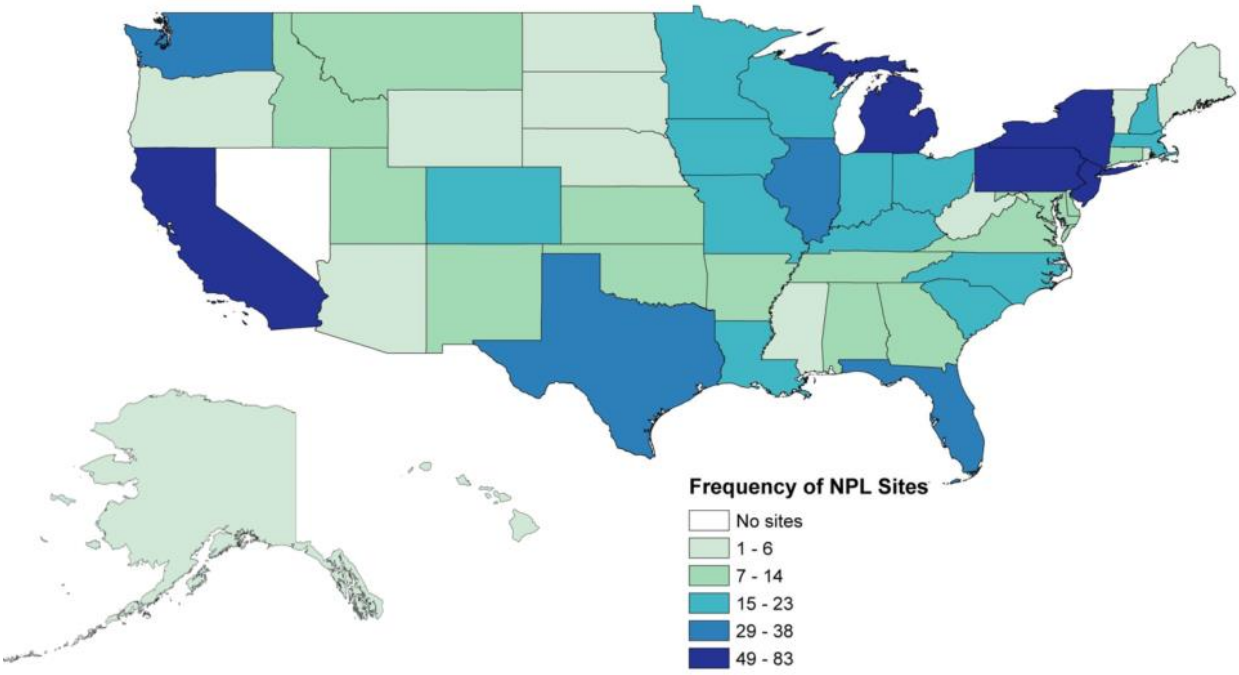
CHAPTER 5. POTENTIAL FOR HUMAN EXPOSURE

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 evaluated for nickel and nickel compounds 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, none are in the Virgin Islands, 4 are located in Puerto Rico, and 1 is located in Guam (not shown).

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



Source: ATSDR 2022

- Nickel is primarily used for stainless and alloy steels, nonferrous alloys, superalloys, and electroplating.
- Nickel is released to the atmosphere from natural sources such as windblown soil particles and anthropogenic sources such as oil combustion.
- Nickel is released to the atmosphere as particulate matter or adsorbed to particulate matter. It is dispersed by wind and removed by various processes. Nickel typically accumulates at the surface

of soils due to deposition and is strongly adsorbed by soil. Nickel does not bio-magnify in the food chain. It does accumulate in plants.

- Nickel levels monitored in ambient air are generally less than 0.003 μg/m^3. Nickel naturally occurs in the earth's crust and is present in the soil. Concentrations of nickel in surface water and groundwater in the United States are generally low.
- The general population may be exposed to nickel through inhalation of ambient air and ingestion of food and drinking water. Exposure may also occur from consumer goods, like toys and jewelry.
- 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, and people who smoke may also be exposed to higher levels of nickel in tobacco products and e-cigarettes.

Nickel and its compounds are naturally present in the Earth's crust and can be found in many minerals. In 2020, nickel in the United States was produced from one mine in Michigan (USGS 2021). The United States imports more nickel than it produces or exports. Nickel is primarily used for stainless and alloy steels, nonferrous alloys and superalloys, and electroplating (USGS 2021). Nickel is also used as an alloy in medical and dental appliances and tools, and for cast iron, chemical uses, and to make U.S. coins.

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. Tomatoes are moderate accumulators of nickel (Correia et al. 2018). Nickel does not appear to accumulate in aquatic organisms or bio-magnify in aquatic food webs. 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 below 3 ng/m^3 (EPA 2020a). 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. 2012a; Peltier and Lippmann 2010b; 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 2010a; Schachter et al. 2020). Nickel is naturally present in soil and sediment, and in food. According to the FDA's Total Diet Study, the average concentration of nickel in various U.S. foods ranges from 0.0004 to 3.2 mg/kg (FDA 2017a). As shown in Table 5-13, nickel is also present in cigarettes and smokeless tobacco products at concentrations ranging from 1.19 to 16.8 µg/g, and in e-cigarette liquid at concentrations up to 22,600 µg/L.

The general population is primarily exposed to nickel in food and exposed to low levels in ambient air and water. The average daily dietary nickel intake for U.S. diets is 69–162 µg (Institute of Medicine 2001; O'Rourke et al. 1999; Pennington and Jones 1987; Thomas et al. 1999). The general population may also be exposed to nickel present in stainless steel cookware, jewelry, clothing buckles and fasteners, technology, and toys.

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. Populations living near these industry sites or near disposal sites may also have high 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.

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. Pentlandite often occurs along with the iron mineral pyrrhotite and the copper mineral chalcopyrite, and part of the smelting and refining process separates the copper and iron from the nickel. 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 1–3% nickel.

Sulfide ores are processed by several pyrometallurgical processes: roasting, smelting, and converting. During these processes, sulfur and iron are removed to yield a sulfur-deficient copper-nickel matte. Especially after roasting and converting, the nickel in the matte may consist primarily of nickel subsulfide. After physical separation of the copper and nickel sulfides, the nickel is refined electrochemically or by 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.

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. The smelting process that does not include adding sulfur produces a ferronickel alloy, containing ≤50% nickel, which can be used directly in steel production. Hydro-metallurgical techniques involve leaching with ammonia or sulfuric acid, after which the nickel is selectively precipitated (Duke 1980b; IARC 1990a; Tien and Howson 1981; Warner 1984). 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 300 million tons of nickel available in identified land-based resources with at least 0.5% nickel (USGS 2021). Approximately 60% of these resources is in laterites and 40% is in sulfide deposits, but nickel can also be found in manganese crusts and nodules on the ocean floor (USGS 2021). Nickel has also been found in meteorites, with the content ranging from 5 to 50% (Duke 1980a; Mastromatteo 1986). In 2020, all of the 16,000 tons of nickel produced in the United States occurred at the underground Eagle Mine in Michigan (USGS 2021). 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 2021).

Table 5-1 lists facilities in each state that manufacture, process, or use nickel or nickel compounds, the intended use reported by the facility, and the range of maximum amounts of these substances that are stored on site. In 2019, there were 2,495 reporting facilities that produced, processed, or used nickel and 1,109 that produced, processed, or used nickel compounds in the United States. The data listed in Table 5-1 are derived from the Toxics Chemicals Release Inventory (TRI) (TRI19 2020). Only certain types of facilities were required to report. Therefore, this is not an exhaustive list.

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

State[a]	Number of facilities	Minimum on site in pounds[b]	Maximum on site in pounds[b]	Activities and uses[c]
AK	4	1000	9999999	1, 5, 8, 12, 13, 14
AL	106	0	10000000000	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
AR	55	1000	9999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
AZ	35	0	9999999	1, 2, 3, 4, 5, 7, 8, 9, 11, 12, 13, 14
CA	142	0	999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
CO	30	0	999999	1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14
CT	62	100	9999999	1, 2, 3, 4, 7, 8, 9, 10, 11, 12, 14
DC	1	1000	9999	1, 3, 11
DE	7	1000	99999	1, 2, 3, 8, 10, 13, 14
FL	44	100	9999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14
GA	63	0	9999999	1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14
HI	2	0	99	1, 5
IA	83	100	9999999	1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
ID	11	1000	999999	1, 5, 7, 8, 11, 12, 13, 14
IL	201	0	9999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
IN	217	0	49999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
KS	53	0	9999999	1, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14
KY	101	0	49999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
LA	72	0	49999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
MA	42	1000	999999	1, 2, 3, 6, 7, 8, 9, 11, 12, 14
MD	21	100	999999	1, 2, 3, 4, 5, 7, 8, 9, 12, 13, 14
ME	11	0	999999	1, 2, 3, 5, 7, 8, 9, 11, 12
MI	177	0	49999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
MN	72	0	9999999	1, 2, 3, 4, 5, 7, 8, 9, 10, 12, 13, 14
MO	73	0	9999999	1, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14
MS	46	1000	9999999	1, 2, 3, 4, 5, 7, 8, 10, 11, 12, 13, 14
MT	10	1000	9999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
NC	87	100	9999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
ND	10	1000	999999	1, 5, 8, 9, 10, 12, 13, 14
NE	36	0	999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
NH	18	100	9999999	2, 3, 4, 7, 8, 9, 11, 14

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

State[a]	Number of facilities	Minimum on site in pounds[b]	Maximum on site in pounds[b]	Activities and uses[c]
NJ	33	1000	9999999	2, 3, 4, 7, 8, 9, 10, 11, 12, 14
NM	7	100	999999	1, 2, 3, 4, 5, 9, 10, 11, 12, 13, 14
NV	21	0	9999999	1, 2, 3, 4, 5, 7, 8, 9, 12, 13, 14
NY	62	0	9999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12, 13, 14
OH	298	0	49999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
OK	104	0	99999999	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14
OR	24	1000	9999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14
PA	294	0	499999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
PR	6	1000	999999	1, 3, 5, 6, 7, 8, 11, 12, 14
RI	12	100	9999999	7, 8, 10, 12, 14
SC	81	0	9999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
SD	11	1000	99999	8, 14
TN	110	0	9999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
TX	289	0	999999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
UT	30	1000	49999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
VA	35	1000	999999	1, 2, 3, 5, 7, 8, 9, 11, 12, 13, 14
VT	4	100	99999	2, 3, 7, 8, 11, 14
WA	36	0	9999999	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14
WI	220	0	9999999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
WV	18	100	9999999	1, 2, 3, 4, 5, 7, 8, 9, 12, 13, 14
WY	8	1000	9999999	1, 2, 3, 4, 5, 9, 10, 12, 13, 14

[a]Post office state abbreviation 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: TRI19 2020; Data are from 2019

5.2.2 Import/Export

According to USGS (2021), an estimated 120 metric tons of nickel ore and concentrates, 110,000 metric tons of primary nickel, and 32,000 metric tons of secondary nickel were imported into the United States in 2020. Between 2016 and 2019, annual imports ranged from 3 to 64 metric tons of ores and concentrates, 111,000 to 150,000 metric tons of primary nickel, and 32,300 to 45,100 of secondary nickel (USGS 2021). Between 2016 and 2019, Canada, Norway, Finland, and Russia supplied 42, 10, 9, and 8% of nickel, respectively (USGS 2021). Canada, Mexico, and the United Kingdom supplied 38, 27, and 9%

of nickel-containing scrap, respectively (USGS 2021). The product class with the highest quantity of imports in 2016 was unwrought cathodes, pellets, briquets, and shot at 95,100 metric tons of contained nickel, followed by stainless steel scrap at 19,700 metric tons of contained nickel (McRae 2020).

Nickel exports of ores and concentrates in the United States ranged from 14,700 to 22,400 metric tons between 2016 and 2019; primary nickel exports ranged from 9,780 to 12,800 and secondary nickel exports ranged from 51,100 to 63,700 (USGS 2021). Exports in 2020 are estimated to be 13,000 metric tons of ores and concentrates, 11,00 metric tons of primary nickel, and 34,000 metric tons of secondary nickel (USGS 2021). In 2016, stainless steel scrap was the product class with the most exports at 49,000 metric tons of contained nickel (McRae 2020). Most exports of nickel in 2016 were to Canada (26,300 metric tons) followed by China (11,700 metric tons) and Taiwan (9,630 metric tons) (McRae 2020).

5.2.3 Use

Nickel is useful in many applications due to its resistance to corrosion, strength, and ability to withstand extreme temperatures. In 2016, 126,000 of the 188,000 metric tons of nickel consumed in the United States was for stainless and heat resistant steel (McRae 2020). In 2020 the estimated total apparent consumption of nickel in the U.S. was 200,000 metric tons (USGS 2021). Total apparent consumption ranged from 217,000 to 273,000 between 2016 and 2019 (USGS 2021). The primary uses of nickel in the United States are for stainless and alloy steels, nonferrous alloys and superalloys, and electroplating (USGS 2021). More than 85% of consumption in the U.S. is typically accounted for by stainless and alloy steel and nickel-containing alloys (USGS 2021). 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 (McRae 2020; USGS 2021). Nickel is used in all U.S. coins but the penny (USDT 2018).

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 50% of nickel consumption in 2020 was derived from secondary, purchased scrap (McRae 2020). According to TRI, 78% of the 7,739,516 pounds of nickel and 89% of the 28,733,807 pounds of nickel compounds disposed of or otherwise released is released to land (TRI19 2020). TRI reported that 180,953,052 pounds of nickel were transferred off-site for waste management and 175,387,142 pounds of nickel compounds were transferred to recycling. Additionally, 44,331,567 pounds of nickel compounds were transferred off-site for waste management and 35,736,253 pounds of nickel compounds were transferred to recycling (TRI19 2020). 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 is removed from electroplating wastes by treatment with hydroxide, lime, and/or sulfide to precipitate the metal (HSDB 2000f). Adsorption with activated carbon, activated alumina, and iron filings is also used for treating nickel-containing waste water (HSDB 2000f).

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

Table 5-2 and Table 5-3 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 TRI data should be used with caution because only certain types of facilities are required to report (EPA 2005). This is not an exhaustive list. Manufacturing and processing facilities are required to report information to the TRI only if they employ ≥10 full-time employees; if their facility is included in Standard Industrial Classification (SIC) Codes 10 (except 1011, 1081, and 1094), 12 (except 1241), 20–39, 4911 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4931 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4939 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4953 (limited to facilities regulated under RCRA Subtitle C, 42 U.S.C. section 6921 et seq.), 5169, 5171, and 7389 (limited S.C. section 6921 et seq.), 5169, 5171, and 7389 (limited to facilities primarily engaged in solvents recovery services on a contract or fee basis); and if their facility produces, imports, or processes ≥25,000 pounds of any TRI chemical or otherwise uses >10,000 pounds of a TRI chemical in a calendar year (EPA 2005).

5. POTENTIAL FOR HUMAN EXPOSURE

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, transformations, and bioavailability are concerned.

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

	Reported amounts released in pounds per year[b]								
							Total Release		
State[c]	RF[d]	Air[e]	Water[f]	UI[g]	Land[h]	Other[i]	On-site[j]	Off-site[k]	On and off-site
IL	160	10,834	28,438	80	1,978,853	5,325	11,613	2,011,918	2,023,530
NE	12	487	22	0	847,229	0	847,608	130	847,738
KS	65	8,422	153	0	639,584	1,383	8,446	641,095	649,541
AZ	22	468	61	0	648,040	164	647,858	875	648,734
WA	24	1,256	831	0	27,975	411,589	1,257	440,395	441,652
ND	218	13,176	3,125	0	113,663	250,994	15,333	365,627	380,960
NH	22	1,069	65	0	235,499	334	1,084	235,883	236,967
AL	67	4,259	9,552	0	38,477	141,650	4,609	189,329	193,938
IN	72	3,229	1,084	0	108,288	65,613	5,375	172,840	178,215
TN	66	6,566	2,689	121	92,045	75,341	10,901	165,861	176,762
CA	101	2,046	7,002	0	149,154	9,567	77,564	90,204	167,768
TX	186	13,366	1,935	69,229	68,184	8,389	103,178	57,927	161,104
CO	17	43	20	0	133,029	0	133,049	42	133,092
MI	51	2,460	74	0	124,700	335	74,988	52,581	127,569
WI	188	6,012	30,177	0	75,142	12,730	6,741	117,320	124,061
OR	211	10,337	2,647	3	74,882	28,244	10,810	105,303	116,113
MT	25	654	2,847	0	108,928	2,847	19,859	95,416	115,275
RI	55	1,258	593	0	55,354	55,998	2,454	110,749	113,203
OK	19	955	380	0	70,627	21,703	53,208	40,458	93,666
ID	140	3,413	2,955	0	73,149	10,249	21,986	67,779	89,766
NM	50	2,910	2,062	0	52,135	14,645	3,278	68,475	71,752
NV	14	48	65	0	10,865	52,867	59	63,786	63,845
UT	14	321	19	0	538	58,136	321	58,693	59,014
HI	7	23	0	0	48,770	3,170	48,757	3,206	51,963
VT	3	0	10	0	1,057	49,381	0	50,448	50,448

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

	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
MA	114	2,748	2,429	0	22,948	17,922	2,904	43,144	46,048
FL	26	1,468	111	5,464	14,191	22,301	6,942	36,593	43,534
VA	27	568	285	1	41,578	476	2,430	40,478	42,909
NJ	2	44	0	0	39,000	0	39,044	0	39,044
WY	2	26	11	0	31,249	0	31,286	0	31,286
MS	59	25,812	842	0	3,714	36	25,839	4,566	30,405
GA	42	3,255	79	0	25,573	67	24,028	4,945	28,973
KY	32	1,050	3,793	3,559	18,639	1	8,451	18,591	27,042
CT	48	1,817	7,890	0	6,781	9,512	1,861	24,140	26,000
MD	35	513	529	0	12,777	11,673	824	24,668	25,493
MN	28	3,350	2,561	0	12,370	295	5,888	12,689	18,577
AR	36	3,827	605	0	6,482	1,982	3,919	8,976	12,895
WV	5	11,701	536	0	0	427	11,776	887	12,663
OH	76	7,028	44	0	4,875	0	7,049	4,898	11,947
NY	64	3,397	105	0	6,353	1,366	4,800	6,422	11,222
LA	8	274	33	0	1,278	2,760	290	4,055	4,345
AK	1	0	0	0	4,200	0	4,200	0	4,200
IA	42	2,129	42	0	679	238	2,151	937	3,088
PA	6	1	1,671	0	0	61	1	1,733	1,734
DE	3	1	0	0	614	84	1	698	699
ME	9	21	12	0	66	369	21	447	469
NC	5	164	7	0	7	0	164	14	178
MO	1	44	5	0	10	0	54	5	59
SC	11	30	1	0	0	2	30	3	33
PR	4	0	0	0	0	0	0	0	0

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

	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
Total	2,495	162,882	118,398	78,457	6,029,552	1,350,227	2,294,288	5,445,228	7,739,516

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

[b]Data in TRI are maximum amounts released by each facility.
[c]Post office state abbreviations are used.
[d]Number of reporting facilities.
[e]The sum of fugitive and point source releases are included in releases to air by a given facility.
[f]Surface water discharges, wastewater treatment-(metals only), and publicly owned treatment works (POTWs) (metal and metal compounds).
[g]Class I wells, Class II-V wells, and underground injection.
[h]Resource Conservation and Recovery Act (RCRA) subtitle C landfills; other onsite landfills, land treatment, surface impoundments, other land disposal, other landfills.
[i]Storage only, solidification/stabilization (metals only), other off-site management, transfers to waste broker for disposal, unknown.
[j]The sum of all releases of the chemical to air, land, water, and underground injection wells.
[k]Total amount of chemical transferred off-site, including to POTWs.

RF = reporting facilities; UI = underground injection

Source: TRI19 2020; Data are from 2019

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

		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
MI	63	8,841	8,104	0	6,236,671	78,729	5,950,271	382,075	6,332,346
UT	16	1,694	616	0	2,734,146	45	2,675,891	60,611	2,736,502
NV	10	18,360	19	0	2,303,896	0	2,284,107	38,168	2,322,275
AK	3	66	8	0	2,000,422	0	2,000,496	0	2,000,496
KY	36	4,445	7,913	0	1,184,746	358,501	377,978	1,177,626	1,555,605
IL	61	19,820	13,003	0	1,118,669	118,575	746,187	523,880	1,270,067
TX	105	21,117	12,526	121,236	914,001	167,073	553,824	682,129	1,235,953
OH	81	20,143	15,207	90,475	956,937	104,377	465,406	721,733	1,187,139
IN	58	8,022	37,849	1,187	967,127	62,805	720,197	356,794	1,076,990
CA	42	3,222	4,141	0	939,371	22,828	823,196	146,366	969,563
AL	39	4,692	3,914	0	847,138	67,638	491,495	431,887	923,382
PA	84	17,742	4,159	24	702,675	66,141	329,517	461,225	790,741
MT	9	1,191	51	0	744,763	94	553,635	192,463	746,098
GA	21	1,367	5,106	0	96,781	545,322	84,186	564,390	648,576
AR	19	785	1,049	0	569,687	5,037	551,056	25,502	576,558
NC	23	3,666	602	0	530,737	877	479,486	56,396	535,882
WV	14	4,285	1,675	0	504,405	10,268	390,995	129,638	520,634
LA	40	19,461	6,141	10,645	341,751	14,422	286,013	106,406	392,419
FL	18	1,925	4,638	46	310,665	27,638	213,469	131,443	344,912
OK	28	1,408	390	5	338,150	11	287,886	52,077	339,963
TN	45	2,414	9,001	0	308,580	14,164	170,979	163,181	334,160
MS	18	6,609	2,687	127,221	54,217	8,981	140,672	59,044	199,715
ID	4	490	52	0	190,149	0	190,395	296	190,691
NJ	11	432	150,615	0	10,874	16,593	626	177,888	178,514
SC	26	2,109	3,354	0	71,913	96,305	12,374	161,307	173,681

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

		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
AZ	13	1,002	10	0	120,131	1,314	118,607	3,851	122,457
WY	6	751	0	0	115,608	3,300	116,359	3,300	119,659
WI	32	733	1,008	2,634	75,048	27,867	2,607	104,683	107,290
CO	13	5,287	208	0	97,154	0	79,508	23,141	102,649
ND	5	1,933	5	20	75,876	5,202	50,038	32,998	83,036
KS	11	821	69	115	31,205	45,490	29,497	48,203	77,700
MN	21	1,379	709	0	41,594	23,603	35,904	31,380	67,284
NE	11	665	306	0	34,581	29,986	18,960	46,578	65,538
NM	5	226	11	7	46,196	15,918	46,439	15,919	62,358
IA	11	966	299	18,000	37,737	0	41,344	15,658	57,002
MO	14	714	162	245	40,507	195	39,759	2,064	41,824
PR	2	119	3	0	34,630	0	119	34,633	34,752
HI	2	14,000	2	0	20,000	0	14,002	20,000	34,002
VA	8	364	9,084	0	20,189	3,123	20,477	12,283	32,760
MA	7	2,029	6,368	0	5,235	17,663	2,029	29,266	31,295
MD	12	736	296	0	26,168	0	1,282	25,918	27,200
NY	12	675	375	0	4,816	20,491	1,664	24,694	26,358
CT	14	3,042	659	0	2,935	19,382	3,271	22,747	26,019
WA	12	2,498	1,308	0	17,141	1,033	4,699	17,281	21,980
OR	5	68	17	0	2,984	0	86	2,983	3,069
DE	4	1,781	396	0	0	573	2,177	573	2,750
ME	3	189	240	0	1,700	3	2,129	3	2,132
RI	6	88	216	0	0	755	88	972	1,060
VT	1	0	0	0	612	0	0	612	612
DC	1	0	12	0	147	0	0	160	160

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

		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
NH	4	0	0	0	0	0	0	0	0
Total	1,109	214,373	314,585	371,861	25,830,665	2,002,324	21,411,382	7,322,425	28,733,807

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

[b]Data in TRI are maximum amounts released by each facility.
[c]Post office state abbreviations are used.
[d]Number of reporting facilities.
[e]The sum of fugitive and point source releases are included in releases to air by a given facility.
[f]Surface water discharges, wastewater treatment (metals only), and publicly owned treatment works (POTWs) (metal and metal compounds).
[g]Class I wells, Class II-V wells, and underground injection.
[h]Resource Conservation and Recovery Act (RCRA) subtitle C landfills; other onsite landfills, land treatment, surface impoundments, other land disposal, other landfills.
[i]Storage only, solidification/stabilization (metals only), other off-site management, transfers to waste broker for disposal, unknown.
[j]The sum of all releases of the chemical to air, land, water, and underground injection wells.
[k]Total amount of chemical transferred off-site, including to POTWs.

RF = reporting facilities; UI = underground injection

Source: TRI19 2020; Data are from 2019

5.3.1 Air

Nickel is released to the air from both anthropogenic and geogenic sources. Natural sources of nickel include windblown dust, volcanic ash, forest fires, meteoric dust, and sea salt spray. It is estimated that 30 million kilograms 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). Pacyna and Pacyna (2001) estimate that oil combustion accounts for 90% of anthropogenic emissions. Other anthropogenic sources include the combustion of coal and the incineration of waste and sewage (Cempel and Nikel 2006). Nickel has been measured in the vapor of e-cigarettes (Goniewicz et al. 2014a; Pappas et al. 2020), and this may also contribute to releases to indoor air.

Emissions also occur from industries that produce, process, and use nickel and its compounds. Estimated releases of 162,882 pounds (~74 metric tons) of nickel to the atmosphere from 2,495 domestic manufacturing and processing facilities in 2019 accounted for about 2.1% of the estimated total environmental releases from facilities required to report to the TRI (TRI19 2020). These releases are summarized in Table 5-2.

Estimated releases of 214,373 pounds (~97 metric tons) of nickel compounds to the atmosphere from 1,109 domestic manufacturing and processing facilities in 2019 accounted for about 0.7% of the estimated total environmental releases from facilities required to report to the TRI (TRI19 2020). These releases are summarized in Table 5-3.

Emissions factors (i.e., kg of nickel emissions per unit consumption or production) have been estimated for various source categories, and these are used by EPA to estimate emissions. Emissions factors from some of these source categories are shown in Table 5-4.

Table 5-4. Nickel Emission Factors from AP-42

Source category	Emission Factor	Reference
Fuel oil combustion	0.0845 lb/10^3 gal	EPA 2010
Anthracite coal combustion	0.026 lb/ton	EPA 1996
Bituminous and subbituminous coal combustion	0.00028 lb/ton	EPA 1998
Natural gas combustion	0.0021 lb/10^6 scf	EPA 1998
Wood residue combustion in boilers	0.000033 lb/MMBtu	EPA 2003
Residential wood stoves		EPA 1996
Conventional	0.000014 lb/ton	
Noncatalytic	0.00002 lb/ton	
Catalytic	0.0000022 lb/ton	
Waste oil combustion		EPA 1996
Small boilers	0.011 lb/10^3 gal	
Space heaters: vaporizing burner	0.05 lb/10^3 gal	

Table 5-4. Nickel Emission Factors from AP-42

Source category	Emission Factor	Reference
Space heaters: atomizing burner	0.16 lb/10^3 gal	
Steel mini-mills	0.0000055 lb/ton	EPA 2009
Electroplating		EPA 1996
Nickel electroplating tank	0.63 grains/ampere-hr	
With wet scrubber	0.0000067 grains/dscf	
Coke production		EPA 2008
Coke oven pushing		
Uncontrolled	0.0000399 lb/ton	
Controlled	0.0000112 lb/ton	
Combustion stacks	0.00000187 lb/ton	
Nonrecovery combustion stacks	0.00058 lb/ton	
Nonrecovery charging		
Uncontrolled	0.0000005 lb/ton	
Controlled	0.00000015 lb/ton	
Sewage sludge incineration		EPA 1995
Uncontrolled	0.016 lb/ton	
Controlled	0.000006 – 0.009 lb/ton	
Refuse combustion[a]		EPA 1996
Modular excess air combustors		
Uncontrolled	0.00393 lb/ton	
Controlled	0.0000258 – 0.00161 lb/ton	
Mass burn and modular excess air combustors		
Uncontrolled	0.00785 lb/ton	
Controlled	0.0000322-0.00027 lb/ton	
Refuse-derived fuel-fired combustors		
Uncontrolled	0.00436 lb/ton	
Controlled	0.0000630 – 0.0181 lb/ton	
Modular starved-air combustors		
Uncontrolled	0.00552 lb/ton	
Controlled	0.00101 lb/ton	

[a]Involves burning of garbage and other nonhazardous solids, also known as municipal solid waste

Residual fuel oil combustion for residential space and water heating is a potential source of nickel releases to air, including indoor air (Habre et al. 2014; Hsu et al. 2012b; Schachter et al. 2020). Huggins et al. (2011) studied emissions from the stacks of eight residual fuel oil burning electric utility steam-generating units in New York, Hawaii, and Florida to determine the nickel species present in particulate matter. 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 or below 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 medium 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 available than embedded nickel.

Nickel emissions from municipal incinerators depend on the nickel content of the refuse and the design and operation of the incinerator. By comparing the nickel content of particles emitted from two municipal incinerators in Washington, DC, with that of atmospheric particulate matter, Greenberg et al. (1978) concluded that refuse incineration is not a major source of nickel in the Washington area. The average nickel concentrations in suspended particles from these incinerators ranged from 170 to 200 ppm. Nickel is not primarily associated with very fine or coarse particles. 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 lb/year and regional point sources contributed 105,660 lb/year of the total nickel emissions (117,195 lb/year) in Milwaukee (de Foy et al. 2012). Emissions from Milwaukee ships accounted for 145 lb/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 contributed the most to nickel emissions (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 authors of a long-term study of nickel in seven Korean cities between 1998 and 2010 concluded 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

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

Emission factors have been estimated for the release of trace metals to water from various source categories and these have been used to estimate inputs of these metals into the aquatic ecosystem. The global anthropogenic input of nickel into the aquatic ecosystem for 1983 is estimated to be between 33 and 194 million kg/year with a median value of 113 million kg/year (Nriagu and Pacyna 1988).

A survey of raw and treated waste water from 20 industrial categories indicated that nickel is commonly found in some waste waters (EPA 1981b). Those industries with mean effluent levels of >1,000 µg/L in raw waste water were inorganic chemicals manufacturing (20,000 µg/L), iron and steel manufacturing (1,700 µg/L), battery manufacturing (6,700 µg/L), coil coating (1,400 µg/L), metal finishing (26,000 µg/L), porcelain enameling (19,000 µg/L), nonferrous metal manufacturing (<91,000 µg/L), and steam electric power plants (95,000 µg/L) (EPA 1981b). Those industries with mean effluent levels >1,000 µg/L in treated waste water were porcelain enameling (14,000 µg/L) and nonferrous metal manufacturing (14,000 µg/L) (EPA 1981b). The maximum levels in treated discharges from these industries were 67,000 and 310,000 µg/L, respectively. In addition, four other industrial categories had maximum concentrations in treated discharges >1,000 µg/L. These were inorganic chemicals manufacturing (1,400 µg/L), iron and steel manufacturing (7,800 µg/L), aluminum forming (20,000 µg/L), and paint and ink formulation (80,000 µg/L).

Domestic waste water is the major anthropogenic source of nickel in waterways (Nriagu and Pacyna 1988). Concentrations of nickel in influents to 203 municipal waste water treatment plants (9,461 observations) ranged from 2 to 111,400 µg/L; the median value was ≈300 µg/L (EPA 1981a). From a study of influent streams of a waste water 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) account 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. However, nickel may be removed by chemical precipitation or coagulation treatment in publicly owned treatment works, which reduces nickel releases (EPA 1981a). For example, improvements in sewage treatment facilities have attributed to a reduction in the flux of nickel in waste water effluents into the Hudson River estuary, decreasing from 518 kg/day in 1974 to 43 kg/day in 1997 (Sañudo-Wilhelmy and Gill 1999).

Effluent water generated from mining and smelting operations comes from seepage, runoff from tailing piles, or from utility water used for mine operations. These discharges consist mostly of less-soluble silicates and sulfides and readily settle out. Tailing effluents from sulfidic ores are acidic due to the bacterial generation of sulfuric acid from the sulfidic minerals in the tailings, and very high concentrations of soluble nickel sulfate may be released. Tailing waters from the Onaping and Sudbury areas of Ontario, Canada, have an average nickel content of 42,500 µg/L, a factor of 8,300 greater than that found in river water (Mann et al. 1989). Since there is presently no nickel mining of sulfidic ore in

the United States, nickel-containing wastewater is not generated by this activity. However, past nickel mining may have contributed to nickel entering our waterways and accumulating in sediment. Old tailing piles may contribute to runoff for decades.

In the EPA-sponsored National Urban Runoff Program, in which 86 samples of runoff from 15 cities throughout the United States were analyzed, nickel was found in 48% of runoff samples, at concentrations of 1–182 µg/L (Cole et al. 1984). The geometric mean nickel concentration in runoff water from the cities studied was between 5.8 and 19.1 µg/L. In a more recent study of nickel concentrations in storm runoff water samples taken from different urban source areas, the arithmetic means of the concentrations for dissolved nickel ranged from <1 to 87 µg/L, and from 17 to 55 µg/L for nickel that also included the metal associated with particulates (Pitt et al. 1995).

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).

Estimated releases of 118,398 pounds (~54 metric tons) of nickel to surface water from 2,495 domestic manufacturing and processing facilities in 2019 accounted for about 1.5% of the estimated total environmental releases from facilities required to report to the TRI (TRI19 2020). An estimated 40,633 pounds (~18 metric tons) were released to publicly owned treatment works (POTWs) (TRI19 2020). These releases are summarized in Table 5-2.

Estimated releases of 314,585 pounds (~143 metric tons) of nickel compounds to surface water from 1,109 domestic manufacturing and processing facilities in 2019 accounted for about 1.1% of the estimated total environmental releases from facilities required to report to the TRI (TRI19 2020). An estimated 41,382 pounds (~19 metric tons) were released to publicly owned treatment works (POTWs) (TRI19 2020). These releases are summarized in Table 5-3.

5.3.3 Soil

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 major sources of anthropogenic nickel release to soil are industrial waste materials, lime, fertilizer, and sewage sludge (McIlveen and Negusanti 1994).

Estimated releases of 6.03 million pounds (~2,735 metric tons) of nickel to soils from 2,495 domestic manufacturing and processing facilities in 2019, accounted for about 78% of the estimated total environmental releases from facilities required to report to the TRI (TRI19 2020). An additional 78,457 pounds (~36 metric tons), constituting about 1% of the total environmental emissions, were released via underground injection (TRI19 2020). These releases are summarized in Table 5-2.

Estimated releases of 25.8 million pounds (~11,703 metric tons) of nickel compounds to soils from 1,109 domestic manufacturing and processing facilities in 2019, accounted for about 89% of the estimated total environmental releases from facilities required to report to the TRI (TRI19 2020). An additional 371,861 pounds (~169 metric tons), constituting about 1.3% of the total environmental emissions, were released via underground injection (TRI19 2020). These releases are summarized in Table 5-3.

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).

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 mass median diameter (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.

Metal deposition is characterized by large temporal and spatial variability. Estimated nickel deposition rates range from 0.01 to 0.5 kg/hectare/year (1–50 mg/m^2/year) and from 0.1 to 5.95 kg/hectare/year (10–595 mg/m^2/year) in rural and urban areas, respectively (Schroeder et al. 1987). 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). 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). However, atmospheric deposition is only a minor contributor to the flow of nickel into the oceans and coastal waterways as compared to riverine and fluvial input of nickel. The nickel that is carried into oceans in both dissolved and particulate forms through riverine input is rated 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, and complexation are processes that affect partitioning. These same processes, which are influenced by pH, redox potential, the ionic strength of the water, the concentration of complexing ions, and the species and concentration of the metal, affect the adsorption of heavy metals to soil (Richter and Theis 1980).

Adsorption of nickel onto suspended particles in water is one of the main removal mechanisms of nickel from the water column. The adsorption of nickel on water-borne particulate matter is in competition with adsorption onto dissolved organic matter, which limits the amount of nickel that can be removed from the water column through the settling of suspended particles (Martino et al. 2003). 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 absorptivity 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 waste water 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 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 typically accumulates at the surface of soils due to deposition (Nriagu et al. 1996). Nickel is strongly adsorbed by soil, although to a lesser degree than other metals such as lead, copper, and zinc (Rai and Zachara 1984). There are many adsorbing species in soil, and many factors affect the extent to which nickel is adsorbed, so the adsorption of nickel by soil is site specific. 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 (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 the most 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 using seven soils and sediments spiked with varying concentrations of nickel to assess the potential mobility of nickel in contaminated subsoil (LaBauve et al. 1988). Nickel was more mobile in soils than lead, cadmium, and zinc. The retention of nickel to 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.

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 capacity of soil to remove nickel and the nature of the bound nickel were evaluated for 10 mineral and 3 organic soils from the southeastern United States (King 1988). Some soil samples were taken from the subsoil as well as the surface. The amount of sorbed nickel removed from solution ranged from 13 to 95%; the low value was found in subsoil, and the high value was found in soil high in organic matter. When extracted with potassium chloride, 5–87% of the nickel was nonexchangeable. Soil pH was the most important factor affecting sorbed and nonexchangeable nickel in all soil horizons. Both King (1988)

and Tyler and McBride (1982) found much stronger nickel absorptivity in organic soil than in mineral soils. Adsorption was improved by the quality and quantity of humus in the soil (Hargitai 1989). Nickel was enriched in humic and fulvic acids from Lake Ontario sediment (Nriagu and Coker 1980). It was estimated that 5– 10% of the nickel in this sediment was bound to organic matter.

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 which 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.

Nickel (II) is poorly removed from waste water 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 removal in activated sludge plants is best correlated with effluent suspended solids (Kempton et al. 1987). Nickel is predominantly soluble in the effluent and is found complexed to humic acid, biopolymers, and other chelating agents (Sedlak et al. 1997).

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 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.

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) greater than 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 bioconcentration factor (BCF) for three carnivorous fish was 36. The concentration 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) was obtained for all organisms. When the authors also included data for exposure concentrations outside the range of 5–50 μg/L, a BCF value of 157±135 was obtained. The 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.

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 (Long et al. 2000; Maret and Skinner 2000).

Uptake and accumulation of nickel into various plant species is known to occur. For example, Peralta-Videa et al. (2002) report 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 concentration was 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 three 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. Tomato plants appear to take up nickel from soil and store it in its fruit (Roccotiello et al. 2022). Nickel concentrations in the tomato plant increased with nickel soil concentration and levels reach toxicity to the plant, with highest nickel concentrations in the root (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 accumulators of nickel (Correia et al. 2018). BCF values also indicate that nickel does not tend to accumulate in the roots of tomatoes (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. Little is known about the chemical forms and physical and chemical transformations of trace elements in the atmosphere primarily because analytical methods provide information concerning the metal content rather than the specific compounds or species. In the absence of specific information, 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. Increases in the concentration of nickel in Sequoia National Park in California during rain coming from the south correlated with a sharp (7–13 times greater concentration) increase in sulfate (Cahill 1989). Nickel sulfate is a probable atmospheric species resulting from the oxidation of nickel in the presence of sulfur dioxide (Schmidt and Andren 1980).

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.

Nickel in sediment may be strongly bound or present in a removable form. 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 5-5 shows the limit of detections typically achieved by analytical analysis in environmental media. Presented in Table 5-6 is a summary of the range of concentrations detected in environmental media at NPL sites.

Table 5-5. 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	0.6 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 5-6. Nickel Levels in Water, Soil, and Air of National Priorities List (NPL) Sites

Medium (units)	Median[a]	Geometric mean[a]	Geometric standard deviation[a]	Number of quantitative measurements	NPL sites
Water (mg/L)	0.188	0.3	12.4	426	242
Soil (mg/kg)	71.7	90.1	10.2	414	224
Air (mg/m^3)	2.0x10^{-4}	3.52x10^{-3}	156.42	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 5-7 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 air concentrations are typically below 0.003 µg/m^3 (3 ng/m^3), with a maximum mean concentration of 0.18 µg/m^3 (180 ng/m^3) in the last 5 years according to this data. Recent studies with data on outdoor air concentrations are presented in Table 5-8. 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 meters (Han et al. 2020).

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 2010a; 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. 2012b; 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. 2012b; Peltier and Lippmann 2010a; Rohr et al. 2014a). Peliter and Lippman (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 to 24.6 ng/m^3 in winter samples and 3.0 to 15.1 ng/m^3 in summer samples (Peltier and Lippmann 2010a). In the winter, fuel oil combustion typically increases for heating residential buildings (Schachter et al. 2020).

Table 5-7. Percentile Distribution of Mean Nickel (TSP) Concentrations (µg/m^3) Measured in Ambient Air at Locations Across the United States

		Percentile				
Year	Number of U.S. locations	25th	50th	75th	95th	Maximum
2016	96	0.00081	0.0012	0.0023	0.0099	0.048
2017	88	0.00073	0.0013	0.0029	0.011	0.18
2018	81	0.00097	0.0014	0.0029	0.0096	0.13
2019	74	0.00092	0.0012	0.0027	0.0059	0.077
2020	22	0.00078	0.0014	0.0049	0.13	0.16

TSP = total suspended particles

Source: EPA 2020a (Data current as of 11/24/2020)

Table 5-8. 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 5-8. 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 2010a
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

Table 5-8. Outdoor Air Monitoring Data for Nickel

Location	Geographic type	Date(s)	Mean concentration	Notes	Reference
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; SD = standard deviation

The results of studies which monitored indoor air concentrations of nickel are presented in Table 5-9. 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 2010a; 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 to 24.6 ng/m^3 in winter samples and 3.0 to 15.1 ng/m^3 in summer samples (Peltier and Lippmann 2010a). 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. 2012b; 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 5-9. 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
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 =	Sax et al. 2006

Table 5-9. Indoor Air Monitoring Data for Nickel

Location	Geographic type	Date(s)	Mean concentration	Notes	Reference
				4.17 ng/m^3. Maximum concentration = 42.5 ng/m^3.	
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

Uncontaminated freshwater and seawater typically contain about 300 ng/L of nickel (Barceloux 1999). The concentration in seawater ranges from 100 to 3,000 ng nickel/L. Higher levels of nickel are found in deeper waters than in surface water (Mart et al. 1984; van Geen et al. 1988; Yeats 1988). Water from the surface of the Atlantic Ocean, deep within the Atlantic Ocean (400 m), and the Atlantic shelf contained 1.8 nM (106 ng/L), 2.7 nM (158 ng/L), and 3.5 nM (205 ng/L) nickel, respectively (van Geen et al. 1988). Nickel concentration in surface water was found to decrease by a factor of approximately 2 with increases in percent salinity from approximately 30 to 36% and increased with increasing phosphorus concentration (Yeats 1988). 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 concentration of nickel in samples reported to the Water Quality Portal (WQP) in which nickel was detected ranged from 0 to 18,200 µg/L in groundwater and 0 to 6,390 µg/L in surface water (WQP 2021). The nickel content of fresh surface water has been reported to average between 15 and 20 µg nickel/L (Grandjean 1984; NAS 1975). The concentration of dissolved nickel in the lower Mississippi River ranged from 1.2 to 1.5 µg/L in seven samples taken at different flow conditions (Shiller and Boyle 1987). In a 1977–1979 study of representative groundwaters and surface waters throughout New Jersey, in which >1,000 wells and 600 surface waters were sampled, the median nickel levels in groundwater and surface water were both 3.0 µg/L. The respective 90 percentile and maximum levels were 11 and 600 µg/L for

groundwater and 10 and 45 µg/L for surface water. The nature of the sites with elevated nickel levels was not indicated. However, groundwater polluted with nickel compounds from a nickel-plating facility contained as high as 2,500 µg/L (IARC 1990b). Nickel concentrations were measured in 30 groundwater samples taken from the South Platte River alluvial aquifer underlying Denver, Colorado (Bruce and McMahon 1996). The samples represented a variety of land-use activities, including commercial, industrial, residential, and agricultural. A median nickel concentration of 3 µg/L was determined, with maximum and minimum concentrations values of 20 and 1 µg/L, respectively.

Nickel concentrations from five stations in Lake Huron in 1980 had median and maximum nickel concentrations of 0.54 and 3.8 µg/L, respectively (Dolan et al. 1986). In a 1982 survey, nickel concentrations in Hamilton Harbor, Lake Ontario, ranged from <1 to 17 µg/L, with a median of 6 µg/L (Poulton 1987). The median nickel concentration from an analogous 1980 survey was 4 µg/L. Suspended sediment in surface samples (0.2 m) at Hamilton Harbor, Lake Ontario, contained 17–23 ppm nickel; samples from a depth of 20 m contained 67–87 ppm, similar to the 66 ppm of nickel found in bottom sediment samples (Poulton 1987). These findings suggest that resuspension of bottom sediment is a major contributor to the suspended sediment at a 20 meter depth. In a 1993 survey of heavy metal concentrations in the Great Lakes, average nickel concentrations of 872 and 752 ng/L were measured in Lakes Erie and Ontario, respectively (Nriagu et al. 1996). Concentrations were highest in near-shore waters due to their proximity to urban centers and polluted river mouths. A decrease in the average concentration of nickel measured in Lake Ontario, from 838 ng/L measured in May/June to a value of 751 ng/L obtained in October, indicates that sedimentation of suspended particles results in a fast depletion of nickel during the summer stratification (Nriagu et al. 1996).

Nickel was not detected in bottled drinking water collected for the FDA’s Total Diet Study between 2006 and 2013 (FDA 2017a). Limited drinking water data is available through the WQP; 28 samples of drinking water analyzed for nickel contained concentrations less than 15 µg/L (WQP 2021). Tap water that is used for drinking purposes generally contains nickel at concentrations ranging from 0.55 to 25 µg/L in the United States (O'Rourke et al. 1999; Thomas et al. 1999). Analysis of data obtained during 1995–1997 from the National Human Exposure Assessment Study (NHEXAS) yielded median concentrations of nickel in tap water (used as drinking water) of 4.3 µg/L (10.6 µg/L, 90% percentile) in the Arizona study and 4.0 µg/L (11 µg/L, 90% percentile) in the EPA Region 5 (Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin) study (O'Rourke et al. 1999; Thomas et al. 1999).

In a national survey of raw, treated, and distributed water from 71 municipalities across Canada, the median nickel concentration in both treated and distributed provincial drinking water were ≤0.6–1.3 µg/L for treated water and 1.8 µg/L for distributed water (Méranger et al. 1981). The maximum value was 72.4

µg/L from Sudbury, Ontario. The similarity between median and maximum values for treated and distributed water suggests that nickel is not generally picked up in the distribution system. An exception is Quebec where the maximum nickel concentration increased from 8.3 to 22.0 µg/L between the treated and distributed water. The median nickel levels in the provincial raw water ranged from ≤0.6 to 2.3 µg/L. The maximum levels in tap waters from British Columbia, Prince Edward Island, the Yukon, and Northwest Territories were below the detection limit. The similarity in values between raw and treated water indicates that treatment methods (mainly treatment with lime, alum, or soda ash) did not remove nickel effectively.

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.

Several investigators reported the presence of nickel concentrations in rain. The annual mean nickel concentration in precipitation at Lewes, Delaware, was 0.79 µg/L (Barrie et al. 1987). The mean concentration (± standard deviation) of nickel collected from rain showers in southern Ontario, Canada, in 1982 was 0.56±0.07 µg/L (Chan et al. 1986). The mean concentrations in northern and central Ontario

were both 0.61 μg/L, indicating a lack of spatial variability. Sudbury, the site of a large nickel smelter, is in central Ontario. The nickel concentration in rainwater collected near a large municipal incinerator in Claremont, New Hampshire, was measured at a mean value of 0.69 μg/L (Feng et al. 2000). Nickel concentrations in rain collected between 1985 and 1990 from remote regions of the Atlantic Ocean ranged from 0.63 to 1.42 μg/L (Helmers and Schrems 1995). The concentration of nickel in cloud water sampled on the Olympic Peninsula of Washington State in May 1993 was measured at 0.5±0.4 μg/L; the air-equivalent concentration is 0.2 ng/m^3 (Vong et al. 1997).

Nickel in snow from Montreal, Canada, was highly enriched compared with ambient air, ranging from 2 to 300 ppb (Landsberger et al. 1983). The nickel content of snow particulate matter was 100–500 ppb. Nickel concentrations were highly correlated with those of vanadium, suggesting that oil combustion was a source. The nickel concentration in snow collected near a large municipal incinerator in Claremont, New Hampshire, was measured at a mean value of 0.62 μg/L (Feng et al. 2000). Snow samples were collected several hundred kilometers from the nearest known nickel emission sources (e.g., smelters and ore processing facilities) in northwestern Russia, near the Finish and Norwegian borders. Mean nickel concentrations of 0.0019 mg/L (1.9 μg/L) were measured in the snow melt or, based on the volume of accumulated snow, 0.26 mg/m^3 (Kashulin et al. 2001).

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 (Iyaka 2011).

Sediment is an important sink for nickel in water. Nickel content in 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 (Koptsik et al. 2003; Rope et al. 1988; Suh et al. 2019; Webber and Shamess 1987). Table 5-10 shows the results of several studies measuring concentrations of nickel in soil and sediment.

Table 5-10. Concentrations of Nickel in Soil and Sediment

Location	Concentration	Notes	Reference
Jiangsu Province, China			Li et al. 2020a
Soil		Nickel is naturally elevated in this area	
Wheat-growing		29 samples	

Table 5-10. Concentrations of Nickel in Soil and Sediment

Location	Concentration	Notes	Reference
Range	53.3-131 mg/kg		
Mean	85.2±24.2 mg/kg		
Rice-growing		29 samples	
Range	42.6-118 mg/kg		
Mean	75.9±21.1 mg/kg		
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		
Idaho National Engineering Laboratory			Rope et al. 1988
Soil			
Geometric mean	23.4 ppm		
Twin Falls County, Idaho		Represents background concentration for Rope et al. 1988	Rope et al. 1988
Soil			
Geometric mean	18.0 ppm		
Lemhi County, Idaho		Represents background concentration for Rope et al. 1988	Rope et al. 1988
Soil			
Geometric mean	11.8 ppm		
Kola Peninsula, Russia		Samples were taken near a nickel-copper smelter	Koptsik et al. 2003
Soil			
Mean 1 km from facility	30 mmoles/kg (1,760 mg/kg)		
Mean 8 km from facility	9.6 mmoles/kg (560 mg/kg)		
Mean 16 km from facility	6.5 mmoles/kg (380 mg/kg)		
Range 41 km from facility	1.0–1.2 mmoles/kg (59–7 mg/kg)		
Copper Cliff, Sudbury, Ontario		Within 5 km of smelting operations	Adamo et al. 1996
Soil			
Mean	580 mg/kg		
Range	80-2,149 mg/kg		
Falconbridge, Sudbury, Ontario		Within 5 km of smelting operations	Adamo et al. 1996

Table 5-10. Concentrations of Nickel in Soil and Sediment

Location	Concentration	Notes	Reference
Soil			
Mean	210 mg/kg		
Range	23-475 mg/kg		
Coniston, Sudbury, Ontario		Within 5 km of smelting operations	Adamo et al. 1996
Soil			
Mean	286 mg/kg		
Range	156-628 mg/kg		
Copper Cliff smelter, Sudbury, Ontario			Taylor and Crowder 1983
Wetland soil/sediment			
Minimum	38 µg/g		
Median	481 µg/g		
Maximum	9,372 µg/g		
Ontario, Canada			Webber and Shamess 1987
Sludge-treated soil		57 samples	
Mean	20 ppm		
Range	6.2 to 34 ppm		
Untreated soil		252 samples	
Mean	16.2 ppm		
Range	4.0–48 ppm		
New Jersey			USGS 2000b
Stream and riverbed-sediment			
Range	18-43 µg/g		
Northern Rockies Intermontane Basin			USGS 2000a
Stream and riverbed-sediment			
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		
Beaufort Sea, Northern Arctic Alaska			Sweeney and Naidu 1989
Sediment			
Harrison Bay		21 samples	
Range	15-49 µg/g		
Mean	31 µg/g		

Table 5-10. Concentrations of Nickel in Soil and Sediment

Location	Concentration	Notes	Reference
Simpson Lagoon-Gwydyr Bay		53 samples	
Range	8.4-59 µg/g		
Mean	25 µg/g		
Stefansson Sound-Prudhoe Bay		27 samples	
Range	15-43 µg/g		
Mean	29 µg/g		
Beaufort Lagoon		17 samples	
Range	11-35 µg/g		
Mean	25 µg/g		
Open Shelf		19 samples	
Range	7.0-49 µg/g		
Mean	25 µg/g		
Lake St. Clair			Rossman 1988
Open water sediment			
Range	8.5-21.1 ppm		
Sand sediment			
Mean	13.6 ppm		
Silty clay sediment			
Mean	17.6 ppm		
Clark Fork-Pend Oreille and Spokane River Basins			USGS 2000a
Sediment			
Range	12-27 ppm		
Casco Bay, Gulf of Maine			Larsen et al. 1983
Sediment			
Mean	17.6 ppm		
Eastern Long Island			Larsen et al. 1983
Sediment			
Mean	7.6 ppm		

5.5.4 Other Media

Table 5-11 and Table 5-12 present the results of the FDA's Total Diet Study from 2006 through 2013 (FDA 2017a) for general food items and for baby food items. For the Total Diet Study, Market Based Surveys were carried out in each of four geographic regions of the United States (north central, west, south, and northeast) by testing foods purchased in each region for different elements, pesticides, and radionuclides. Foods with at least one positive detection of nickel are reported in Table 5-11 and Table 5-12. Products with the highest nickel concentrations are legumes and nuts; cereals containing largely whole wheat, corn, oats, or rice; and chocolate products.

Table 5-11. Nickel Detections in Food from the U.S. Food and Drug Administration (FDA) Total Diet Study, 2006-2013

TDS Food Name	Number of analyses	Number of detects	Mean (mg/kg)	Standard deviation (mg/kg)
Sunflower seeds (shelled), roasted, salted	32	32	3.200	0.996
Oat ring cereal	32	32	2.100	0.573
Granola with raisins	32	32	0.947	0.220
Candy bar, milk chocolate, plain	32	32	0.947	0.244
Syrup, chocolate	32	32	0.927	0.168
Brownie	32	32	0.641	0.191
Chocolate chip cookies	32	31	0.610	0.153
Pinto beans, dry, boiled	32	32	0.600	0.149
Granola bar, with raisins	32	32	0.598	0.125
Lima beans, immature, frozen, boiled	32	32	0.577	0.285
Cake, chocolate with icing	32	32	0.554	0.145
Refried beans, canned	32	32	0.526	0.141
Peanuts, dry roasted, salted	32	32	0.489	0.117
Peanut butter, smooth/creamy	32	31	0.472	0.142
Sandwich cookies w/ crème filling	32	32	0.467	0.184
Pork and beans, canned	32	32	0.423	0.167
Fruit-flavored cereal, presweetened	32	32	0.385	0.148
Candy bar, chocolate, nougat, and nuts	32	32	0.380	0.095
Oatmeal, plain, cooked	32	32	0.355	0.108
Avocado, raw	32	32	0.340	0.393
White beans, dry, boiled	32	32	0.316	0.146
Popcorn, microwave, butter-flavored	32	31	0.293	0.092
Chili con carne with beans, canned	32	31	0.264	0.111
Doughnut, cake-type, any flavor, from donut store	32	31	0.237	0.090
Burrito with beef, beans and cheese, from Mexican carry-out	32	32	0.236	0.063
Peas, green, fresh/frozen, boiled	32	32	0.207	0.089
Corn/tortilla chips	32	32	0.205	0.053
Bread, multigrain (formerly cracked wheat)	32	32	0.204	0.052
Bread, whole wheat	32	32	0.202	0.034
Raisin bran cereal	32	32	0.193	0.071
French fries, fast-food	32	32	0.188	0.062
Soup, bean with bacon/pork, canned, condensed, prepared with water	32	31	0.172	0.099
Crisped rice cereal	32	32	0.166	0.059
Milk shake, chocolate, fast-food	32	32	0.158	0.071
Prune juice, bottled	32	32	0.143	0.042

Table 5-11. Nickel Detections in Food from the U.S. Food and Drug Administration (FDA) Total Diet Study, 2006-2013

TDS Food Name	Number of analyses	Number of detects	Mean (mg/kg)	Standard deviation (mg/kg)
Catfish, pan-cooked with oil	32	10	0.143	0.341
Shredded wheat cereal	32	32	0.139	0.119
Potato chips	32	32	0.134	0.075
Beef, ground, regular, pan-cooked	32	10	0.130	0.310
Chicken nuggets, fast-food	32	31	0.130	0.063
Taco/tostada with beef and cheese, from Mexican carry-out	32	31	0.129	0.059
Tomato salsa, bottled	32	31	0.129	0.050
Lasagna with meat, frozen, heated	32	31	0.129	0.043
Pineapple juice, frozen concentrate, reconstituted	32	32	0.128	0.040
Bread, rye	32	32	0.126	0.031
Green beans, fresh/frozen, boiled	32	32	0.124	0.076
Lettuce, iceberg, raw	32	32	0.120	0.080
Mixed vegetables, frozen, boiled	32	32	0.120	0.073
Asparagus, fresh/frozen, boiled	32	31	0.119	0.080
Biscuits, refrigerated-type, baked	32	32	0.118	0.040
Sweet roll/Danish pastry	32	32	0.113	0.037
Brown gravy, canned or bottled	32	25	0.108	0.097
Tomato sauce, plain, bottled	32	32	0.098	0.033
Pie, pumpkin, fresh/frozen	32	31	0.098	0.06
Pork sausage (link/patty), oven-cooked	32	20	0.097	0.152
Pancakes, frozen, heated	32	32	0.097	0.061
Apricots, canned in heavy/light syrup	32	32	0.097	0.036
Pudding, ready-to-eat, flavor other than chocolate	32	30	0.097	0.081
Corn flakes cereal	32	32	0.096	0.030
Crackers, graham	32	32	0.096	0.024
Tortilla, flour	32	32	0.093	0.023
Mustard, yellow, plain	32	31	0.093	0.026
Squash, winter (Hubbard/acorn), fresh/frozen, boiled	31	30	0.092	0.066
Sweet & sour sauce	32	32	0.090	0.052
Bread, white, enriched	32	32	0.089	0.028
Spaghetti with meat sauce, homemade	32	32	0.087	0.062
Pineapple, canned in juice	32	32	0.086	0.038
Green beans, canned	32	32	0.086	0.054
Pepper, sweet, green, raw	32	26	0.086	0.096

Table 5-11. Nickel Detections in Food from the U.S. Food and Drug Administration (FDA) Total Diet Study, 2006-2013

TDS Food Name	Number of analyses	Number of detects	Mean (mg/kg)	Standard deviation (mg/kg)
Sweet potatoes, canned	32	31	0.086	0.045
Cornbread, homemade	32	31	0.085	0.043
Soup, tomato, canned, condensed, prepared with water	32	31	0.084	0.048
Pizza, cheese and pepperoni, regular crust, from pizza carry-out	32	31	0.084	0.026
English muffin, plain, toasted	32	32	0.082	0.018
Clam chowder, New England, canned, condensed, prepared with whole milk	32	31	0.081	0.066
Breakfast tart/toaster pastry	32	32	0.081	0.051
Milk, chocolate, lowfat, fluid	32	32	0.080	0.023
Crackers, saltine	32	32	0.079	0.017
Black olives	32	31	0.078	0.031
Peach, raw/frozen	32	32	0.077	0.051
Bagel, plain, toasted	32	32	0.076	0.014
Tomato juice, bottled	32	32	0.075	0.038
Fish sticks or patty, frozen, oven-cooked	32	31	0.073	0.025
Cantaloupe, raw/frozen	32	32	0.072	0.043
Liver (beef/calf), pan-cooked with oil	32	9	0.071	0.189
Tomato catsup	32	31	0.071	0.023
Raisins	32	30	0.070	0.035
Pretzels, hard, salted	32	30	0.070	0.030
Crackers, butter-type	32	32	0.069	0.023
Fish sandwich on bun, fast-food	32	32	0.069	0.026
Beef with vegetables in sauce, from Chinese carry-out	32	32	0.068	0.024
Peach, canned in light syrup	32	32	0.067	0.021
Chicken with vegetables in sauce, from Chinese carry-out	32	32	0.067	0.042
Fruit cocktail, canned in light syrup	32	32	0.066	0.013
Fried rice, meatless, from Chinese carry-out	32	32	0.064	0.017
Cake, white with icing (formerly yellow cake)	32	32	0.064	0.048
Lettuce, leaf, raw	32	30	0.062	0.038
Chicken filet (broiled) sandwich on bun, fast-food	32	30	0.061	0.027
Sugar cookies	32	31	0.060	0.034
Watermelon, raw/frozen	32	32	0.059	0.048
Broccoli, fresh/frozen, boiled	32	29	0.059	0.041

Table 5-11. Nickel Detections in Food from the U.S. Food and Drug Administration (FDA) Total Diet Study, 2006-2013

TDS Food Name	Number of analyses	Number of detects	Mean (mg/kg)	Standard deviation (mg/kg)
Potato, baked (with peel)	32	29	0.059	0.040
Soup, chicken noodle, canned, condensed, prepared with water	32	14	0.058	0.100
Stew, beef and vegetable, canned	23	23	0.058	0.033
Meal replacement, liquid RTD, any flavor	32	32	0.055	0.034
Quarter-pound hamburger on bun, fast-food	32	30	0.054	0.024
Quarter-pound cheeseburger on bun, fast-food	32	31	0.054	0.033
Cauliflower, fresh/frozen, boiled	32	29	0.053	0.036
Soup, vegetable beef, canned, condensed, prepared with water	32	32	0.053	0.030
Pear, raw (with peel)	32	28	0.051	0.031
Margarine, regular (not lowfat), salted	32	18	0.050	0.054
Egg, cheese, and ham on English muffin, fast-food	32	30	0.050	0.019
Pork bacon, oven-cooked	32	22	0.049	0.063
Spinach, fresh/frozen, boiled	32	32	0.049	0.031
Potato salad, mayonnaise-type, from grocery/deli	32	25	0.048	0.038
Carrot, fresh, peeled, boiled	32	31	0.047	0.023
Tuna noodle casserole, homemade	32	25	0.046	0.035
Chicken potpie, frozen, heated	32	28	0.045	0.021
Cheese, American, processed	32	23	0.044	0.039
Muffin, blueberry	32	29	0.044	0.018
Okra, fresh/frozen, boiled	32	28	0.044	0.028
Strawberries, raw/frozen	32	31	0.043	0.023
Beef stroganoff with noodles, homemade	32	22	0.043	0.062
Carrot, baby, raw	32	31	0.043	0.019
Rice, white, enriched, cooked	32	31	0.042	0.020
Summer squash, fresh/frozen, boiled	32	25	0.042	0.035
Corn/hominy grits, enriched, cooked	32	30	0.040	0.017
Banana, raw	32	25	0.040	0.033
Collards, fresh/frozen, boiled	32	26	0.040	0.024
Brussels sprouts, fresh/frozen, boiled	32	29	0.039	0.024
Salami, luncheon-meat type (not hard)	32	18	0.036	0.041
Pear, canned in light syrup	32	28	0.036	0.021
Orange (navel/Valencia), raw	32	26	0.035	0.026
Potato, boiled (without peel)	32	26	0.034	0.030

Table 5-11. Nickel Detections in Food from the U.S. Food and Drug Administration (FDA) Total Diet Study, 2006-2013

TDS Food Name	Number of analyses	Number of detects	Mean (mg/kg)	Standard deviation (mg/kg)
Pie, apple, fresh/frozen	32	21	0.034	0.028
Bologna (beef/pork)	32	20	0.033	0.03
Corn, canned	32	27	0.033	0.024
Onion, mature, raw	32	24	0.033	0.026
Wine, dry table, red/white	32	32	0.032	0.009
Tea, decaffeinated, from tea bag	32	30	0.032	0.019
Corn, fresh/frozen, boiled	32	27	0.031	0.020
Beets, canned	32	24	0.031	0.025
Potatoes, mashed, prepared from fresh	32	25	0.029	0.021
Celery, raw	32	29	0.028	0.018
Salmon, steaks/fillets, baked	32	7	0.028	0.067
Noodles, egg, enriched, boiled	32	26	0.027	0.020
Jelly, any flavor	32	23	0.027	0.022
Sour cream dip, any flavor	32	11	0.027	0.067
Lamb chop, pan-cooked with oil	32	11	0.026	0.045
Grapefruit, raw	32	27	0.026	0.027
Spaghetti, enriched, boiled	32	26	0.026	0.016
Coleslaw, mayonnaise-type, from grocery/deli	32	17	0.026	0.028
Soup, Oriental noodles (ramen noodles), prepared with water	32	22	0.025	0.018
Frankfurter (beef/pork), boiled	32	16	0.024	0.028
Tea, from tea bag	32	28	0.023	0.013
Chicken leg, fried, fast-food (with skin)	32	13	0.023	0.034
Turkey breast, oven-roasted	32	15	0.021	0.030
Cucumber, peeled, raw	32	31	0.021	0.010
Salad dressing, Italian, regular	32	9	0.020	0.036
Orange juice, frozen concentrate, reconstituted	32	30	0.019	0.008
Grapefruit juice, bottled	31	26	0.019	0.025
Macaroni and cheese, prepared from box mix	32	17	0.019	0.019
Dill cucumber pickles	32	14	0.019	0.024
Yogurt, lowfat, fruit-flavored	32	18	0.019	0.022
Ham, cured (not canned), baked	32	12	0.018	0.026
Cream of wheat (farina), enriched, cooked	32	18	0.018	0.018
Fruit juice blend (100% juice), canned/bottled	32	28	0.018	0.010
Meatloaf, beef, homemade	32	8	0.017	0.036

Table 5-11. Nickel Detections in Food from the U.S. Food and Drug Administration (FDA) Total Diet Study, 2006-2013

TDS Food Name	Number of analyses	Number of detects	Mean (mg/kg)	Standard deviation (mg/kg)
Grape juice, frozen concentration, reconstituted	32	26	0.017	0.011
Chicken breast, fried, fast-food (with skin)	32	11	0.017	0.031
Chicken thigh, oven-roasted (skin removed)	32	13	0.017	0.023
Salad dressing, creamy/buttermilk type, low-calorie	32	15	0.017	0.019
Cabbage, fresh, boiled	32	24	0.016	0.012
Tomato, raw	32	22	0.016	0.014
Chicken breast, oven-roasted (skin removed)	32	4	0.016	0.054
Mushrooms, raw	32	5	0.016	0.067
Turnip, fresh/frozen, boiled	32	13	0.016	0.022
Cream substitute, non-dairy, liquid/frozen	32	8	0.015	0.036
Pork chop, pan-cooked with oil	32	6	0.014	0.033
Cranberry juice cocktail, canned/bottled	32	23	0.014	0.012
Orange juice, bottled/carton	32	25	0.014	0.008
Grapes (red/green), raw	32	9	0.013	0.038
Syrup, pancake	32	4	0.013	0.052
Candy, hard, any flavor	32	10	0.013	0.021
Butter, regular (not lowfat), salted	32	6	0.012	0.027
Honey	32	10	0.011	0.018
Sherbet, fruit-flavored	32	18	0.010	0.010
Macaroni salad, from grocery/deli	32	7	0.009	0.018
Beef roast, chuck, oven-roasted	32	5	0.008	0.021
Pork roast, loin, oven-roasted	32	5	0.008	0.019
Applesauce, bottled	32	8	0.008	0.015
Apple juice, bottled	32	18	0.008	0.007
Luncheon meat (chicken/turkey)	32	9	0.008	0.013
Coffee, decaffeinated, from ground	32	14	0.008	0.011
Eggs, boiled	32	2	0.006	0.024
Shrimp, boiled	32	4	0.006	0.016
Eggplant, fresh, peeled, boiled	32	7	0.006	0.012
Apple (red), raw (with peel)	32	2	0.005	0.022
Salad dressing, creamy/buttermilk type, regular	32	1	0.005	0.027
Coffee, from ground	32	10	0.004	0.008
Beef steak, loin/sirloin, broiled	32	3	0.004	0.014
Cream, half & half	32	1	0.003	0.017

Table 5-11. Nickel Detections in Food from the U.S. Food and Drug Administration (FDA) Total Diet Study, 2006-2013

TDS Food Name	Number of analyses	Number of detects	Mean (mg/kg)	Standard deviation (mg/kg)
Ice cream, regular (not lowfat), vanilla	32	2	0.003	0.013
Popsicle, fruit-flavored	32	2	0.003	0.012
Cottage cheese, creamed, lowfat (2% milk fat)	32	3	0.003	0.010
Tuna, canned in water, drained	32	2	0.003	0.011
Lemonade, frozen concentrate, reconstituted	32	5	0.002	0.005
Ice cream, light, vanilla	32	3	0.002	0.007
Cheese, Swiss, natural	32	1	0.002	0.011
Cream cheese	32	1	0.002	0.010
Luncheon meat, ham	32	2	0.002	0.009
Cheese, cheddar, natural (sharp/mild)	32	1	0.001	0.006
Eggs, scrambled with oil	32	1	0.001	0.006
Gelatin dessert, any flavor	32	1	0.001	0.004
Carbonated beverage, cola, regular	32	3	0.001	0.004
Fruit drink, from powder	32	1	0.001	0.008
Beer	32	2	0.001	0.003
Sour cream	32	1	0.001	0.007
Fruit drink (10% juice), canned or bottled	32	3	0.001	0.004
Olive oil	32	1	0.001	0.008
Vegetable oil	32	1	0.001	0.007
Milk, skim, fluid	32	1	0.0004	0.002

RTD = ready-to-drink; TDS = Total Diet Study
Source: FDA 2017a

Table 5-12. Nickel Detections in Baby Food from the U.S. Food and Drug Administration (FDA) Total Diet Study, 2006-2013

TDS Food Name	Number of analyses	Number of detects	Mean (mg/kg)	Standard deviation (mg/kg)
Cereal, oatmeal, dry, prepared with water	32	32	0.419	0.089
Teething biscuits	31	31	0.178	0.119
Peaches	32	32	0.159	0.074
Squash	32	32	0.151	0.067
Green beans	32	32	0.138	0.050
Peas	32	32	0.136	0.071
Vegetables and beef	32	31	0.135	0.048

Table 5-12. Nickel Detections in Baby Food from the U.S. Food and Drug Administration (FDA) Total Diet Study, 2006-2013

TDS Food Name	Number of analyses	Number of detects	Mean (mg/kg)	Standard deviation (mg/kg)
Chicken noodle dinner	32	32	0.131	0.051
Chicken and broth/gravy	32	30	0.124	0.154
Pears	32	32	0.119	0.032
Vegetables and chicken	32	31	0.118	0.056
Sweet potatoes	32	31	0.117	0.064
Cereal, rice with apples, dry, prepared with water	13	13	0.094	0.029
Mixed vegetables	32	32	0.086	0.037
Turkey and rice	32	30	0.081	0.053
Carrots	32	30	0.078	0.063
Macaroni, tomato, and beef	32	32	0.069	0.027
Vegetables and ham	4	4	0.068	0.017
Fruit dessert/pudding	22	22	0.061	0.024
Bananas	32	32	0.056	0.018
Cereal, rice, dry, prepared with water	32	27	0.053	0.036
Infant formula, soy-based, RTF	32	32	0.027	0.004
Custard/pudding	23	15	0.025	0.025
Turkey and broth/gravy	32	19	0.024	0.029
Beef and broth/gravy	32	15	0.023	0.046
Lamb and broth/gravy	17	6	0.019	0.033
Applesauce	32	9	0.015	0.037
Veal and broth/gravy	17	5	0.010	0.017
Juice, apple	32	15	0.008	0.009
Infant formula, milk-based, low iron, RTF	10	2	0.004	0.008
Infant formula, milk-based, iron fortified RTF (formerly high iron)	32	6	0.002	0.005

RTF = ready-to-feed; TDS = Total Diet Study
Source: FDA 2017a

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).

Many studies have measured nickel levels in cigarettes, smokeless tobacco products, and e-cigarettes. These studies are shown in Table 5-13. According to these studies, the mean concentration of nickel ranges from 2.1 to 3.9 µg/g in traditional cigarettes, 1.19 to 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 5-13. 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, GA 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 ug/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±0.11-2.73±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±2.5-35±2.5 µg/g.	Mohammad et al. 2019
Shisha	27.67±5.31 µg/g	Mean of 3 products from stores in the UAE. Mean of each product ranged 20±3.33-36.6±7.4 µg/g.	Mohammad et al. 2019
Mainpuri	10.6±0.34 to 16.8±0.46 µg/g	Range of means of 12 brands purchased in Pakistan.	Arain et al. 2013; Arain et al. 2015
Gutkha	1.19±0.13 to 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 to 22,600±24,400 µg/L	Range of means of 5 commercial brands in the U.S. Range across the 48 samples was 13.7-72,700 µg/L. Medians for each brand ranged from 58.1-15,400 µg/L.	Hess et al. 2017

Table 5-13. Concentrations of Nickel in Cigarettes, Electronic Cigarettes, and Smokeless Tobacco Products

Product	Concentration	Notes	Source
Aerosols	490–190,000 nickel-containing particles per 10 puffs	5 brands were studied. 2 brands were not able to give accurate particle counts. Mean particle size ranged from 55±17-138±23.	Pappas et al. 2021
Vapor	0.11±0.06 to 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. 2014b

[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

In a comprehensive survey of heavy metals in sewage sludge, 31 sludges from 23 American cities were analyzed by electrothermal atomic absorption spectroscopy (AAS) (Mumma et al. 1984). The nickel concentration in the sludges ranged from 29.0 to 800 ppm (dry weight) and had a median value of 195 ppm. The highest concentration of nickel in sludge was in Detroit, Michigan. For comparison, the concentration of nickel in cow manure was 28.0 ppm. In another study of heavy metal in sludges generated at waste water treatment plants in 16 large U.S. cities, nickel concentrations (dry weight) were found to range from 18 to 186 ppm, with a median value of 66.8 ppm (Gutenmann et al. 1994).

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).

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 and water.

Table 5-14 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.

Table 5-14. Geometric Mean and Selected Percentiles of Urinary Nickel (in µg/L) for the U.S. Population from the National Health and Nutrition Examination Survey (NHANES) (CDC 2020)

			Selected percentiles				
	Survey years	Geometric mean (95% CI)	50th	75th	90th	95th	Sample size
Total	2017-2018	1.11 (1.03−1.20)	1.16	1.95	3.03	4.23	2791
Age group							
12-19 years	2017-2018	1.30 (1.20−1.40)	1.30	2.30	3.57	4.17	362
20-59 years	2017-2018	0.99 (0.90−1.10)	1.03	1.69	2.67	3.88	1037
60 years and older	2017-2018	1.18 (1.05−1.31)	1.22	2.00	2.98	4.34	665
Sex							
Females	2017-2018	1.14 (1.04−1.25)	1.19	1.89	3.00	4.31	1376
Males	2017-2018	1.09 (0.97−1.22)	1.12	2.00	3.08	4.15	1415
Race/ethnicity							
Mexican American	2017-2018	1.15 (1.05−1.26)	1.17	2.08	3.06	3.85	434
Other Hispanic	2017-2018	1.09 (0.97−1.22)	1.10	1.92	2.84	3.98	241
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
Other race	2017-2018	1.12 (1.00−1.26)	1.21	2.16	3.30	4.12	571

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 5-11). The Tolerable Upper Intake Level for nickel by life stage group is shown in Table 5-15.

Table 5-15. Tolerable Upper Intake Levels for Nickel

Life Stage Group	UL (mg/day)
0 – 12 months	ND[a]
1 – 3 years	0.2
4 – 8 years	0.3
9 – 13 years	0.6
14 – 18 years	1.0
19 years and older	1.0
Pregnant females, 14 – 18 years	1.0
Pregnant females, 19-50 years	1.0
Lactating females, 14 – 18 years	1.0
Lactating females, 19-50 years	1.0

[a]Data are insufficient to determine a UL.
ND = not determined; UL = Tolerable Upper Intake Level
Source: Institute of Medicine 2001

Using data for the 1991 to 1997 Total Diet Study and the 1988 to 1994 NHANES, the Institute of Medicine (2001) estimates that the nickel intake from food for the general population is less than 0.5 mg/day and supplements provide 9.6 to 15 µg/day. Based on several older dietary studies, the average daily dietary intake of nickel in food ranges between 69 and 162 µg/day (Institute of Medicine 2001; O'Rourke et al. 1999; Pennington and Jones 1987; Thomas et al. 1999). 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. However, recent studies quantifying the daily intake of nickel in the U.S. from food are lacking.

Some studies have assessed the dietary intake of nickel outside of the U.S. The mean concentration of nickel measured in cucumbers and bell peppers in Iran was 0.18 and 0.08 µg/g, respectively (Khoshgoftarmanesh et al. 2009). The estimated total dietary intake from these two foods is 0.06 to 0.17 ug/kg for children, 0.07-0.24 on average, and 0.03 to 0.19 for adults over 55 years of age (Khoshgoftarmanesh et al. 2009). The nickel concentrations in these foods from Iran are similar to those for cucumbers (0.21 mg/kg) and raw sweet green peppers (0.086 mg/kg) in the U.S. Total Diet Study (FDA 2017a). Thus, the daily nickel intake in the U.S. from cucumbers and bell peppers may be comparable. The concentration of nickel in drinks (48.4 to 319 µg/kg), legumes (149 to 744 µg/kg), breakfast cereals (413 to 485 µg/kg), soy based foods (281 to 2,389 µg/kg), dried fruits (184 to 1,085 µg/kg), nuts (1,061 to 2,649 µg/kg), and chocolate (4,114 to 4,785 µg/kg) was measured in Belgium (Babaahmadifooladi et al. 2021). Based on these concentrations, the mean daily exposure to nickel through the consumption of different foods ranges from 0.31 to 4.70 µg/kg bw/day in individuals aged 3 to 9 years, 0.13 to 2.00 in individuals aged 10 to 17 years µg/kg bw/day, and 0.09 to 1.20 µg/kg bw/day in individuals aged 18 to 64 years (Babaahmadifooladi et al. 2021). The exposure decreases when considering the bioaccessible fraction and dialyzable fraction (Babaahmadifooladi et al. 2021). Li et al. (2020a) estimated that the daily intake of nickel from wheat and soil grown in soils with naturally elevated nickel concentrations in China was 12.2±8.41 µg/kg bw/day for rice and 0.84±0.40 µg/kg bw/day for wheat. 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 (less than 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).

There is limited evidence that stainless steel pots and utensils may release nickel into acid solution (IARC 1990b). 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. 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 1990b). 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. 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). This indicates that while the general population is expected to be exposed to nickel in food, exposure may increase if an individual uses stainless steel cookware.

People may also be exposed to nickel in jewelry. 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. 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. The concentration of nickel in inexpensive earrings and fashion jewelry in the U.S. was less than 0.5 to 65%, with a median of 18%. After being immersed in artificial sweat for a week, nickel release was detected in 79 of the 96 samples at a rate ranging from 0.01 to 598 μg/cm^2/week (Hamann et al. 2015).

Nickel is a common allergen for children in the U.S., who may be exposed to nickel in jewelry, clothing buckles and fasteners, and technology (Tuchman et al. 2015). Jensen et al. (2014) describes children's toys as another potential source of nickel exposure. To evaluate nickel release from children's toys, Jensen et al. (2014) purchased 63 toys from toy and thrift shops in the U.S. and an online retailer and 149 toys from 8 toy stores in Denmark. Of the toys in the U.S., 50.8% tested positive for nickel release with a DMG test compared to 27.5% of the toys from Denmark (Jensen et al. 2014). Other sources of nickel exposure in children are food consumption and accidental ingestion of soil containing nickel. Nickel

concentrations in baby food in the U.S. range from 0.002 to 0.149 mg/kg (FDA 2017a). 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 is 1.12 µg/kg bw for 6 month old children, 2.76 µg/kg bw for 1 year old children, and 3.13 µg/kg bw for 2 year old children (Pereira et al. 2020). Wittsiepe et al. (2009) estimated that the daily dietary intake rate for 4 to 7-year old children in Germany was 12 to 560 µg/day based on concentrations in food samples, or 35 to 1050 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 bw/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 the 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 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 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 to 10 µg/cm^2/week and from dental alloys in the range of 0.0046 to 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 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 hand washing (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 concentration of nickel in blood was 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 µg/L 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, Kulkarni 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 14.24-769.8 ng/m^3 and decreased to levels like background concentrations at 600 meters away (Han et al. 2020). Han et al. (2020) estimated that the cancer risk due to inhalation of nickel was 0.21 to 14 cases per million at the fence line, 0.03 to 1.1 cases per million in near neighborhoods, and 0.21 to 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 mixture), the average nickel concentration among 17 commercially available brands is 2.28 µg/g. Using artificial saliva, study authors found that 20 to 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 intake was 10.6 to 25.9 µg/10 g of gutkha (chewing tobacco mixture), 75.6 to 141 µg/10 g of moist snuff (finely ground or pulverized tobacco leaves), and 103 to 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 are two to three 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 to 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).