2. Production, Use, Occurrence and Analysis

2.1 Production

Nickel was first isolated in 1751 by a Swedish chemist, Cronstedt, from an arsenosulfide ore (Considine, 1974).

(*a*) *Metallic nickel and nickel alloys*

Table 5 gives world mine production of nickel by region. Table 6 shows world nickel plant production, including refined nickel, ferronickel and nickel recycled from scrap (Chamberlain, 1988).

Various combinations of pyrometallurgical, hydrometallurgical and vapometallurgical operations are used in the nickel producing industry (Boldt & Queneau, 1967; Evans *et al.*, 1979; Tien & Howsen, 1981; Tyroler & Landolt, 1988). The description that follows is a generalized discussion of some of the more common smelting and refining processes.

Table 5. World mine production of nickel, by region (thousand tonnes)[a]

Region	1982	1983	1984	1985	1986
Albania	6.0	7.2	9.2	9.6	9.7
Australia	87.7	76.6	77.1	85.8	69.9
Botswana	17.8	18.2	18.6	19.6	20.0
Brazil	14.5	15.6	23.6	20.3	23.1
Burma	0.02	0.02	0.02	0.02	0.02
Canada	88.7	128.1	174.2	170.0	181.0
China	12.0	13.0	14.0	25.1	25.5
Colombia	1.8	17.5	21.9	15.5	22.1
Cuba	36.2	37.7	31.8	32.4	32.7
Dominican Republic	5.4	19.6	24.0	25.4	22.1
Finland	6.3	5.3	6.9	7.9	6.5
France (New Caledonia)	60.2	46.2	58.3	73.0	65.1
German Democratic Republic	2.5	2.2	2.0	1.6	1.5
Greece	5.0	16.8	16.7	18.7	17.5
Indonesia	46.0	49.4	47.6	40.6	43.9
Morocco	0.13	–	–	–	–
Norway	0.39	0.36	0.33	0.44	0.40
Philippines	19.7	13.9	13.6	28.2	13.6
Poland	2.1	2.1	2.1	2.0	2.0
South Africa	22.0	20.5	25.1	25.1	25.1
USA	2.9	–	13.2	5.6	1.1
USSR	165.1	170.0	174.2	180.0	186.0
Yugoslavia	4.0	3.0	4.0	5.0	5.0
Zimbabwe	15.8	12.0	12.2	11.1	11.0
Total	622.24	675.28	770.65	802.96	784.82

[a] From Chamberlain (1988)

Table 6. World production of processed nickel by region (thousands of tonnes)[a]

Region	1982	1983	1984	1985	1986
Australia	45.9	41.8	38.7	40.9	41.9
Brazil	3.5	8.3	9.2	13.3	13.5
Canada	58.6	87.2	104.0	100.0	115.0
China	12.0	13.0	14.0	22.5	22.5
Colombia	1.3	13.1	17.1	11.8	18.6
Cuba	9.0	9.3	8.5	8.5	7.7
Czechoslovakia	1.5	3.0	4.5	4.5	4.5
Dominican Republic	5.3	21.2	24.2	25.8	22.0

Table 6 (contd)

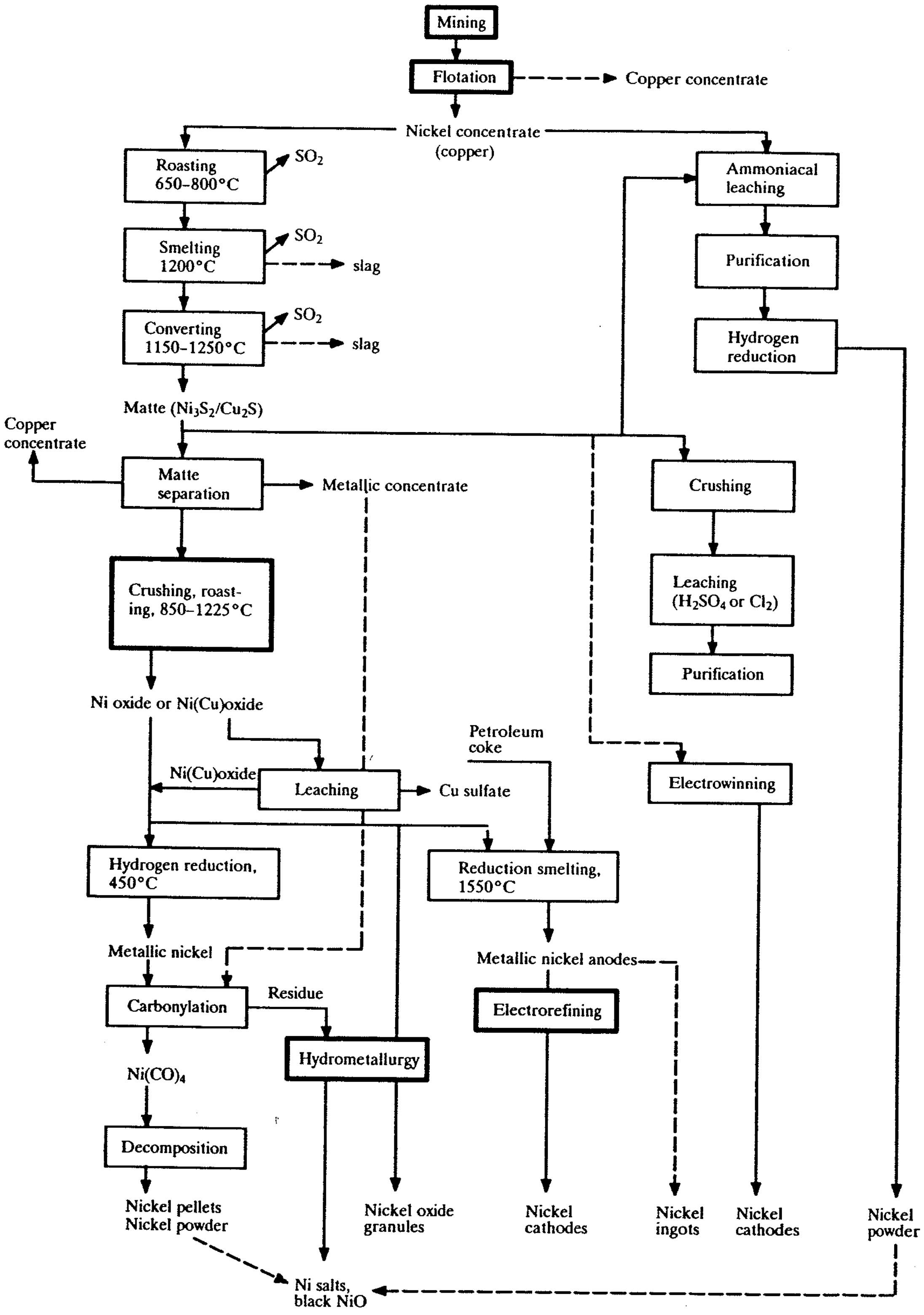
Region	1982	1983	1984	1985	1986
Finland	12.6	14.8	15.3	15.7	16.0
France	7.4	4.9	5.2	7.1	10.0
France (New Caledonia)	28.0	21.7	29.2	36.1	33.0
German Democratic Republic	3.0	3.0	3.0	3.0	3.0
Germany, Federal Republic of	1.2	1.2	1.0	0.7	-
Greece	4.5	12.9	15.8	16.0	12.0
Indonesia	5.0	4.9	4.8	4.8	5.0
Japan	90.6	82.2	89.3	92.7	88.8
Norway	25.8	28.6	35.6	37.5	38.2
Philippines	11.2	6.1	3.5	17.0	2.1
Poland	2.1	2.1	2.1	2.1	2.1
South Africa	14.4	17.0	20.5	20.0	20.0
UK	7.4	23.2	23.3	17.8	31.0
USA	40.8	30.3	40.8	33.0	1.5
USSR	180.0	185.1	191.4	198.0	215.0
Yugoslavia	1.5	1.5	2.0	3.0	3.0
Zimbabwe	13.3	10.2	10.3	9.4	9.8
Total	585.9	646.6	713.3	741.2	736.2

[a] From Chamberlain (1988)

Nickel is produced from two kinds of ore: sulfide and silicate-oxide. The latter occurs in tropical regions, such as New Caledonia, and in regions that used to be tropical, such as Oregon (USA). Both types of ore generally contain no more than 3% nickel (Warner, 1984). Mining is practised by open pit and underground methods for sulfide ores and by open pit for silicate-oxide ores. Sulfide ores are extracted by flotation and magnetic separation into concentrates containing nickel and various amounts of copper and other metals, such as cobalt, precious metals and iron. Silicate-oxide ores are extracted by chemical means.

The extractive metallurgy of sulfide nickel ores (see Fig. 1) is practised in a large variety of processes. Most of these processes begin with oxidation of iron and sulfur at high temperatures in multiple hearth roasters or in fluid bed roasters, or, in the early days, in linear calciners or on travelling grate sinter machines ('sintering'). The roaster calcine is smelted in reverberatory or electric furnaces to remove rock and oxidized iron as a slag, leaving a ferrous nickel (copper) matte. In modern processes, both operations — roasting and smelting — are combined in a single operation called 'flash smelting'. The furnace matte is upgraded by oxidizing and slagging most of the remaining iron in converters. If the converter matte or 'Bessemer matte' contains copper, the matte can be separated into nickel subsulfide, copper sulfide

Fig. 1. Extraction and refining of nickel and its compounds from sulfides ores[a]



[a]Modified from Mastromatteo (1986)

and metallic concentrates by a slow cooling process followed by magnetic concentration and froth flotation.

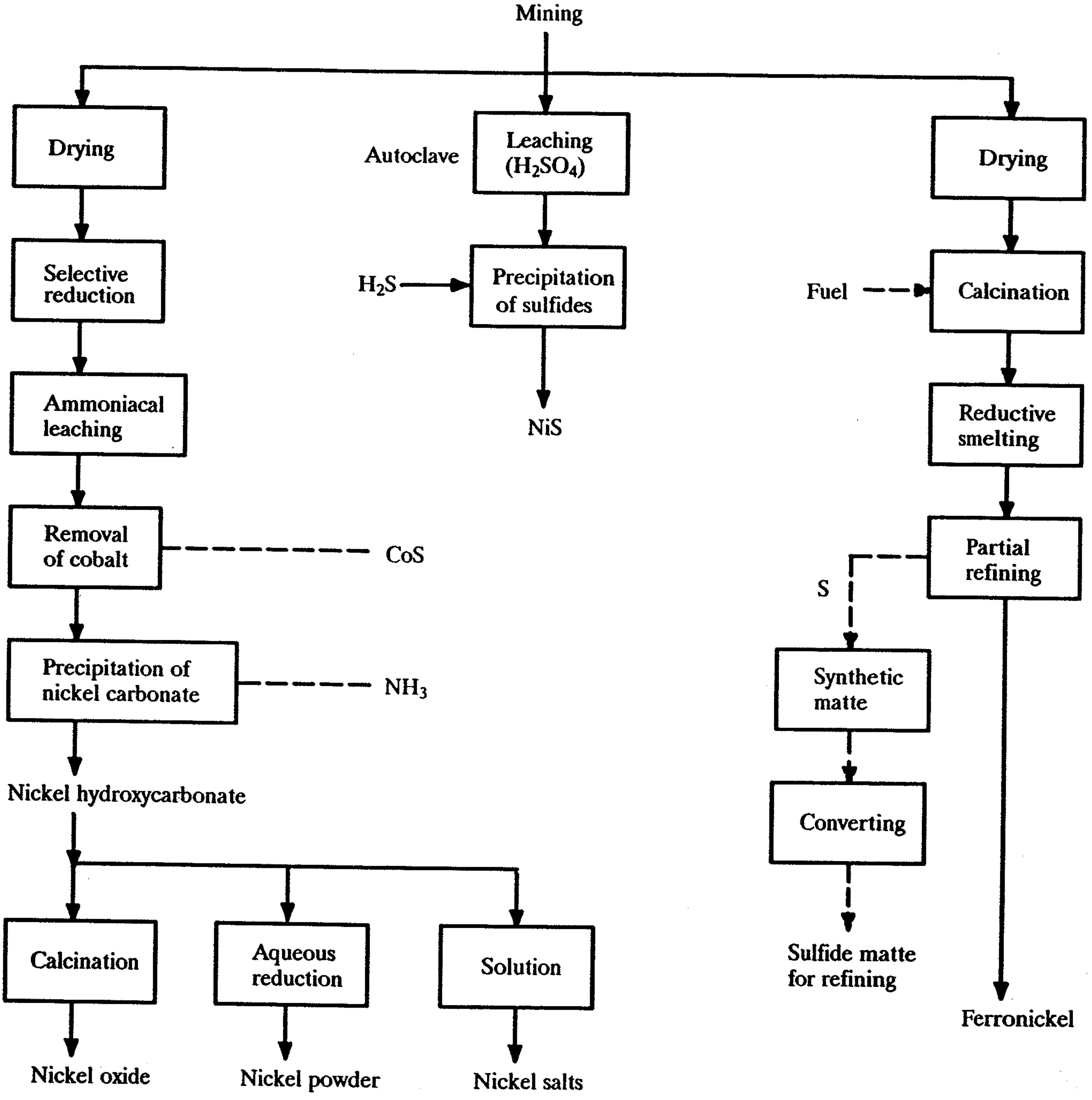
The high-grade nickel subsulfide concentrate is then refined by various processes. Most of them begin with roasting of the concentrate to a crude nickel oxide. When the copper content is low, this crude oxide is directly saleable ('Sinter 75'). In older processes, copper was leached directly from the crude oxide with sulfuric acid (as in Clydach, Wales) or by an acidic anolyte from copper electrowinning (as in Kristiansand, Norway). Refining can be pursued after reducing the crude nickel oxide to metal either in a rotary kiln or in an electric furnace with addition of a carbonaceous reductant. In the first case, the crude particulate metallic nickel is refined by the atmospheric pressure nickel-carbonyl process (Mond carbonyl process) which allows a clear-cut separation of nickel from other metals. Nickel is then produced either as nickel powder or as nickel pellets. The carbonylation residue is further processed to recover precious metals and some nickel and cobalt salts. In the second case, the molten crude nickel is cast into anodes which are 'electrorefined'. The anolyte is purified outside the electrolytic cell by removal of the main impurities, which are iron, arsenic, copper and cobalt. These impurities are generally extracted as filter cakes containing significant amounts of nickel, warranting recycling upstream in the process. Nickel is then produced in the form of electrolytic cathodes or small 'rounds'. This electrorefining process, which was used in Kristiansand, Norway, and Port Colborne, Ontario, is no longer practised there.

The Bessemer nickel (copper) matte can also be refined without roasting, either by a combination of hydrometallurgy and electrolysis ('electrowinning') or by hydrometallurgy alone. There are three types of nickel 'electrowinning' processes: (i) directly from matte cast into (soluble) anodes; (ii) from nickel sulfate solutions obtained by leaching matte with a very low sulfur content; and (iii) from nickel chloride solutions obtained by leaching matte with chloride solution in the presence of chlorine gas. In the three cases, the solutions obtained by dissolving the matte must be purified before plating pure nickel, as for the electrorefining process. In the chloride-electrowinning process, purification is accomplished through solvent extraction methods using tributylphosphate and aliphatic amines diluted in petroleum extracts.

Complete hydrometallurgy can be practised directly on sulfide concentrates or on Bessemer matte by ammonia leaching in sulfate medium in autoclaves. The solution is purified by precipitation of sulfides, and nickel is recovered as metal powder by hydrogen precipitation in autoclaves. The nickel powder can be further sintered into briquettes.

Silicate-oxide ores ('garnierites'/'laterites') are processed either by pyrometallurgy or by hydrometallurgy (Fig. 2). Pyrometallurgy consists of drying, calcining in rotary kilns, then reduction/smelting in electric furnaces. The crude ferronickel

Fig. 2. Extraction and refining of nickel and its compounds from silicate-oxide (laterite) ores[a]



[a]Modified from Mastromatteo (1986)

obtained (containing 20-40% Ni) is partially refined by thermic processes (in ladles) before being cast into ingots or granulated in water. With pyrometallurgy, nickel matte can be produced from silicate-oxide ore either by smelting the ore in the presence of calcium sulfate in a blast furnace (old process) or in an electric furnace, or by direct injection of molten sulfur into molten ferronickel.

Hydrometallurgy of silicate-oxide ores, preferentially poor in silica and magnesia, is practised by ammoniacal leaching or by sulfuric acid leaching. Ammoniacal leaching is used for ore that is selectively reduced in rotary kilns by a mixture of hydrogen and carbon monoxide. Cobalt, the main dissolved impurity, is removed from solution by precipitation as cobalt monosulfide (containing nickel monosulfide). This by-product is further refined to separate and refine nickel and cobalt. The purified nickel stream is then transformed into the hydroxycarbonate by ammonia distillation. The hydroxycarbonate is then dried, calcined and partially reduced to a saleable nickel oxide sinter. Sulfuric acid leaching is conducted under pressure in autoclaves. Nickel and cobalt are extracted from the process liquor by precipitation with hydrogen sulfide, and the mixed nickel-cobalt (10:1) sulfide is further refined in one of the processes described above.

Nickel is obtained not only by recovery from nickel ores but also by recycling process or consumer scrap. Nickel scrap is generated in forming and shaping operations in fabricating plants where nickel-containing materials are used and is also recovered from obsolete consumer goods containing nickel. Small amounts of nickel are also produced as a coproduct of copper and platinum metal refining (Sibley, 1985).

Nickel-containing steels (stainless steels and others) are produced by melting cast iron and adding ferronickel and/or pure nickel or steel scraps in large electric furnaces. The melt is transferred to a refining vessel to adjust the carbon content and impurity levels and is then cast into ingots or continuously into casting shapes. Defects in cast steel are repaired by cutting or scarfing or by chipping or grinding. The desired shapes are produced by a variety of operations, including grinding, polishing and pickling (Warner, 1984). Production volumes of stainless-steel are given in Table 7.

The technology for the production of *nickel alloys* is very similar to that used for steel production, except that melting and decarburizing units are generally smaller, and greater use is made of vacuum melting and remelting (Warner, 1984). In western Europe, it was estimated that 15% of nickel consumption was in nonferrous nickel alloys (Eurométaux, 1986).

Table 7. Stainless-steel[a] production (in thousands of tonnes) in selected regions[b]

Region	1987	1988
Austria	54	67
Belgium	182	254
Finland	189	206
France	720	784
Germany, Federal Republic of	957	1186
Italy	550	623
Spain	327	426
Sweden	457	482
United Kingdom	393	427
Yugoslavia	30	30
Total Europe	3859	4485
USA	1840	1995
Japan	2722	3161
Other countries	787	798
Total	9208	10 439

[a] Stainless steels with and without nickel
[b] ERAMET-SLN (1989a)

(*b*) *Nickel oxides and hydroxides*

Nickel oxide sinter (a coarse, somewhat impure form of nickel monoxide) is manufactured by roasting a semipure nickel subsulfide at or above 1000°C or by decomposing nickel hydroxycarbonate. The sinters produced commercially contain either 76% nickel or, in partially reduced form, 90% nickel. Nickel oxide sinter is produced in Australia, Canada and Cuba (Sibley, 1985).

Green nickel oxide, a finely divided, relatively pure form of nickel monoxide, is produced by firing a mixture of nickel powder and water in air at 1000°C (Antonsen, 1981). Nickel monoxide is currently produced by two companies in the USA, six in Japan, two in the UK and one in the Federal Republic of Germany (Chemical Information Services Ltd, 1988).

Black nickel oxide, a finely divided, pure nickel monoxide, is produced by calcination of nickel hydroxycarbonate or nickel nitrate at 600°C (Antonsen, 1981). It is produced by one company each in Argentina, Brazil, Canada, Japan, Mexico, the UK and the USA (Chemical Information Services Ltd, 1988).

Nickel hydroxide is prepared by (1) treating a nickel sulfate solution with sodium hydroxide to yield a gelatinous nickel hydroxide which forms a fine precipitate when neutralized, (2) electrodeposition at an inert cathode using metallic nickel as the anode and nickel nitrate as the electrolyte, or (3) extraction with hot alcohol of the gelatinous precipitate formed by nickel nitrate solution and potassium hydroxide (Antonsen, 1981). Nickel hydroxide is currently produced by four companies in Japan, three in the USA and one each in the Federal Republic of Germany and the UK (Chemical Information Services Ltd, 1988).

(*c*) *Nickel sulfides*

Purified *nickel sulfide* can be prepared by (i) fusion of nickel powder with molten sulfur or (ii) precipitation using hydrogen sulfide treatment of a buffered solution of a nickel[II] salt (Antonsen, 1981).

Nickel subsulfide can be made by the direct fusion of nickel with sulfur. Impure nickel subsulfide is produced during the processing of furnace matte.

Nickel sulfide and nickel subsulfide are formed in large quantities as intermediates in the processing of sulfidic and silicate-oxide ores and are traded and transported in bulk quantities for further processing. No data on production volumes are available for any of the nickel sulfides.

(*d*) *Nickel salts*

Nickel acetate is produced by heating nickel hydroxide with acetic acid in the presence of metallic nickel (Sax & Lewis, 1987). This salt is currently produced by six companies in the USA, three each in Argentina, Brazil, Italy, Japan and the UK, two each in the Federal Republic of Germany and Mexico, and one each in Australia and Spain (Chemical Information Services Ltd, 1988).

An impure basic *nickel carbonate* (roughly $2NiCO_3.3Ni(OH)_2.4H_2O$) is obtained as a precipitate when sodium carbonate is added to a solution of a nickel salt. A pure nickel carbonate is prepared by oxidation of nickel powder in ammonia and carbon dioxide (Antonsen, 1981). Nickel carbonate is currently produced by six companies each in the USA and Japan, three each in India and the Federal Republic of Germany, two each in Argentina, France, Italy, Mexico and the UK, and one each in Belgium, Brazil, Canada, Spain and Switzerland (Chemical Information Services Ltd, 1988). Finland and Japan produce the largest volumes of nickel carbonate (ERAMET-SLN, 1989b).

Nickel ammonium sulfate is prepared by reacting nickel sulfate with ammonium sulfate and crystallizing the salt from a water solution (Antonsen, 1981; Sax & Lewis, 1987). Nickel ammonium sulfate (particular form unknown) is currently produced by three companies in the UK, two in the USA and one in Japan (Chemical Information Services, Ltd, 1988).

Nickel chloride (hexahydrate) is prepared by the reaction of nickel powder or nickel oxide with hot aqueous hydrochloric acid (Antonsen, 1981). It is currently produced by eight companies in the USA, six in India, four each in the Federal Republic of Germany, Japan and the UK, three in Mexico, two each in Brazil, France and Italy and one each in Spain, Switzerland and Taiwan (Chemical Information Services Ltd, 1988). The countries or regions that produce the largest volumes are: Czechoslovakia, Federal Republic of Germany, France, Japan, Taiwan, UK, USA and USSR (ERAMET-SLN, 1989b).

Nickel nitrate (anhydrous) can be prepared by the reaction of fuming nitric acid and nickel nitrate hexahydrate. The hexahydrate is prepared by reaction of dilute nitric acid and nickel carbonate (Antonsen, 1981). Nickel nitrate hexahydrate is manufactured on a commercial basis by three methods: (1) slowly adding nickel powder to a stirred mixture of nitric acid and water; (2) a two-tank reactor system, one with solid nickel and one with nitric acid and water; and (3) adding nitric acid to a mixture of black nickel oxide powder and hot water (Antonsen, 1981). Nickel nitrate is currently produced by six companies in the USA, four each in Brazil, Japan and the UK, two each in the Federal Republic of Germany, France, India, Italy and Spain and one each in Argentina, Australia, Belgium, Mexico and Switzerland (Chemical Information Services Ltd, 1988).

Nickel sulfate hexahydrate is made by adding nickel powder or black nickel oxide to hot dilute sulfuric acid or by the reaction of nickel carbonate and dilute sulfuric acid. Large-scale manufacture of the anhydrous form may be achieved by gas-phase reaction of nickel carbonyl with sulfur dioxide and oxygen at 100°C or in a closed-loop reactor that recovers the solid product in sulfuric acid (Antonsen, 1981).

Nickel sulfate hexa- and heptahydrates are currently produced by nine companies each in Japan and the USA, six in India, four each in Argentina, the Federal Republic of Germany, Mexico and the UK, three in Canada, two each in Austria, Belgium, Brazil and Italy, and one each in Australia, Czechoslovakia, Finland, the German Democratic Republic, Spain, Sweden, Switzerland, Taiwan and the USSR (Chemical Information Services Ltd, 1988). The countries or regions that produce nickel sulfate in the largest volumes are: Belgium, Czechoslovakia, the Federal Republic of Germany, Finland, Japan, Taiwan, the UK, the USA and the USSR (ERAMET-SLN, 1989b).

(*e*) *Other nickel compounds*

Nickel carbonyl can be prepared by the Mond carbonyl process, described above for nickel. Two commercial processes are used to manufacture nickel carbonyl. In the UK, the pure compound is produced by an atmospheric method in which carbon monoxide is passed over freshly reduced nickel. In Canada, high-pressure carbon monoxide is used in the formation of iron and nickel carbonyl, which are separated by distillation. In the USA, nickel carbonyl was prepared commercially by the reaction of carbon monoxide with nickel sulfate solution (Antonsen, 1981). Nickel carbonyl is currently produced by two companies each in the Federal Republic of Germany and the USA and by one in Japan (Chemical Information Services, Ltd., 1988).

Nickelocene is formed by the reaction of nickel halides with sodium cyclopentadienide (Antonsen, 1981). It is currently produced by two companies in the USA (Chemical Information Services Ltd, 1988).

Nickel selenide (particular form unknown) is produced by one company each in Japan and the USA, *nickel titanate* by one company each in the UK and the USA and *potassium nickelocyanate* by one company each in India and the USA (Chemical Information Services Ltd, 1988).

2.2 Use

Uncharacterized alloys of nickel have been used in tools and weapons since 1200 AD or earlier (Considine, 1974; Tien & Howsen, 1981). In fact, the principal use of nickel has always been in its metallic form combined with other metals and nonmetals as alloys. Nickel alloys are typically characterized by their strength, hardness and resistance to corrosion (Tien & Howsen, 1981). The principal current uses of nickel are in the production of stainless and heat-resistant steels, nonferrous alloys and superalloys. Other major uses of nickel and nickel salts are in electroplating, in catalysts, in the manufacture of alkaline (nickel-cadmium) batteries, in coins, in welding products (coated electrodes, filter wire) and in certain pigments and electronic products (Antonsen, 1981; Tien & Howsen, 1981; Mastromatteo, 1986). Nickel imparts strength and corrosion resistance over a wide range of temperatures and pressures (Sibley, 1985; Chamberlain, 1988).

Worldwide demand for nickel in 1983 was 685 000 tonnes (Sibley, 1985). US consumption of nickel ranged from approximately 93 000 to 122 000 tonnes over the period 1982-86 (Chamberlain, 1988). Table 8 shows the US consumption pattern by end-use for 1983. In 1978, 44% was used in stainless steels and alloy steels, 33% in nonferrous and high-temperature alloys, 17% in electroplating and the remaining 6% primarily as catalysts, in ceramics, in magnets and as salts (Tien & Howson, 1981). In western Europe, it was estimated that, in 1982, 50% of the nickel was used in stainless steels, 10% in alloy steel, 15% in nonferrous alloys, 10% in foundry alloys, 10% in plating and 5% in other applications, such as catalysts and batteries (Eurométaux, 1986).

Table 8. US consumption pattern of nickel in 1983 (%)[a]

Use	Consumption (%)
Transportation	
Aircraft	10.3
Motor vehicles and equipment	10.2
Ship and boat building and repairs	4.3
Chemicals	15.6
Petroleum	8.2
Fabricated metal products	8.8
Electrical	10.7
Household appliances	7.9
Machinery	7.2
Construction	9.7
Other	7.1

[a] From Sibley (1985)

(*a*) *Metallic nickel and nickel alloys*

Pure nickel metal is used to prepare nickel alloys (including steels). It is used as such for plating, electroforming, coinage, electrical components, tanks, catalysts, battery plates, sintered components, magnets and welding rods (Eurométaux, 1986).

Ferronickel is used to prepare steels. Stainless and heat-resistant steels accounted for 93% of its end use in 1986 (Chamberlain, 1988).

Nickel-containing steels with low nickel content (<5% Ni) are used for construction and tool fabrication. Stainless steels are used for general engineering equipment, chemical equipment, domestic applications, hospital equipment, food processing, architectural panels and fasteners, pollution control equipment, cryogenic uses, automotive parts and engine components.

Nickel-copper *alloys* are used for coinage, in industrial piping and valves, marine components, condenser tubes, heat exchangers, architectural trim, thermocouples, desalination plants, ship propellers, etc. Nickel-chromium alloys are used in many high-temperature applications, such as furnaces, jet engine parts and reaction vessels. Molybdenum-containing nickel alloys are notable for their corrosion resistance and thermal stability, as are the nickel-iron-chromium alloys, and are used in nuclear and fossil-fuel steam generators, food-processing equipment and chemical-processing and heat-treating equipment. The majority of permanent magnets are made from nickel-cast iron alloys (Mastromatteo, 1986). The other groups of nickel alloys are used according to their specific properties for acid-resistant equipment, heating elements for furnaces, low-expansion alloys, cryogenic uses, storage of liquefied gases, high magnetic-permeability alloys and surgical implant prostheses.

(*b*) *Nickel oxides and hydroxides*

The *nickel oxide sinters* are used in the manufacture of alloys, steels and stainless steels (Antonsen, 1981).

Green nickel oxide is used to make nickel catalysts and in the ceramics industry. In specialty ceramics, it is added to frit compositions used for porcelain enamelling of steel; in the manufacture of magnetic nickel-zinc ferrites used in electric motors, antennas and television tube yokes; and as a colourant in glass and ceramic stains used in ceramic tiles, dishes, pottery and sanitary ware (Antonsen, 1981).

Black nickel oxide is used in the manufacture of nickel salts and specialty ceramics. It is also used to enhance the activity of three-way catalysts containing rhodium, platinum and palladium used in automobile exhaust control. Like green nickel oxide, black nickel oxide is also used for nickel catalyst manufacture and in the ceramic industry (Antonsen, 1981).

The major use of *nickel hydroxide* is in the manufacture of nickel-cadmium batteries. It is also used as a catalyst intermediate (Antonsen, 1981).

(*c*) *Nickel sulfides*

Nickel sulfide is used as a catalyst in petrochemical hydrogenation when high concentrations of sulfur are present in the distillates. The major use of nickel monosulfide is as an intermediate in the hydrometallurgical processing of silicate-oxide nickel ores.

(*d*) *Nickel salts*

Nickel acetate is used as a catalyst intermediate, as an intermediate in the formation of other nickel compounds, as a dye mordant, as a sealer for anodized aluminium and in nickel electroplating (Antonsen, 1981).

Nickel carbonate is used in the manufacture of nickel catalysts, in the preparation of coloured glass, in the manufacture of nickel pigments, in the production of nickel oxide and nickel powder, as a neutralizing compound in nickel electroplating solutions, and in the preparation of specialty nickel compounds (Antonsen, 1981).

Nickel ammonium sulfate has limited use as a dye mordant and is used in metal-finishing compositions and as an electrolyte for electroplating (Sax & Lewis, 1987).

Nickel chloride is used as an intermediate in the manufacture of nickel catalysts and to absorb ammonia in industrial gas masks. The hexahydrate is used in nickel electroplating (Antonsen, 1981) and hydrometallurgy (Warner, 1984).

Nickel nitrate hexahydrate is used as an intermediate in the manufacture of nickel catalysts, especially sulfur-sensitive catalysts, and as an intermediate in loading active mass in nickel-cadmium batteries of the sintered-plate type (Antonsen, 1981).

Nickel sulfate hexahydrate is used as an electrolyte primarily for nickel electroplating and also for nickel electrorefining. It is also used in 'electro-less' nickel plating, as a nickel strike solution for replacement coatings or for nickel flashing on steel that is to be porcelain-enamelled, as an intermediate in the manufacture of other nickel chemicals, such as nickel ammonium sulfate, and as a catalyst intermediate (Antonsen, 1981).

(*e*) *Other nickel compounds*

The primary use for *nickel carbonyl* is as an intermediate in the Mond carbonyl-refining process to produce highly pure nickel. Other uses of nickel carbonyl are in chemical synthesis as a catalyst, as a reactant in carbonylation reactions such as the synthesis of acrylic and methacrylic esters from acetylene and alcohols, in the vapour plating of nickel, and in the fabrication of nickel and nickel alloy components and shapes (Antonsen, 1981; Sax & Lewis, 1987).

Nickelocene is used as a catalyst and complexing agent and *nickel titanate* as a pigment (Sax & Lewis, 1987).

No information was available on the use of *nickel selenides* or *potassium nickelocyanate.*

2.3 Occurrence

(*a*) *Natural occurrence*

Nickel is widely distributed in nature, forming about 0.008% of the earth's crust (0.01% in igneous rocks). It ranks twenty-fourth among the elements in order of abundance (Grandjean, 1984), just above copper, lead and zinc (Mastromatteo, 1986). The core of the earth contains about 8.5% nickel; meteorites have been found to contain 5-50% (National Research Council, 1975). Nickel is also an important constituent of deep-sea nodules, typically comprising about 1.5% (Mastromatteo, 1986). Nickel-containing ores are listed in Table 9.

Laterites are formed by the long-term weathering of igneous rocks which are rich in magnesia and iron and contain about 0.25% nickel. Leaching by acidified groundwater over a long period removes the iron and magnesia, leaving a nickel-enriched residue with nickel contents up to 2.5%. Nickel is found as mixed nickel/iron oxide and as nickel magnesium silicate (garnierite) (Grandjean, 1986; Mastromatteo, 1986). Laterite deposits have been mined in many regions of the world, including New Caledonia, Cuba, the Dominican Republic, Indonesia, the USSR, Greece, Colombia, the Philippines, Guatemala and the USA (Mastromatteo, 1986).

Table 9. Nickel-containing minerals[a]

Name	Chemical composition
Breithauptite	$NiSb$
Niccolite	$NiAs$
Zaratite	$NiCO_3 2Ni(OH)_2.4H_2O$
Bunsenite	NiO
Morenosite	$NiSO_4.7H_2O$
Millerite	NiS
Vaesite	NiS_2
Polydomite	Ni_3S_4
Heazlewoodite	Ni_3S_2
Pentlandite	$(Ni,Fe)_9S_8$
Pyrrhotite, nickeliferous	$(Fe,Ni)_{1-x}S$[b]
Garnierite	$(Ni, Mg) SiO_3.nH_2O$

[a] From Grandjean (1986)
[b] From Warner (1984); Grandjean (1986)

Nickel and sulfur combine in a wide range of stoichiometric ratios. Nickel monosulfide (millerite), nickel subsulfide (heazlewoodite), nickel disulfide (vaesite) and Ni_3S_4 (polydymite) are found in mineral form in nature (Considine, 1974). Sulfide nickel ores contain a mixture of metal sulfides, principally pentlandite, chalcopyrite ($CuFeS_2$) and nickeliferous pyrrhotite in varying proportions. The major nickel mineral is pentlandite. While pentlandite may contain about 35% of nickel by weight, the nickel content of pyrrhotite is usually 1% or less, and the sulfide ore available for nickel production generally contains only 1-2% nickel (Grandjean, 1986). A large deposit of pentlandite is located in Sudbury, Ontario, Canada.

Other nickel ores include the nickel-arsenicals and the nickel-antimonials, but these are of much less commercial importance (Mastromatteo, 1986).

(*b*) *Occupational exposures*

Occupational exposure to nickel may occur by skin contact or by inhalation of dusts, fumes or mists containing nickel or by inhalation of gaseous nickel carbonyl. Nickel-containing dusts may also be ingested by nickel workers (Grandjean, 1984). The National Institute for Occupational Safety and Health (1977a) published a list of occupations with potential exposure to nickel (Table 10); it has estimated that about 1.5 million workers in the USA are exposed to nickel and nickel compounds (National Institute for Occupational Safety and Health, 1977b).

Table 10. Occupations with potential exposure to nickel[a]

Battery makers, storage	Mould makers
Catalyst workers	Nickel miners
Cemented carbide makers	Nickel refiners
Ceramic makers	Nickel smelters
Chemists	Nickel workers
Disinfectant makers	Oil hydrogenators
Dyers	Organic chemical synthesizers
Electroplaters	Paint makers
Enamellers	Penpoint makers
Gas-mask makers	Petroleum refinery workers
Ink makers	Spark-plug makers
Jewellers	Stainless-steel makers
Magnet makers	Textile dyers
Metallizers	Vacuum tube makers
Mond process workers	Varnish makers
Nickel-alloy makers	Welders

[a] Adapted from National Institute for Occupational Safety and Health (1977b)

Occupational exposure to nickel is evaluated by monitoring air and blood serum, plasma or urine. (For recent reviews on this subject, see Rigaut, 1983; Grandjean, 1984; Nieboer *et al.*, 1984a; Warner, 1984; Grandjean, 1986; Sunderman *et al.*, 1986a). Tables 11-13 summarize exposure to nickel as measured by air and biological monitoring in various industries and occupations. The biological indicator levels are influenced by the chemical and physical properties of the nickel compound studied and by the time of sampling. It should be noted that the nickel compounds, the timing of collection of biological samples (normally at the end of a shift) and the analytical methods used differ from study to study, and elevated levels of nickel in biological fluids and tissue samples (Table 11) are mentioned only as indications of uptake of nickel, and may not correlate directly to exposure levels (Angerer *et al.*, 1989). (See also section 3.3(*b*) and the monographs on chromium and chromium compounds, and on welding.)

Table 11. Occupational exposure to nickel in the nickel producing industry

Industry and activity (country) [year, when available]	No. of workers	Air (µg/m³)		Urine (µg/l)		Serum (µg/l) (mean ±SD)	Reference
		Mean ±SD	Range	Mean ±SD	Range		
Mines, Ontario (Canada) [1976]		20	6–40				Rigaut (1983)
Mines, Oregon (USA) [1981]		30					Rigaut (1983)
Mines, New Caledonia [1982]		20	6–40				Rigaut (1983)
Smelter, producing ferronickel and matte, New Caledonia		5–76[a]	2–274[b]	< 10 (86% of samples) < 20 (98% of samples)			Warner (1984)
Laterite mining and smelting, Oregon (USA)[b]							Warner (1984)
Ore handling	3	52	5–145				
Drying	4	17	9–21				
Calcining	4	90	37–146				
Skull drilling	8	16	4–43				
Ferrosilicon manufacturing	15	32	4–214				
Mixing	17	6	4–7				
Refining	10	11	4–34				
Handling of finished products	6	5	4–9				
Maintenance	9	39	7–168				
Miscellaneous	3	193	8–420				
Refinery, Clydach (Wales, UK)							Morgan & Rouge (1984)
Kiln							
Before shut-down[c]		310 (26 samples)	10–5000	24±24 (67 samples)		8.9±5.9 (37 samples)	
On return to work[c]				14±7 (20 samples)		3.0±2.0 (20 samples)	

Table 11 (contd)

Industry and activity (country) [year, when available]	No. of workers	Air (µg/m³)		Urine (µg/l)		Serum (µg/l) (mean ±SD)	Reference
		Mean ±SD	Range	Mean ±SD	Range		
Refinery, Clydach (Wales, UK)							
Kiln (contd)							
One month later		190 (30 samples)	10–2890	22±10 (14 samples)		5.5±2.0 (16 samples)	
New powder plant		310 (20 samples)	90–1530				
Before shut-down[c]				37±30 (48 samples)		7.2±4.8 (25 samples)	
On return to work[c]				13±12 (17 samples)		4.0±2.3 (17 samples)	
One month later		500 (22 samples)	50–1810	31±13 (16 samples)		7.6±3.5 (15 samples)	
Old powder plant		1460 (5 samples)	80–5000	33±13 (12 samples)		9.0±3.7 (6 samples)	
Wet-treatment (A)[d]		1540 (8 samples)	220–4180	39±28 (15 samples)		7.4±5.1 (7 samples)	
Wet-treatment (B)[e]		90 (17 samples)	30–150	34±24 (36 samples)		3.4±1.9 (13 samples)	
Refinery, Kristiansand (Norway)[b]							Høgetveit *et al.* (1978)
Roasting–smelting	24	860±1200		65±58		7.2±2.8	
Electrolytic department	90	230±420		129±106		11.9±8.0	
Other processes	13	420±490		45±27		6.4±1.9	

Table 11 (contd)

Industry and activity (country) [year, when available]	No. of workers	Air (μg/m³)		Urine (μg/l)		Serum (μg/l) (mean ±SD)	Reference
		Mean ±SD	Range	Mean ±SD	Range		
Refinery, Kristiansand (Norway)							Torjussen & Andersen (1979)
Roasting-smelting	97			34±35		5.2±2.7	
Electrolysis	144			73±85		8.1±6.0	
Other processes	77			22±18		4.3±2.2	
Electrolytic refinery (USA)	15	489	20–2200	222 124 (μg/g creatinine)	8.6–813 6.1–287		Bernacki *et al.* (1978a)
Electrolytic refinery (FRG)		50		14.8 (μg/g creatinine)	2.5–63		Raithel (1987)
Electrolytic refinery (Czechoslovakia)		600	86–1265	264	125–450		Rigaut (1983)
Hydrometallurgical refinery (Canada)							Warner (1984)
Acid leaching of matte		99	5–1630				
Purification of nickel electrolyte:							
Tube filterman	12	144	13–316				
	12[f]	129	11–316				
Filter pressman	16	209	61–535				
	16[f]	152	31–246				
Filter-press area	11	242	64–508				
	11[f]	221	52–466				

Table 11 (contd)

Industry and activity (country) [year, when available]	No. of workers	Air (µg/m³)		Urine (µg/l)		Serum (µg/l) (mean ±SD)	Reference
		Mean ±SD	Range	Mean ±SD	Range		
Hydrometallurgical refinery (Canada) (contd)							
Purification of nickel electrolyte[a]:							
Cementation of copper on nickel in Pachuca tanks	39	168	48-644				
	39[f]	38	1-133				
Removal of iron slimes with a tube filter	56	200	27–653				
	56[f]	85	3–433				
Oxidizing cobalt with chlorine	47	183	30–672				
	47[f]	66	1-267				
General operations in a tank house using insoluble anodes	96[a]	336	40–1100				
	45[b]	185	80–400				
Tankhouse using nickel matte anodes:							
General area	11[a]	48	14–223				
	11[a,f]	29	5-210				
Tankman	15[b]	48	18-88				
	15[b,f]	30	12–71				
Anode scrapman	11[b]	179	43-422				
	11[b,f]	52	1-236				

[a] Area air sampling

[b] Personal air sampling

[c] Specimens obtained before and after six months' closure of refinery operations

[d] Short exposures to high levels of insoluble nickel compounds

[e] Chronic exposures to soluble nickel sulfate

[f] Soluble nickel

Table 12. Occupational exposure in industries using primary nickel products

Industry and activity (country)	No. of workers	Air (µg/m³)		Urine (µg/l)		Reference
		Mean	Range	Mean	Range	
Stainless-steel production						Warner (1984)
Electric furnace shop	8[a]	36	9-65			
Argon-oxygen decarburization	5	35	13-58			
Continuous casting	2	14	11-15			
Grinding/polishing (machine)	6	134	75-189			
Grinding/chipping (hand tool)	2	39	23-48			
Welding, cutting and scarfing[b]	5	111[c]	13-188[c]			
Heat treating	1	54[d]	< 1-104[d]			
Rolling and forging	6	49	< 11-72			
Other operations (maintenance, pickling)	5	58	10-107			
High nickel alloy production (FRG) (a few persons exposed to nickel powder)	59	300[e]		2.6	0.5-52	Raithel (1987)
High nickel alloy production[f]						Warner (1984)
Weighing and melting	369	83[f]	1-4400			
Hot working	153	111	1-4200			
Cold working	504	64	1-2300			
Grinding	96	298	1-2300			
Pickling and cleaning	18	8	1-15			
Maintenance	392	58	1-73			
Production of wrought nickel and alloys *via* metal powder foundries	226	1500[f]	1-60000			Warner (1984)

Table 12 (contd)

Industry and activity (country)	No. of workers	Air (µg/m³)		Urine (µg/l)		Reference
		Mean	Range	Mean	Range	
Six jobbing foundries processing alloys containing 0–60% nickel, averaging 10–15% nickel:						Scholz & Holcomb (1980)
Melting	15	21	< 5–62			
Casting	7	14	< 4–35			
Cleaning room:						
Cutting and gouging	11	233	7–900			
Welding	14	94	20–560			
Hand grinding	24	94	< 5–440			
Swing grinding	3	19	13–30			
Jobbing foundry processing carbon, alloy and stainless steel containing 0–10% nickel:						Warner (1984)
Melting and casting	16	13	ND[g]–70			
Cleaning room:						
Air arc gouging	7	310	40–710			
Welding	34	67	10–170			
Three low alloy (0–2% nickel) iron and steel foundries						Warner (1984)
Melting and casting	16	13	4–32			
Cleaning room (grinding, air arc gouging, welding)	18	54	7–156			
Steel foundry (Finland) (steel cutters)	4	518	145–1100	39	18–77	Aitio *et al.* (1985)
Production of soluble nickel salts (Wales, UK)[f]	66 60	500 450	10–20 000 < 10–12 070	(68) 65[h] (60) 49[h]	10–200[h] < 10–210[h]	Morgan & Rouge (1979)

Table 12 (contd)

Industry and activity (country)	No. of workers	Air (µg/m³)		Urine (µg/l)		Reference
		Mean	Range	Mean	Range	
Production of nickel salts from nickel or nickel oxide:						Warner (1984)
Nickel sulfate	12	117[f]	9-590			
Nickel chloride	10	196[f,i]	20-485[i]			
Nickel acetate/nitrate	6	155[f]	38-525			

[a] Companies reporting exposures

[b] Samples taken outside protective hood

[c] Excludes one suspiciously high measurement (1460 µg Ni/m³)

[d] Excludes one suspiciously high measurement (500 µg Ni/m³)

[e] The median nickel concentration in workroom air was 300 µg/m³; values that exceeded 500 µg/m³ were found at 2 of 8 measuring stations

[f] Mainly from personal sampling

[g] Not detected

[h] Corrected to 1.6 g/l creatinine

[i] Excludes one suspiciously high value (2780 µg Ni/m³)

Table 13. Occupational exposure in industries using nickel in special applications

Industry and activity (country)	No. of workers	Air (μg/m³)		Urine (μg/l)		Serum (μg/l)		Reference
		Mean	Range	Mean ± SD	Range	Mean	Range	
Ni/Cd-battery production with nickel and nickel hydroxide; assembly and welding of plates	36	$378^{a,b}$	$20–1910^{a,b}$					Warner (1984)
Ni/Cd-battery production (FRG)	51			4.0^{c}	1.9–10.9			Raithel (1987)
Ni/Cd or Ni/Zn-battery production (USA)	6			11.7±7.5 10.2	3.4–25 7.2–23 (μg/g creatinine)			Bernacki *et al.* (1978a)
Ni/H_2-battery production	7			32.2±40.4	2.8–103			
Ni/Cd-battery production			12–33		24–27 (μg/g creatinine)			Adamsson *et al.* (1980)
Ni-catalyst production (Netherlands)	73		< 200–5870	64 (μg/g creatinine)	9–300	8	2–41	Zwennis & Franssen (1983)
Ni-catalyst production from nickel sulfate (USA)	7 5	150^{a} 370^{d}	$10–600^{a}$ $190–530^{d}$					Warner (1984)
Ni-catalyst use; coal gasification workers (USA)	9			4.2 3.2	0.4–7.9 0.1–5.8 (μg/g creatinine)			Bernacki *et al.* (1978a)
Electroplating								Warner (1984)
Sulfate bath, 45°C								
Area 1 sample	16	< 6	< 5–< 8					
Area 2 samples	3	< 4	< 2–< 7					
Personal samples	6	< 11	< 7–< 16					

Table 13 (contd)

Industry and activity (country)	No. of workers	Air (μg/m³)		Urine (μg/l)		Serum (μg/l)		Reference
		Mean	Range	Mean ± SD	Range	Mean	Range	
Electroplating (contd)								
Sulfate bath, 70°C								
Area samples	6	<3	<2–<3					
Sulfamate bath, 45–55°C								
Area 1 sample	9	<4	<4					
Area 2 samples	6	<4	<4					
Electroplating (Finland)		90	20–170	53.5	12–109	6.1	1.2–14.1	Tossavainen *et al.* (1980)
Electroplating (Finland)		–	30–160	–	25–120	–	3–14	Tola *et al.* (1979)
Electroplating (USA)		9.3[a]	0.5–21.2	48	5–262			Bernacki *et al.* (1980)
Electroplating (USA)	21			30.4 (21.0	3.6–85 2.4–62 μg/g creatinine)			Bernacki *et al.* (1978a)
Electroplating (India)	12			12.2	11–26			Tandon *et al.* (1977)
Electroplating (FRG)		10 (soluble anode)						Gross (1987)
		110 (insoluble anode)						
		7 (insoluble anode and wetting agent)			1.7–3.6			
Exposed persons in the hollow glass industry (FRG)	9		3–3800	11.9 (946 samples)	3.6–42.1[e]	1.6	0.75–3.25[e] (288 samples)	Raithel (1987)
Flame sprayer			3–600	25.3 (114 samples)	8.5–81.5	1.95	0.75–3.25 (40 samples)	

Table 13 (contd)

Industry and activity (country)	No. of workers	Air (µg/m^3)		Urine (µg/l)		Serum (µg/l)		Reference
		Mean	Range	Mean ± SD	Range	Mean	Range	
Grinder, polisher			18–3800	7.4 (406 samples)	2.9–24.3	0.9	0.75–2.05 (140 samples)	
Mixed mechanical work and flame spraying			300–410	17.5 (394 samples)	4.9–53.9	1.65	0.75–4.10 (108 samples)	
Plasma spraying (FRG)	6	200			3.4–12.5			Gross (1987)
Spark eroding (FRG)	6	< 10			0.7–2.1			Gross (1987)
Flame spraying (USA)	5	2.4	< 1–6.5	17.2 (16.0	1.4–26 1.4–54 µg/g creatinine)			Bernacki *et al.* (1978a)
Plasma cutting (FRG)	17		< 100		1.1–6.5			Gross (1987)
Painting								
Spray painting in a construction shipyard (USA)	13			3.2	< 0.5–9.2	4.4	< 0.5–17.2	Grandjean *et al.* (1980)
Painting in repair shipyard (USA)	18					5.9	< 0.5–13	Grandjean *et al.* (1980)
Manufacturing paints (USA)	10			15.3±11.1	6–39			Tandon *et al.* (1977)
Buffing, polishing, grinding								
Buffers and polishers (aircraft engine factory) (USA)	7	26	< 1–129	4.1 (2.4	0.5–9.5 0.5–4.7 µg/g creatinine)			Bernacki *et al.* (1978a)
Grinders (abrasive wheel grinding of aircraft parts) (USA)	9	1.6	< 1–9.5	5.4 (3.5	2.1–8.8 1.7–6.1 µg/g creatinine)			Bernacki *et al.* (1978a)

Table 13 (contd)

Industry and activity (country)	No. of workers	Air (µg/m³)		Urine (µg/l)		Serum (µg/l)		Reference
		Mean	Range	Mean ± SD	Range	Mean	Range	
Polisher, grinder (FRG)	15	140			0.7–9.9			Gross (1987)
Polisher, grinder (stainless steel) (FRG)	46	350[c]	10–10 000[f]	28	(12) 3–7[l]			Heidermanns *et al.* (1983)
Miscellaneous exposure								
Bench mechanics (assembling, fittings and finishing aircraft parts made of Ni-alloys) (USA)	8	52	< 1–252	12.2 (7.2	1.4–41 0.7–20 µg/g creatinine)			Bernacki *et al.* (1978a)
Riggers/carpenters (construction shipyard) (USA)	16			3.7	1.1–13.5	3.3	1.1–13.5	Grandjean *et al.* (1980)
Riggers/carpenters (repair shipyard) (USA)	11					3.6	< 0.5–7.4	Grandjean *et al.* (1980)
Shipfitters/pipefitters (construction shipyard (USA)	6			4.9	3.7–7.1	4.1	1.5–6.8	Grandjean *et al.* (1980)
Shipfitters/pipefitters (repair shipyard) (USA)	15					9.1	0.5–3.8	Grandjean *et al.* (1980)

[a]Personal air sampling

[b]Excludes three suspiciously high values (5320; 18 300; 53 300 µg/m³)

[c]Median

[d]Area air monitoring

[e]68th percentile range

[f]90th percentile range

(i) *Nickel mining and ore comminution*

On the basis of personal gravimetric sampling among Canadian underground miners of nickel, the time-weighted average concentration of total airborne nickel was about 25 $\mu g/m^3$ and that of respirable nickel, < 5 $\mu g/m^3$ (see Table 11; Warner, 1984). Ore miners may also be exposed to radon, oil mist, diesel exhausts and asbestos (see IARC, 1977, 1988a, 1989).

(ii) *Nickel roasting, calcining, smelting and refining*

The nickel content of air samples from a Sudbury (Canada) smelter seldom exceeded 0.5 mg/m^3 but could be as high as 1 mg/m^3. The average concentrations of airborne nickel were higher in the roaster areas (0.048 mg/m^3) than in the converter areas (0.033 mg/m^3), because the handling of fine solids is a greater source of dust than the handling of molten phases. Thus, work-place air may contain roaster feed and product, which include various nickel-containing minerals and solid solutions of nickel in iron oxides. Nickel-bearing dusts from converters contain mainly nickel subsulfide (Warner, 1984). Arsenic, silica, copper, cobalt and other metal compounds may also occur in work-place air.

Emissions from the high-temperature ore calcining and smelting furnaces used to produce ferronickel from lateritic ores would contain nickel predominantly in the form of silicate oxides and iron-nickel mixed/complex oxides of the ferrite or spinel type. The nickel content of these dusts can range from 1 to 10% (International Committee on Nickel Carcinogenesis in Man, 1990).

Average concentrations of airborne nickel in refining operations can be considerably higher than those encountered in mining and smelting because of the higher nickel content of the materials being handled in the refining process (Table 11). The nickel species that may be present in various refining operations include nickel subsulfide, nickel monoxide, nickel-copper oxides, nickel-iron oxides, metallic nickel, pure and alloyed, nickel sulfate, nickel chloride and nickel carbonate. Other possible exposures would be to hydrogen sulfide, ammonia, chlorine, sulfur dioxide, arsenic and polycyclic aromatic hydrocarbons (Warner, 1984; International Committee on Nickel Carcinogenesis in Man, 1990).

A recent attempt has been made, in conjunction with a large epidemiological study (International Committee on Nickel Carcinogenesis in Man, 1990), to estimate past exposures in various nickel refineries using different processes. Exposure estimates were made first for total airborne nickel, based either on historical measurements (after 1950) or on extrapolation of recent measurements. In all cases, further estimates were made of nickel species (metallic, oxidic, sulfidic and soluble), as defined in the report, on the basis of knowledge of the processes and rough estimates of the ratio of the various species generated in each process.

Prior to the widespread use of personal samplers, high-volume samplers were used to take area samples; however, in many instances, neither personal gravimetric nor high-volume samples were available, and konimeter readings were the only available means of assessing the level of airborne dust. No measurement of the actual concentration of nickel, and especially nickel species, in work places exists for any refining operation prior to 1950. More recently, measurements have been made of total dust and, in some cases, total nickel content of dust or mist in refinery work-place air. Conversion of high-volume sampler and konimeter measurements to concentrations comparable to personal gravimetric sampler measurements introduces another uncertainty in the environmental estimates. The main reason for this uncertainty is that it is impossible to derive unique conversion factors to interrelate measurements from the three devices; different particle size distributions give rise to different conversion factors. Information concerning particle size in airborne dusts was seldom available in the work places under study (International Committee on Nickel Carcinogenesis in Man, 1990).

Estimates of nickel exposure were further divided into four categories representing different nickel species: (i) metallic nickel, (ii) oxidic nickel [undefined, but generally understood to include nickel oxide combined with various other metal oxides, such as iron, cobalt and copper oxides], (iii) sulfidic nickel (including nickel subsulfide) and (iv) soluble nickel, defined as consisting 'primarily of nickel sulfate and nickel chloride but may in some estimates include the less soluble nickel carbonate and nickel hydroxide'. No actual measurement of specific nickel species in work-place air was available upon which to base exposure estimates. As a result, the estimates are necessarily very approximate. This is clear, for example, from the estimates for linear calciners at the Clydach refinery (Wales, UK), which gave total nickel concentrations of 10-100 mg/m^3, with 0-5% soluble nickel. Because of the inherent error in the processes of measurement and speciation and the uncertainty associated with extrapolating estimates from recent periods to earlier periods, the estimated concentrations of nickel species in work places in this study (International Committee on Nickel Carcinogenesis in Man, 1990) must be interpreted as broad ranges indicating only estimates of the order of magnitude of the actual exposures.

(iii) *Production of stainless steel and nickel alloys*

While some stainless steels contain up to 25-30% nickel, nearly half of that produced contains only 8-10% nickel. Nickel oxide sinter is used as raw material for stainless and alloy steelmaking in some plants, and oxidized nickel may be found in the fumes from many melting/casting and arc/torch operations in the melting trades. The nickel concentrations in air in the stainless and alloy producing industries were given in Table 12. Occupational exposure in alloy steel making should generally be lower than those observed for comparable operations with stainless steel. The normal range of nickel in alloy steels is 0.3-5% but the nickel content can be as high as 18% for certain high-strength steels. The production of 'high nickel' alloys consumes about 80% of the nickel used for nonferrous applications. The technology is very similar to that used for stainless steel production except that melting and decarburizing units are generally smaller and greater use is made of vacuum melting and remelting. Since these alloys contain more nickel than stainless and alloy steels, the concentrations of nickel in workroom air are generally higher than for comparable operations with stainless and alloy steels (Warner, 1984).

(iv) *Steel foundries*

In foundries, shapes are cast from a wide variety of nickel-containing materials. Melts ranging in size from 0.5 to 45 tonnes are prepared in electric arc or induction furnaces and cast into moulds made of sand, metal or ceramic. The castings are further processed by chipping and grinding and may be repaired by air arc gouging and welding. Foundry operations can thus be divided roughly into melting/casting and cleaning room operations. Typical levels of airborne nickel in steel foundries were presented in Table 12 (Warner, 1984). Health hazards in foundry operations include exposure to silica and metal fumes and to degradation products from moulds and cores, such as carbon monoxide, formaldehyde and polycyclic aromatic hydrocarbons (see IARC, 1984).

(v) *Production of nickel-containing batteries*

The principal commercial product in nickel-containing batteries is the electrochemical couple nickel/cadmium. Other couples that have been used include nickel/iron, nickel/hydrogen and nickel/zinc. In nickel-cadmium batteries, the positive electrode is primarily nickel hydroxide, contained in porous plates. The positive material is made from a slurry of nickel hydroxide, cobalt sulfate and sodium hydroxide, dried and ground with graphite flake. Sintered nickel plates impregnated with the slurry may also be used. The nickel/hydrogen system requires a noble metal catalyst and operates at high pressures, requiring a steel pressure vessel. Nickel/iron batteries can be produced using nickel foil (Malcolm, 1983).

The concentrations of nickel in air and in biological samples from workers in the nickel-cadmium battery industry were summarized in Table 13. Workers in such plants are also exposed to cadmium.

(vi) *Production and use of nickel catalysts*

Metallic nickel is used as a catalyst, often alloyed with copper, cobalt or iron, for hydrogenation and reforming processes and for the methane conversion and Fischer-Tropsch reactions. Mixed, nickel-containing oxides are used as partial oxidation catalysts and as hydrodesulfuration catalysts (cobalt nickel molybdate) (Gentry *et al.*, 1983). Occupational exposure occurs typically in the production of catalysts from metallic nickel powder and nickel salts such as nickel sulfate (Warner, 1984), but coal gasification process workers who use Raney nickel as a hydrogenation catalyst have also been reported to be exposed to nickel (Bernacki *et al.*, 1978a). Exposure levels are generally higher in catalyst production than during the use of catalysts (see Table 13).

(vii) *Nickel plating*

Metal plating is an operation whereby a metal, commonly nickel, is deposited on a substrate for protection or decoration purposes. Nickel plating can be performed by electrolytic processes (electroplating) or 'electroless' processes (chemical plating), with aqueous solutions (the 'baths'). During electroplating, nickel is taken out of the solution and deposited on the substrate, which acts as the cathode. Either soluble anodes, made from metallic nickel feed, or insoluble anodes, in which the nickel is introduced as the hydroxycarbonate, are used. The baths contain a mixture of nickel sulfate and/or chloride or, less often, sulfamate. In electroless processes, a hypophosphite medium is used, the nickel feed being nickel sulfate.

The electrolyte contains soluble nickel salts, such as nickel fluoborate, nickel sulfate and nickel sulfamate (Warner, 1984). Nickel plating can be performed with a soluble (metallic nickel) or insoluble anode. The principal source of air contamination in electroplating operations is release of the bath electrolyte into the air. Electroplaters are exposed to readily absorbed soluble nickel salts by inhalation, which subsequently causes high levels in urine (Tola *et al.*, 1979; see Table 13).

(viii) *Welding*

Welding produces particulate fumes that have a chemical composition reflecting the elemental content of the consumable used. For each couple of process/material of application, there is a wide range of concentrations of elements present in the fume. Nickel and chromium are found in significant concentrations in fumes from welding by manual metal arc, metal inert gas and tungsten inert gas processes on stainless and alloy steels. Typical ranges of total fume and nickel, as found in the breathing zone of welders, are presented in Table 14. Certain special process applications not listed can also produce high nickel and chromium concentrations, and manual metal arc and metal inert gas welding of nickel in confined spaces produce significantly higher concentrations of total fume and elemental constituents. Exposure to welding fumes that contain nickel and chromium can lead to elevated levels of these elements in tissues, blood and urine (see monograph on welding for details).

(ix) *Thermal spraying of nickel*

Thermal spraying of nickel is usually performed by flame spraying or plasma spraying (Gross, 1987). For flame spraying, nickel in wire form is fed to a gun

Table 14. Total fume and nickel concentrations found in the breathing zone of welders[a]

Process[b]	Total fume[c] (mg/m³)	Ni (μg/m³)
MMA/SS	4-10	10-1000
MIG/SS	2-5	30-500
TIG/SS	2-6	10-40

[a] Compiled from Table 4 of monograph on welding

[b] MMA, manual metal arc; SS, stainless steel; MIG, metal inert gas; TIG, tungsten inert gas

[c] 50-90% range

fuelled by a combustible gas such as acetylene, propane or natural gas. The wire is melted in the oxygen-fuel flame, atomized with compressed air, and propelled from the torch at velocities up to 120 m/s. The material bonds to the workpiece by a combination of mechanical interlocking of the molten particles and a cementation of partially oxidized material.

The material can also be sprayed in powder form, the fuel gases being either acetylene or hydrogen and oxygen. The powder is aspirated by an air stream, and the molten particles are deposited on the workpiece with high efficiency. For plasma spraying, an electric arc is established in the controlled atmosphere of a special nozzle. Argon is passed through the arc, where it ionizes to form a plasma that continues through the nozzle and recombines to create temperatures as high as 16 700 °C. Powder is melted in the stream and released from the gun at a velocity of approximately 10 m/s (Burgess, 1981; Pfeiffer & Willert, 1986).

Workers who construct or repair nickel-armoured moulds in hollow-glass and ceramics factories use flame spraying with metallic powder (70-98% Ni) and are exposed to nickel dusts (as metallic and oxidic nickel) and fumes. After the moulds have been polished with grinding discs, abrasives and emery paper, they are installed in glass-making machines. Exposure levels in various types of thermal spraying, cutting and eroding were shown in Table 13.

(x) *Production and use of paints*

Some pigments for paints (e.g., nickel flake) and colours for enamels (e.g., nickel oxide) contain nickel. Exposure to nickel can occur when spraying techniques are used and when the paints are manufactured (Tandon *et al.*, 1977; Mathur & Tandon, 1981). Paint and pigment workers have slightly higher concentrations of nickel in plasma and urine than controls (see Table 13). Sandblasters may be exposed to dusts from old paints containing nickel and, additionally, to nickel-containing abrasive materials (Stettler *et al.*, 1982).

(xi) *Grinding, polishing and buffing of nickel-containing metals*

Grinding, polishing and buffing involve controlled use of bonded abrasives for metal finishing operations; in many cases the three operations are conducted in sequence (for review, see Burgess, 1981). Grinding includes cutting operations in foundries for removal of gates, sprues and risers, rough grinding of forgings and castings, facing off of welded assemblies and grinding out major surface imperfections. Grinding is done with wheels made of selected abrasives in bonding structural matrices. The commonly used abrasives are aluminium oxide and silicon carbide. The wheel components normally make up only a small fraction of the total airborne particulates released during grinding, and the bulk of the particles arise from the workpiece. Polishing techniques are used to remove workpiece surface imperfections such as tool marks, and this may remove as much as 0.1 mm of stock from a workpiece. In buffing, little metal is removed from the workpiece, and the process merely provides a high lustre surface by smearing any surface roughness with a high weight abrasive; e.g., ferric oxide and chromium oxide are used for soft metals, aluminium oxide for harder metals. Sources of airborne contaminants from grinding, polishing and buffing have been identified (Burgess, 1981; König *et al.*, 1985). Grinding, polishing and buffing cause exposures to metallic nickel and to nickel-containing alloys and steels (see Table 13).

(xii) *Miscellaneous exposure to nickel*

A group of employees exposed to metallic nickel dust was identified among employees of the Oak Ridge Gaseous Diffusion Plant in the USA. In one department, finely-divided, highly pure, nickel powder was used to manufacture 'barrier', a special porous medium employed in the isotope enrichment of uranium by gaseous diffusion. The metallic powder was not oxidized during processing. Routine air sampling was performed at the plant from 1948 to 1963, during which time 3044 air samples were collected in seven areas of the barrier plant and analysed for nickel content. The median nickel concentration was 0.13 mg/m^3 (range, <0.1-566 mg/m^3), but the authors acknowledged that the median exposures were probably underestimated (Godbold & Tompkins, 1979). Other determinations of nickel in miscellaneous industries and activities were presented in Table 13.

(*c*) *Air*

Nickel enters the atmosphere from natural sources (e.g., volcanic emissions and windblown dusts produced by weathering of rocks and soils), from combustion of fossil fuels in stationary and mobile power sources, from emissions from nickel mining and refining operations, from the use of metals in industrial processes and from incineration of wastes (Sunderman, 1986a; US Environmental Protection Agency, 1986). The estimated global emission rates are given in Table 15. The predominant forms of nickel in the ambient air appear to be nickel sulfate and complex oxides of nickel with other metals (US Environmental Protection Agency, 1986).

Table 15. Emission of nickel into the global atmosphere[a]

Source	Emission rate (10^6 kg/year)
Natural	
Wind-blown dusts	4.8
Volcanoes	2.5
Vegetation	0.8
Forest fires	0.2
Meteoric dusts	0.2
Sea spray	0.009
Total	8.5
Anthropogenic[b]	
Residual and fuel oil combustion	27
Nickel mining and refining	7.2
Waste incineration	5.1
Steel production	1.2
Industrial applications	1.0
Gasoline and diesel fuel combustion	0.9
Coal combustion	0.7
Total	43.1

[a] From Bennett (1984)
[b] Emissions during the mid-1970s

Nickel concentrations in the atmosphere at remote locations were about 1 ng/m³ (Grandjean, 1984). Ambient levels of nickel in air ranged from 5 to 35 ng/m³ at rural and urban sites (Bennett, 1984). Surveys have indicated wide variations but no overall trend. In the USA, atmospheric nickel concentrations averaged 6 ng/m³ in nonurban areas and 17 ng/m³ (in summer) and 25 ng/m³ (in winter) in urban areas (National Research Council, 1975). Salmon *et al.* (1978) reported nickel concentrations in 1957-74 at a semirural site in England to range from 10 to 50 ng/m³ (mean, 19 ng/m³). Nickel concentrations at seven sites in the UK ranged, with one exception, from <2 to 4.8 ng/kg [<2.5 to 5.9 ng/m³] (Cawse, 1978). Annual averages in four Belgian cities were 9-60 ng/m³ during 1972-77 (Kretzschmar *et al.*, 1980). Diffuse sources (traffic, home heating, distant sources) generally predominated.

High levels of nickel in air (110-180 ng/m^3) were recorded in heavily industrialized areas and larger cities (Bennett, 1984).

Local airborne concentrations of nickel are high around locations where nickel is mined (e.g., 580 ng/m^3 in Ontario, Canada) (McNeely *et al.*, 1972). The average atmospheric nickel concentration near a nickel refinery in West Virginia (USA) was 1200 ng/m^3, compared to 40 ng/m^3 at six sampling stations not contiguous to the nickel plant. The highest concentration on a single day was about 2000 ng/m^3 near a large nickel production facility (Grandjean, 1984).

Average exposure to nickel by inhalation has been estimated to be 0.4 μg/day (range, 0.2-1.0 μg/day) for urban dwellers and 0.2 μg/day (range, 0.1-0.4 μg/day) for rural dwellers (Bennett, 1984).

(*d*) *Tobacco smoke*

Cigarette smoking can cause a daily absorption of nickel of 1 μg/pack due to the nickel content of tobacco (Grandjean, 1984). Sunderman and Sunderman (1961) and Szadkowski *et al.* (1969) found average nickel contents of 2.2 and 2.3 μg/cigarette, respectively, with a range of 1.1-3.1. The latter authors also showed that 10-20% of the nickel in cigarettes is released in mainstream smoke; most of the nickel was in the gaseous phase. The nickel content of mainstream smoke ranges from 0.005 to 0.08 μg/cigarette (Klus & Kuhn, 1982). It is not yet known in what form nickel occurs in mainstream smoke (US Environmental Protection Agency, 1986); it has been speculated that it may be present as nickel carbonyl (Grandjean, 1984), but, if so, it must occur at concentrations of < 0.1 ppm (Alexander *et al.*, 1983). Pipe tobacco, cigars and snuff have been reported to contain nickel at levels of the same magnitude (2-3 μg/g tobacco) (National Research Council, 1975).

(*e*) *Water and beverages*

Nickel enters groundwater and surface water by dissolution of rocks and soils, from biological cycles, from atmospheric fallout, and especially from industrial processes and waste disposal, and occurs usually as nickel ion in the aquatic environment. Most nickel compounds are relatively soluble in water at pH values less than 6.5, whereas nickel exists predominantly as nickel hydroxides at pH values exceeding 6.7. Therefore, acid rain has a pronounced tendency to mobilize nickel from soil and to increase nickel concentrations in groundwater.

The nickel content of groundwater is normally below 20 μg/l (US Environmental Protection Agency, 1986), and the levels appear to be similar in raw, treated and distributed municipal water. In US drinking-water, 97% of all samples ($n = 2503$) contained ≤ 20 μg/l, while about 90% had ≤ 10 μg/l (National Research Council, 1975). Unusually high levels were found in groundwater polluted with soluble nickel compounds from a nickel-plating facility (up to 2500 μg/l) and in water from 12 wells (median, 180 μg/l) (Grandjean, 1984). The median level in Canadian groundwater was < 2 μg/l, but high levels were reported in Ontario (Méranger *et al.*, 1981). In municipal tap-water near large open-pit nickel mines, the average nickel concentration was about 200 μg/l, while that in a control area had an average level of about 1 μg/l (McNeely *et al.*, 1972).

Nickel concentrations in drinking-water in European countries were reported to range in general from 2-13 μg/l (mean, 6 μg/l) (Amavis *et al.*, 1976). Other studies have suggested low background levels in drinking-water, e.g., in Finland an average of about 1 μg/l (Punsar *et al.*, 1975) and in Italy mostly below 10 μg/l. In the German Democratic Republic, drinking-water from groundwater showed an average level of 10 μg/l nickel, slightly below the amount present in surface water (Grandjean, 1984). In the Federal Republic of Germany, the mean concentration of nickel in drinking-water was 9 μg/l, with a maximal value of 34 μg/l (Scheller *et al.*, 1988).

The nickel concentration in seawater ranges from 0.1 to 0.5 μg/l, whereas the average level in surface waters is 15-20 μg/l. Freshly fallen arctic snow was reported to contain 0.02 μg/kg, a level that represents 5–10% of those in annual condensed layers (Mart, 1983).

Nickel concentrations of 100 μg/l have been found in wine; average levels of about 30 μg/l were measured in beer and levels of a few micrograms per litre in mineral water (Grandjean, 1984). In the Federal Republic of Germany, however, the mean concentration of nickel in mineral waters was 10 μg/l, with a maximal value of 31 μg/l (Scheller *et al.*, 1988).

(*f*) *Soil*

The nickel content of soil may vary widely, depending on mineral composition: a normal range of nickel in cultivated soils is 5-500 μg/g, with a typical level of 50 μg/g (National Research Council, 1975). In an extensive survey of soils in England and Wales, nickel concentrations were generally 4-80 μg/g (median, 26 μg/g; maximum, 228 μg/g) (Archer, 1980). Farm soils from different parts of the world contained 3-1000 μg/g. Nickel may be added to agricultural soils by application of sewage sludge (National Research Council, 1975).

The nickel content of coal was 4-24 μg/g, whereas crude oils (especially those from Angola, Colombia and California) contained up to 100 μg/g (Tissot & Weltle, 1984; World Health Organization, 1990).

(*g*) *Food*

Nickel levels in various foods have been summarized recently (Grandjean, 1984; Smart & Sherlock, 1987; Scheller *et al.*, 1988; Grandjean *et al.*, 1989). Table 16 gives the results of analyses for nickel in various foodstuffs in Denmark; the mean level of nickel in meat, fruit and vegetables was $\leq$0.2 mg/kg fresh weight. This result was confirmed by analysis of hundreds of food samples from Denmark, the Federal Republic of Germany and the UK (Nielsen & Flyvholm, 1984; Veien & Andersen, 1986; Smart & Sherlock, 1987; Scheller *et al.*, 1988): the nickel content of most samples was < 0.5 mg/kg. The nickel concentration in nuts was up to 3 mg/kg (Veien & Andersen, 1986) and that in cocoa up to 10 mg/kg (Nielsen & Flyvholm, 1984). The nickel content of wholemeal flour and bread was significantly higher than that of more refined products due to the high nickel content of wheat germ (Smart & Sherlock, 1987). High nickel levels in flour may also originate from contamination during milling. In addition, fats can contain nickel, probably owing to the use of nickel catalysts in commercial hydrogenation. Margarine normally contains less than 0.2 mg/kg, but levels up to 6 mg/kg have been found (Grandjean, 1984).

Table 16. Nickel content (mg/kg) in foods in the average Danish diet[a]

Food	No. of samples	Range	Mean
Milk products			
Full milk	63	BDL[b]-0.13	0.02
Yogurt	3	0.004-0.03	0.01
Cream	3	0.01-0.04	0.03
Cheese	25	0.02-0.34	0.10
Meat, fish, eggs			
Beef	32	0.01-0.03	0.02
Pork	20	< 0.02-0.02	0.02
Chicken	9	0.02-0.24	0.11
Lamb	12	< 0.02-0.02	0.02
Liver, kidney	108	0-0.94	0.11
Fish	658	0.005-0.303	0.04
Egg	30	0.01-0.35	0.05
Roots and vegetables			
Potatoes	45	BDL-0.44	0.14
Carrots	17	< 0.01-0.16	0.04
Celery root	8	0.04-0.1	0.06
Beetroot	7	0.01-0.3	0.12
Cabbage	31	0.01-0.63	0.17
Cauliflower	5	0.03-1.0	0.3

Table 16 (contd)

Food	No. of samples	Range	Mean
Roots and vegetables (contd)			
Kale	2	0.15-0.24	0.20
Lettuce	21	BDL-1.4	0.36
Spinach	15	0.02-2.99	0.52
Asparagus	1	-	0.42
Cucumber	8	0.01-0.11	0.04
Tomatoes	21	0.01-0.25	0.07
Peas	24	0.13-0.8	0.42
Fruits			
Apples	11	BDL-0.03	0.01
Pears	10	0.07-0.42	0.14
Plums	10	0.03-0.20	0.12
Currants	13	0.01-0.2	0.06
Strawberries	9	0.03-0.08	0.05
Rhubarb	10	0.01-0.22	0.13
Grapes	4	0.01-0.04	0.02
Raisins	3	0.02-0.04	0.03
Citrus fruits	3	0.01-0.04	0.03
Bananas	4	0.01-0.03	0.02
Canned fruits	65	0.02-1.36	0.31
Juice	11	0.01-0.17	0.04
Meal, grain and bread			
Wheat flour	32	0.03-0.3	0.13
Rye flour	15	0.03-0.3	0.1
Oatmeal	18	0.80-4.7	1.76
Rice	16	0.08-0.45	0.21
Other			
Butter	4	0.03-0.2	0.1
Margarine	13	0.2-2.5	0.34
Sugar	22	0.01-0.09	0.05

[a] From Grandjean *et al.* (1989)
[b] BDL, below detection limit [not specified]

Stainless-steel kitchen utensils have been shown to release nickel into acid solutions, especially during boiling (Christensen & Möller, 1978). The amount of nickel liberated depends on the composition of the utensil, the pH of the food and the length of contact. The average contribution of kitchen utensils to the oral intake of nickel is unknown, but they could augment alimentary exposure by as much as 1 mg/day (Grandjean *et al.*, 1989).

A study of hospital diets in the USA showed that the general diet contained 160 μg/day, and special diets varied by less than 40% from this level (Myron *et al.*, 1978). A recent study (Nielsen & Flyvholm, 1984) suggested a daily intake of 150 μg in the average Danish diet. Knutti and Zimmerli (1985) found dietary intakes in Switzerland of 73 ± 9 μg in a restaurant, 83 ± 9 μg in a hospital, 141 + 33 μg in a vegetarian restaurant and 142 ± 20 μg in a military canteen. The mean nickel intake in the UK in 1981-84 was 140-150 μg/day (Smart & Sherlock, 1987).

(*h*) *Humans tissues and secretions*

The estimated average body burden of nickel in adults is 0.5 mg/70 kg (7.4 μg/kg bw). In post-mortem tissue samples from adults with no occupational or iatrogenic exposure to nickel compounds, the highest nickel concentrations were found in lung, bone, thyroid and adrenals, followed by kidney, heart, liver, brain, spleen and pancreas in diminishing order (Seemann *et al.*, 1985; Sunderman, 1986b; Raithel, 1987; Raithel *et al.*, 1987; Rezuke *et al.*, 1987; Kollmeier *et al.*, 1988; Raithel *et al.*, 1988). Reference values for nickel concentrations in autopsy tissues from nonexposed persons are listed in Table 17.

The mean nickel concentration in lung tissues from 39 nickel refinery workers autopsied during 1978-84 was 150 (1-1344) μg/g dry weight. Workers employed in the roasting and smelting department had an average nickel concentration of 333 (7-1344) μg/g, and those who had worked in the electrolysis department had an average nickel concentration of 34 (1-216) μg/g dry weight. Lung tissue from 16 persons who were not connected with the refinery contained an average level of 0.76 (0.39-1.70) μg/g dry weight (Andersen & Svenes, 1989).

The concentrations of nickel in body fluids have diminished substantially over the past ten years as a consequence of improved analytical techniques, including better procedures to minimize nickel contamination during collection and assay. Concentrations of nickel in human body fluids and faeces are given in Table 18 (see also Sunderman, 1986b; Sunderman *et al.*, 1986a).

(*i*) *Iatrogenic exposures*

Potential iatrogenic sources of exposure to nickel are dialysis treatment, leaching of nickel from nickel-containing alloys used as prostheses and implants and contaminated intravenous medications (for review, see Grandjean, 1984; Sunderman *et al.*, 1986a).

Table 17. Concentrations of nickel in human autopsy tissues

Tissue	No. of subjects	Nickel concentration				Reference
		ng/g wet weight		ng/g dry weight		
		Mean±SD	Range	Mean±SD	Range	
Lung	4	16 ± 8	8-24	86 ± 56	33-146	Rezuke *et al.* (1987)
	8	119 ± 50	48-221	-	-	
	9	-	-	132 ± 99	50-290	
	41	7 ± 10	< 1-70	-	-	
	9	18 ± 12	7-46	173 ± 94	71-371	
	15	-	-	180 ± 105	43-361	Seemann *et al.* (1985)
	70	137 ± 187	-	754 ± 1010	-	Kollmeier *et al.* (1988)
	30	20-40[a]	8-120[a]	107-195[a]	42-600[a]	Raithel *et al.* (1988)
	16	-	-	760 ± 390	390-1700	Andersen & Svenes (1989)
Kidney	8	11 ± 4	7-15	-	-	Rezuke *et al.* (1987)
	6	-	-	125 ± 54	50-120	
	36	14 ± 27	< 1-165	-	-	
	10	9 ± 6	3-25	62 ± 43	19-171	
	18	-	-	34 ± 22	< 5-84	Seemann *et al.* (1985)
Liver	4	9 ± 3	5-13	32 ± 12	21-48	Rezuke *et al.* (1987)
	8	8 ± 2	6-11	-	-	
	10	10 ± 7	8-21	50 ± 31	11-102	
	23	-	-	18 ± 21	< 5-86	Seemann *et al.* (1985)
Heart	4	6 ± 2	4-8	23 ± 6	16-30	Rezuke *et al.* (1987)
	8	7 ± 2	4-9	-	-	
	9	8 ± 5	1-14	54 ± 40	10-110	
Spleen	22	-	-	23 ± 20	< 5-85	Seemann *et al.* (1985)
	10	7 ± 5	1-15	37 ± 31	9-95	Rezuke *et al.* (1987)

[a] Range of median values and 68th percentile of range on the basis of 600 lung specimens from 30 autopsies

Table 18. Nickel concentrations in specimens from healthy, unexposed adults[a]

Specimen	Mean ± SD	Range	Units
Whole blood	0.34 ± 0.28	<0.05-1.05	μg/l
Serum	0.28 ± 0.24	<0.05-1.08	μg/l
Urine (spot collection)	2.0 ± 1.5	0.5-6.1	μg/l
	2.0 ± 1.5	0.4-6.0	μg/g creatinine
	2.8 ± 1.9	0.5-8.8	μg/l[b]
Urine (24-h collection)	2.2 ± 1.2	0.7-5.2	μg/l
	2.6 ± 1.4	0.5-6.4	μg/day
Faeces (3-day collection)	14.2 ± 2.7	10.8-18.7	μg/g (dry weight)
	258 ± 126	80-540	μg/day

[a] From Sunderman *et al.* (1986a)
[b] Factored to specific gravity = 1.024

Hypernickelaemia has been observed in patients with chronic renal disease who are maintained by extracorporeal haemodialysis or peritoneal dialysis (Table 19; Linden *et al.*, 1984; Drazniowsky *et al.*, 1985; Hopfer *et al.*, 1985; Savory *et al.*, 1985; Wills *et al.*, 1985). In one severe incident, water from a nickel-plated stainless-steel water-heater contaminated the dialysate to approximately 250 μg/l, resulting in plasma nickel levels of 3000 μg/l and acute nickel toxicity (Webster *et al.*, 1980). Even during normal operation, the average intravenous uptake of nickel may be 100 μg per dialysis (Sunderman, 1983a).

Nickel-containing alloys may be implanted in patients as joint prostheses, plates and screws for fractured bones, surgical clips and steel sutures (Grandjean, 1984). Corrosion of these prostheses and implants can result in accumulation of alloy-specific metals in the surrounding soft tissues and in release of nickel to the extracellular fluid (Sunderman *et al.*, 1986a, 1989a).

High concentrations of nickel have been reported in human albumin solutions prepared by six manufacturers for intravenous infusion. In three lots that contained 50 g/l albumin, the average nickel concentration was 33 μg/l (range, 11-17 μg/l); in nine lots that contained 250 g/l albumin, the average nickel concentration was 83 μg/l (range, 26-222 μg/l) (Leach & Sunderman, 1985). Meglumine diatrizoate ('Renografin-76'), an X-ray contrast medium, tends to be contaminated with nickel. Seven lots of this preparation (containing 760 g/l diatrizoate) contained

Table 19. Nickel concentrations in dialysis fluids and in serum specimens from patients with chronic renal disease (CRD)[a]

Region and patients	No. of subjects	Ni conc. in dialysis fluid (μg/l)	Serum Ni concentration (μg/l)	
			Pre-dialysis	Post-dialysis
USA				
Healthy controls	30		0.3 ± 0.2	
Non-dialysed CRD patients	7		0.6 ± 0.3	
CRD patients on haemodialysis				
Hospital A	40	0.82	6.2 ± 1.8	7.2 ± 2.2
Hospital B	9	0.40-0.42	3.9 ± 2.0	5.2 ± 2.5
Hospital C	10	0.68	3.0 ± 1.3	3.7 ± 1.3
USA				
Healthy controls	50		0.4 ± 0.2	
CRD patients on haemodialysis	28		3.7 ± 1.5	
UK and Hong Kong				
Healthy controls	71		1.0 (<0.6-3.0)	
Non-dialysed CRD patients	31		1.6 (<0.6-3.6)	
CRD patients on haemodialysis				
Hospital A	25	2-3	8.6 (0.6-16.6)	8.8 (3.0-21.4)
Hospital B	16		2.9 (1.8-4.0)	3.4 (2.2-5.4)
CRD patients on peritoneal dialysis	13	2-3	8.6 (5.4-11.4)	

[a] From Sunderman *et al.* (1986a)

nickel at 144 ± 44 μg/l. Serum nickel concentrations in 11 patients who received intra-arterial injections of 'Renografin-76' (164 ± 10 ml per patient [giving 19.1 ± 4.0 μg Ni per patient]) for coronary arteriography increased from a pre-injection level of 1.33 μg/l (range, 0.11-5.53 μg/l) to 2.95 μg/l (range, 1.5-7.19 μg/l) 15 min post-injection. Serum levels remained significantly elevated for 4 h and returned to baseline levels only 24 h post-injection (Leach & Sunderman, 1987).

(*j*) *Regulatory status and guidelines*

Occupational exposure limits for nickel in various forms are given in Table 20.

Table 20. Occupational exposure limits for airborne nickel in various forms[a]

Country or region	Year	Nickel species	Concentration (mg/m³)	Interpretation[b]
Belgium	1987	Nickel metal and insoluble nickel compounds (as Ni)	0.1	TWA
		Nickel carbonyl (as Ni)	0.35	TWA
Brazil	1987	Nickel carbonyl (as Ni)	0.28	TWA
Chile	1987	Soluble nickel compounds (as Ni)	0.08	TWA
China	1987	Nickel carbonyl (as Ni)	0.001	TWA
Denmark	1988	Nickel metal	0.5	TWA
		Nickel carbonyl	0.007	TWA
		Soluble nickel compounds (as Ni)	0.1	TWA
		Insoluble nickel compounds (as Ni)	1	TWA
Finland	1987	Nickel metal	1	TWA
		Nickel carbonyl	0.007	TWA
		Soluble nickel compounds (as Ni)	0.1	TWA
France	1986	Nickel sulfide (as Ni)	1	TWA
German Democratic Republic	1987	Nickel compounds (as Ni)	0.25	TWA
		Nickel carbonyl (as Ni)	0.01	TWA
		Nickel compounds (as Ni)	0.5	STEL
		Nickel carbonyl (as Ni)	0.03	STEL
Hungary	1987	Nickel compounds (as Ni)	0.005	TWA/STEL
		Nickel carbonyl (as Ni)	0.007	TWA/STEL
India	1987	Nickel carbonyl (as Ni)	0.35	TWA
Indonesia	1987	Nickel metal and insoluble nickel compounds (as Ni)	1	TWA
		Nickel carbonyl (as Ni)	0.007	TWA
Italy	1987	Nickel carbonyl (as Ni)	0.007	TWA
Japan	1987	Nickel	1	TWA
		Nickel carbonyl (as Ni)	0.007	TWA
Mexico	1987	Nickel metal and insoluble nickel compounds (as Ni)	1	TWA
		Soluble nickel compounds (as Ni)	0.1	TWA
		Nickel carbonyl (as Ni)	0.35	TWA

Table 20 (contd)

Country or region	Year	Nickel species	Concentration (mg/m³)	Interpretation[b]
Netherlands	1986	Nickel	1	TWA
		Soluble nickel compounds (as Ni)	0.1	TWA
		Nickel carbonyl (as Ni)	0.35	TWA
Poland	1987	Nickel carbonyl (as Ni)	0.007	TWA
Romania	1987	Nickel carbonyl (as Ni)	0.002	TWA
		Nickel carbonyl (as Ni)	0.005	Ceiling
Sweden	1987	Nickel metal	0.5	TWA
		Nickel carbonyl	0.007	TWA
		Nickel subsulfide	0.01	TWA
		Other nickel compounds (as Ni)	0.1	TWA
Switzerland	1987	Nickel metal and insoluble nickel compounds (as Ni)	0.5	TWA
		Soluble nickel compounds (as Ni)	0.05	TWA
Taiwan	1987	Nickel carbonyl (as Ni)	0.35	TWA
UK	1987	Nickel and insoluble nickel compounds (as Ni)	1	TWA
		Soluble nickel compounds (as Ni)	0.1	TWA
		Soluble nickel compounds (as Ni)	0.3	STEL (10 min)
		Insoluble nickel compounds (as Ni)	3	STEL (10 min)
		Nickel carbonyl (as Ni)	0.35	TWA
USA				
ACGIH	1988	Nickel metal; nickel sulfide roasting, fume and dust (as Ni)	1	TWA
		Soluble compounds (as Ni)	0.1	TWA
		Nickel carbonyl	0.35	TWA
NIOSH	1988	Nickel, inorganic compounds (as Ni)	0.015	TWA
		Nickel carbonyl	0.007	TWA
OSHA	1987	Metallic nickel	1	TWA
		Nickel carbonyl	0.007	TWA
		Soluble nickel compounds (as Ni)	0.1	TWA

Table 20 (contd)

Country or region	Year	Nickel species	Concentration (mg/m³)	Interpretation[b]
USSR	1987	Nickel metal and insoluble nickel compounds (as Ni)	0.5	MAC
		Nickel carbonyl (as Ni)	0.0005	MAC
		Nickel monoxide, oxide, sulfide	0.5	MAC

[a] From Arbeidsinspectie, 1986; Institut National de Recherche et de Sécurité, 1986; National Institute for Occupational Safety and Health (NIOSH), 1988; Arbetarskyddsstyrelsens, 1987; Cook, 1987; Health and Safety Executive, 1987; Työsuojeluhallitus, 1987; US Occupational Safety and Health Administration (OSHA), 1987; American Conference of Governmental Industrial Hygienists (ACGIH), 1988; Arbejdstilsynet, 1988

[b] TWA, time-weighted average; STEL, short-term exposure limit; MAC, maximum allowable concentration

2.4 Analysis

Typical methods for the analysis of nickel in air, water, food and biological materials are summarized in Table 21. A method has been developed for classifying nickel in airborne dust samples into four species — 'water-soluble', 'sulfidic', 'metallic' and 'oxidic' — on the basis of a sequential leaching procedure (Blakeley & Zatka, 1985; Zatka, 1987, 1988; Zatka *et al.*, undated).

Atomic absorption spectrometry and differential pulse anodic stripping voltammetry (DPASV) are the most common methods for analysis of nickel in environmental and biological media. Air samples are collected on cellulose ester membrane filters, wet digested with nitric acid—perchloric acid and analysed by electrothermal atomic absorption spectrometry (EAAS) or inductively coupled argon plasma emission spectrometry (ICP) (National Institute for Occupational Safety and Health, 1984; Kettrup *et al.*, 1985). The National Institute for Occupational Safety and Health (1977b, 1981) has recommended standard procedures for personal air sampling and analysis of nickel. The routine procedure does not permit identification of individual nickel compounds.

Assessment of individual nickel compounds, especially as components of complex mixtures, necessitates procedures such as X-ray diffraction and would not be feasible for routine monitoring. Sampling and analytical methods used to monitor air, water and soil have been summarized (US Environmental Protection Agency, 1986).

Nickel concentrations in blood, serum or urine are used as biological indicators of exposure to or body burden of nickel. Biological monitoring as a part of biomedical surveillance has been evaluated in several reviews (Aitio, 1984; Norseth,

Table 21. Methods for the analysis of nickel

Sample matrix	Sample preparation	Assay procedure[a]	Sensitivity/detection limit	Reference
Air	Collect on cellulose ester membrane filter; digest with nitric acid and perchloric acid	AAS	–	National Institute for Occupational Safety and Health (1981)
	Collect on cellulose acetate membrane filter; digest with nitric acid and hydrochloric acid	AAS	1 μg absolute; 10 μg/m³ (sample volume, 0.1 m³)	Hauptverband der gewerblichen Berufsgenossenschaften (1981)
	Collect on cellulose ester membrane filter; digest with nitric acid and perchloric acid	ICP	1.5 μg/sample	National Institute for Occupational Safety and Health (1984)
	Collect on cellulose ester membrane filter; digest with nitric acid	AAS	20 ng/m³ (sample volume, 1.5 m³)	Kettrup *et al.* (1985)
Water	Chelate; extract with ammonium pyrrolidine dithiocarbamate: methyl isobutyl ketone	AAS	0.04 μg/l	McNeely *et al.* (1972)
	Filter; irradiate with ultraviolet	DPASV (dimethylglyoxime-sensitized)	1 ng/l	Pihlar *et al.* (1981)
	Chelate; extract with ammonium pyrrolidine dithiocarbamate: methyl isobutyl ketone	EAAS	0.2 μg/l	Sunderman (1986b)
Food	Digest with acid	AAS	–	Evans *et al.* (1978)
	Wet digest with nitric acid, hydrogen peroxide and sulfuric acid	DPASV (dimethylglyoxime-sensitized)	1 ng/l digestion solution	Pihlar *et al.* (1981)
	Dry ash	DPASV (dimethylglyoxime-sensitized)	5 ng/sample	Meyer & Neeb (1985)
	Dry ash, chelate with sodium(ditrifluorethyl)dithiocarbamate	Chelate–GC	100 ng/sample	Meyer & Neeb (1985)
Blood	Wet digest with nitric acid, hydrogen peroxide and sulfuric acid	DPASV (dimethylglyoxime-sensitized)	1 ng/l digestion solution	Pihlar *et al.* (1981)

Table 21 (contd)

Sample matrix	Sample preparation	Assay procedure[a]	Sensitivity/detection limit	Reference
Serum/whole blood	Digest with nitric acid; heat	EAAS (Zeeman)	0.05 μg/l serum 0.1 μg/l whole blood	Sunderman *et al.* (1984a)
Body fluids/ tissues	Digest with nitric acid, perchloric acid and sulfuric acid; chelate; extract with ammonium pyrrolidine dithiocarbamate: methyl isobutyl ketone	EAAS	0.2 μg/l body fluids 0.4 μg/kg tissues	Sunderman (1986b)
Tissues	Homogenize; digest with nitric acid, perchloric acid and sulfuric acid	EAAS (Zeeman)	0.01 μg/g dry wt	Sunderman *et al.* (1985a)
	Digest with nitric acid and sulfuric acid	EAAS (Zeeman)	0.8 μg/g wet wt	Raithel *et al.* (1987)
Serum/urine	Digest with nitric acid, perchloric acid and sulfuric acid; chelate; extract with ammonium pyrrolidine dithiocarbamate: methyl isobutyl ketone	EAAS	-	Brown *et al.* (1981)
Urine	Chelate; extract with ammonium pyrrolidine dithiocarbamate: methyl isobutyl ketone	EAAS	0.5 μg/l	Schaller & Zober (1982)
	Digest with nitric acid, perchloric acid and sulfuric acid	DPASV	1 μg/l	Schramel *et al.* (1985)
	Chelate; extract with hexamethylene ammonium: hexamethylene dithiocarbamate: diisopropylketone	AAS	0.2 μg/l	Angerer & Schaller (1985)
	Dilute with nitric acid	EAAS (Zeeman)	0.5 μg/l	Sunderman *et al.* (1986b)
	Dilute directly with nitric acid	EAAS	1.2 μg/l	Kiilunen *et al.* (1987)

[a] AAS, flameless atomic absorption spectrometry; ICP, inductively coupled argon plasma spectrometry; DPASV, differential pulse anodic stripping voltammetry; EAAS, electrothermal atomic absorption spectrometry; GC, gas chromatography

1984; Sunderman *et al.*, 1986a). Choice of specimen, sampling strategies, specimen collection, transport, storage and contamination control are of fundamental importance for an adequate monitoring programme (Sunderman *et al.*, 1986a). As discussed in recent reviews (Stoeppler, 1980; Schaller *et al.*, 1982; Stoeppler, 1984a,b; Sunderman *et al.*, 1986a, 1988a), EAAS and DPASV are practical, reliable techniques that furnish the requisite sensitivity for measurements of nickel concentrations in biological samples. The detection limits for determination of nickel by EAAS with Zeeman background correction are approximately 0.45 µg/l for urine, 0.1 µg/l for whole blood, 0.05 µg/l for serum or plasma, and 10 ng/g (dry wet) for tissues, foods and faeces (Andersen *et al.*, 1986; Sunderman *et al.*, 1986a,b; Kiilunen *et al.*, 1987; Angerer & Heinrich-Ramm, 1988). An EAAS procedure for the determination of nickel in serum and urine, which was developed on the basis of collaborative interlaboratory trials involving clinical biochemists in 13 countries, has been accepted as a reference method by the International Union of Pure and Applied Chemists (Brown *et al.*, 1981). This procedure, with additional applications for analysis of nickel in biological matrices, water and intravenous fluids, has also been accepted as a reference method by the IARC (Sunderman, 1986b). A new working method based on EAAS and Zeeman background correction for the analysis of nickel in serum, whole blood, tissues, urine and faeces has been recommended (Sunderman *et al.*, 1986a,b, 1988a). Sample preparation depends on the specimen and involves acid digestion for tissue and faeces, protein precipitation with nitric acid and heat for serum and whole blood, and simple acidification for urine.

Greater sensitivity can be achieved with DPASV analysis using a dimethylglyoxime-sensitized mercury electrode; this method has been reported to have a detection limit of 1 ng/l for determination of nickel in biological media (Flora & Nieboer, 1980; Pihlar *et al.*, 1981; Ostapczuk *et al.*, 1983). However, DPASV techniques are generally more cumbersome and time consuming than EAAS procedures. Isotope dilution mass spectrometry provides the requisite sensitivity, specificity and precision for determination of nickel (Fassett *et al.*, 1985) but has not yet been used to analyse nickel in biological samples.

Nickel carbonyl has been measured in air and exhaled breath by gas chromatography and chemiluminescence (Sunderman *et al.*, 1968; Stedman *et al.*, 1979).