chromium oxide layer on the product, which helps prevent corrosion (Kamerud et al. 2013). The initial nickel content of the tomato sauce tested prior to cooking was 90–244 µg/kg; an average of 698 µg/kg nickel was reported after the 10th 6-hour cooking cycle in stainless steel cookware. This is equivalent to 88 µg nickel per 126 g serving of tomato, which is below the ULs reported in Table 5-16 (Kamerud et al. 2013). A standardized citric acidic leaching study of several grades of stainless steel (204, 201, 316L, 304, and LDX 2101) showed decreased nickel release in tests up to 240 hours heating citric acid at 40°C after the initial 2-hour trial heating citric acid at 70°C (Hedberg et al. 2014). None of the products released nickel in excess of its corresponding release limit set by the

Council of Europe (0.14 µg/cm^2). The use of nickel-containing catalysts in the hydrogenation of food fats may contribute to elevated nickel levels in food (Mastromatteo 1986). Grain milling may also lead to higher nickel levels (IARC 1990). The results from a study that attempted to identify the influence of the container on the trace metal content of preserved pork products showed no clear evidence that the metal container contributed to the metal content of the food (Brito et al. 1990). The nickel concentration was highest in products in China and glass containers, rather than those in metal and plastic containers. These studies indicate that while the general population is expected to be exposed to nickel in food, dietary exposure may slightly increase if an individual uses stainless steel cookware to prepare acidic foods for prolonged cook times.

Nickel is a common allergen, and the general population may be exposed to nickel in jewelry. The European Union Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) has set allergy protective thresholds for nickel release at 0.35 µg/cm^2/week for piercing posts and 0.88 µg/cm^2/week for other items in direct and prolonged contact with the skin (Uter and Wolter 2018). In a study of earrings in Germany, 16% of piercing posts released nickel at a rate exceeding 0.35 µg/cm^2/week, while 5.9% of clasp parts and 4% of decorative parts released at least 0.88 µg/cm^2/week (Uter and Wolter 2018). Thyssen and Maibach (2008) tested 277 earrings bought from local artists, tourist stores, and chain stores in San Francisco, California. Eighty-five earrings had a positive dimethylglyoxime spot test, which indicates nickel release (Thyssen and Maibach 2008). Positive reactions were identified in 69% of earrings from local artists, 42.9% of earrings from tourist stores, 24.1% of earrings from chain stores targeting girls and young women, and 1.7% of chain stores targeting adult women (Thyssen and Maibach 2008). Hamann et al. (2015) further analyzed the samples from the Thyssen and Maibach (2008) study. After being immersed in artificial sweat for a week, nickel release was detected in 79 of the 96 jewelry samples at a rate ranging from 0.01 to 598 µg/cm^2/week (Hamann et al. 2015). The prevalence of samples that exceeded the REACH criteria was not discussed; however, data for five samples exceeding the criteria (1.6–598 µg/cm^2/week) were reported by the study authors (Hamann et al. 2015).

Children may be exposed to nickel in jewelry, clothing buckles and fasteners, and technology (Tuchman et al. 2015). Jensen et al. (2014) described children's toys as another potential source of nickel exposure. To evaluate nickel release from children's toys, 63 toys were purchased from toy and thrift shops in the United States and an online retailer and 149 toys from 8 toy stores in Denmark. Of the toys in the United States, 50.8% tested positive for nickel release with a dimethylglyoxime (DMG) screening test compared to 27.5% of the toys from Denmark (Jensen et al. 2014). This study did not quantify nickel release from

the toys and limited dermal contact considerations were discussed. Other sources of nickel exposure in children are food consumption and accidental ingestion of soil containing nickel. Nickel concentrations in baby food in the United States ranged from 0 (not detected) to 450 µg/kg (FDA 2023c). In Portugal, where samples of commercial premade baby foods contained nickel at concentrations up to 225.7 µg/kg, the average estimated daily intake of nickel in these foods was 1.12 µg/kg body weight for 6-month-old children, 2.76 µg/kg body weight for 1-year-old children, and 3.13 µg/kg body weight for 2-year-old children (Pereira et al. 2020). Wittsiepe et al. (2009) estimated that the daily dietary intake rate for 4–7-year-old children in Germany was 12–560 µg/day based on concentrations in food samples or 35–1,050 µg/day based on dietary records; both estimates were higher than recommendations. Children living in urban areas who consumed food from family gardens or local food and local animal products were exposed to higher nickel levels in food than children who ate food primarily from supermarkets (Wittsiepe et al. 2009). It is possible that children who play outside may be exposed to nickel through incidental soil ingestion. Li et al. (2020a) found that nickel intake from soil ingestion from soils with elevated nickel concentrations is negligible. Through this pathway, intake was estimated to be 0.02±0.01 µg/kg body weight/day (Li et al. 2020a).

5.7 POPULATIONS WITH POTENTIALLY HIGH EXPOSURES

Individuals who work in the mining of nickel or the production of nickel and nickel products may be exposed to higher levels of nickel than the general population. Several studies have assessed exposures in industries by measuring dermal exposures, occupational air concentrations, and serum or blood concentrations in exposed groups. Hughson et al. (2010) measured dermal and inhalable nickel exposure in workers in primary nickel production and primary nickel user industries, including workers involved in front-end refinery processes, electrowinning/electrolysis, packing solid nickel metal products, packing nickel compounds, packing nickel metal powders, powder metallurgy, and stainless steel production; these workers had inconsistent use of personal protective equipment. The highest mean total dermal exposures were found on the face of individuals packing nickel powder (15.16 µg/cm^2) (Hughson et al. 2010). Those packing nickel powder also had the highest exposures on the hands and forearms at a mean total nickel exposure of 6.20 µg/cm^2. Mean inhalable total nickel exposures were: 0.13 mg/m^3 (front-end refinery), 0.04 mg/m^3 (electro-winning/electrolysis), 0.08 mg/m^3 (packing nickel metal products), 0.02 mg/m^3 (packing nickel compounds), 0.77 mg/m^3 (packing nickel powders), 0.05 mg/m^3 (powder metallurgy), and 0.03 mg/m^3 (stainless steel production) (Hughson et al. 2010). Julander et al. (2010) studied skin deposition in 24 workers who worked in the development and manufacturing of gas turbines and space propulsion structures; study participants were tasked with sharpening tools, producing

combustion structures, and thermal application of metal-containing powders. Nickel could be found on all skin surfaces of the forehead and hands. The department with the highest nickel exposure was the thermal applications department, in which the highest level detected was 15 μg/cm^2/hour on the index and middle fingers (Julander et al. 2010). The study authors concluded that the exposures to nickel likely resulted from direct skin contact with items rather than from airborne dust deposition.

Vuskovic et al. (2013) assessed nickel exposure in nickel refinery workers in Jinchang, residents of Jinchang, and residents of Zhangye. Urinary nickel levels were significantly higher in refinery works (8.43±3.22 μg/L) than in Jinchang residents (6.55±3.51 μg/L) or Zhangye residents (6.83±3.53 μg/L) (Vuskovic et al. 2013). A study of electroplating workers in Egypt showed that serum nickel concentrations in exposed workers were 12.30 μg/L and were significantly higher than the serum concentration of 0.40 μg/L in non-occupationally exposed controls (El Safty et al. 2018).

Since nickel is used in dental applications, dental technicians are expected to have higher nickel exposures than the general population. In a study of metal release from dental tools and alloys immersed in artificial sweat for a week, nickel was released from dental tools in the range of 0.0051–10 μg/cm^2/week and from dental alloys in the range of 0.0046–0.024 μg/cm^2/week (Kettelarij et al. 2014). A study of dental technicians in Sweden compared dental technicians exposed to cobalt-chrome via work tasks, such as preparing prostheses and metal constructions for dental crowns, to non-exposed technicians aiming to quantify exposure to nickel, cobalt, and chromium (Kettelarij et al. 2016). The study authors reported that nickel was found on all participants both after 2 hours of exposure with no handwashing and at the end of the workday, indicating that exposure might be attributed to use of tools and materials that release nickel. Before work, the median concentrations of nickel on the skin were 0.014 μg/cm^3 in exposed technicians and 0.026 μg/cm^3 in non-exposed technicians, then increased to 0.0.57 μg/cm^3 in exposed technicians and 0.012 μg/cm^3 for non-exposed technicians after 2 hours of work with no handwashing (Kettelarij et al. 2016). At the end of the day, the median concentrations were 0.018 μg/cm^3 in exposed technicians and 0.014 μg/cm^3 in non-exposed technicians (Kettelarij et al. 2016). Nickel was found in 4 of 10 air samples taken during this study at concentrations ranging from 0.48 to 3.7 μg/m^3 and metal urine concentrations were normal (Kettelarij et al. 2016). Berniyanti et al. (2020) measured blood concentrations of nickel in exposed dental technicians and controls. The mean concentrations of nickel in blood were 36.76 μg/L in exposed individuals and 3.35 μg/L in controls (Berniyanti et al. 2020). Hariyani et al. (2015) found similar results, calculating mean blood nickel concentrations of 36.76 and 3.19 μg/L in dental technicians and controls, respectively. Lower mean blood nickel levels were observed in groups who used gloves, protective clothing, and masks, although these results were not

statistically significant (Hariyani et al. 2015). While dental technicians are likely to have higher exposures to nickel, Kulkami et al. (2016) concluded that nickel releases from stainless steel crowns and space maintainers are unlikely to release high enough concentrations of nickel to produce toxicity.

Populations living near other industries known to emit nickel may be at risk of high exposure to nickel. Populations near oil refineries and coal-fired power plants, including children, have increased urinary nickel concentrations (Chen et al. 2017). Mean urinary nickel in the elderly living near these facilities was 11.28±15.34 µg/g-creatinine compared to 8.33±29.64 µg/g-creatinine in elderly living further from the facilities (Chen et al. 2017). In children, mean urinary nickel was 10.41±16.62 µg/g-creatinine in subjects living close to the facilities and 3.70±2.89 µg/g-creatinine in those living further from the facilities (Chen et al. 2017). A study of metal concentrations in air was conducted in four communities near metal recyclers in Houston, Texas (Han et al. 2020). Mean concentrations at the fence lines of the four facilities ranged from 14.24 to 769.8 ng/m^3 and decreased to levels similar to background concentrations at 600 meters away (Han et al. 2020). Han et al. (2020) estimated that the cancer risks due to inhalation of nickel were 0.21–14 cases per million at the fence line, 0.03–1.1 cases per million in near neighborhoods, and 0.21–0.47 cases per million in far neighborhoods.

Many studies have measured nickel in tobacco products and e-cigarettes indicating that people who smoke cigarettes or e-cigarettes, or who use smokeless tobacco products may have higher exposures than the general population. Smoking is associated with nickel sensitization (Thyssen et al. 2010). Pappas et al. (2008) found that in smokeless tobacco products including snuff products and iqmik (tobacco and ash mixture), the average nickel concentration among 17 commercially available brands is 2.28 µg/g. Using artificial saliva, the study authors found that 20–46% of nickel contained in the products is extractable (Pappas et al. 2008). In a study analyzing smokeless tobacco products in Pakistan, Arain et al. (2015) found that nickel intakes were 10.6–25.9 µg/10 g of gutkha (chewing tobacco mixture), 75.6–141 µg/10 g of moist snuff (finely ground or pulverized tobacco leaves), and 103–173 µg/10 g of mainpuri (chewing tobacco mixture). Whole blood and scalp hair nickel concentrations of people who do not consume smokeless tobacco products were 2–3 times lower than those of people who do consume these products (Arain et al. 2015). In a separate study, Arain et al. (2013) estimated that people who consume 10 g of mainpuri product have a mean daily nickel intake of 135 µg. The levels of nickel in blood and scalp hair of oral cancer patients who used these smokeless tobacco products were 5–6 times higher than levels in controls (Arain et al. 2015). Other studies have measured nickel in the serum (7.0 µg/L), urine (0.9 µg/L), saliva (2.3 µg/L), and exhaled breath condensate (1.3 µg/L) of cigarette and e-cigarette users (Aherrera et al. 2017; Badea et al. 2018).