NICKEL AND NICKEL COMPOUNDS

Nickel and nickel compounds were considered by previous IARC Working Groups, in 1972, 1975, 1979, 1982 and 1987 (IARC, 1973, 1976, 1979, 1982, 1987). Since that time, new data have become available, and these are included in the present monograph and have been taken into consideration in the evaluation.

1. Chemical and Physical Data

The list of nickel alloys and compounds given in Table 1 is not exhaustive, nor does it necessarily reflect the commercial importance of the various nickel-containing substances, but it is indicative of the range of nickel alloys and compounds available, including some compounds that are important commercially and those that have been tested in biological systems. A number of intermediary compounds occur in refineries which cannot be characterized and are not listed.

1.1 Synonyms, trade names and molecular formulae of nickel and selected nickel-containing compounds

Table 1. Synonyms (Chemical Abstracts Service names are given in bold), trade names and atomic or molecular formulae or compositions of nickel, nickel alloys and selected nickel compounds

Chemical name	Chem. Abstr. Serv. Reg. Number[a]	Synonyms and trade names	Formula	Oxidation state[b]
Metallic nickel and nickel alloys				
Nickel	7440-02-0 (8049-31-8; 17375-04-1; 39303-46-3; 53527-81-4; 112084-17-0)	C.I. 77775; N1; Ni 233; Ni 270; Nickel 270; Nickel element; NP 2	Ni	0

Table 1 (contd)

Chemical name	Chem. Abstr. Serv. Reg. Number[a]	Synonyms and trade names	Formula	Oxidation state[b]
Ferronickel	11133-76-9 (11148-37-1; 12604-55-6)	**Iron alloy (base), Fe,Ni**; nickel alloy (non-base), Fe, Ni	Fe, Ni	0
Nickel aluminium alloys	61431-86-5 37187-84-1	**Raney nickel**; Raney alloy	NiAl	0
Nickel-containing steels[c]	12681-83-3	**Iron alloy (base)**; 21-6-9; 21-6-9 alloy; Alloy 21-6-9; AMS 5656C; Armco 21-6-9; ASTM XM10; 21-6-9 austenitic steel; Nitronic 40; Nitronic 40 stainless steel; Pyromet 538; 21-6-9 Stainless steel; Stainless steel 21-6-9; 21-6-9 steel; Steel 21-6-9	Fe 60-69, Cr 18-21, Mn 8-10, Ni 5-7, Si 0-1, N 0.2-0.4, C 0-0.1, P 0-0.1	0
High nickel alloys[c]	12605-70-8	**ASTM B344-60Ni, 16 Cr**; Chromel C; 06Kh15N60; Kh15N60N; Nichrome; NiCr 60/15; PNKh; Tophet C	Ni 57-62, Fe 22-28, Cr 14-18, Si 0.8-1.6, Mn 0-1, C 0-0.2	0
	11121-96-3	AFNOR ZFeNC45-36; AISI 332; Alloy 800; **ASTM B163-800**; DIN 1.4876; IN 800; Incoloy alloy 800; JIS NCF 800; NCF Steel; NCF 800 HTB; Pyromet 800; Sanicro 31; Thermax 4876; TIG N800	Fe 39-47, Ni 30-35; Cr 19-23, Mn 0-1.5, Si 0-1; Cu 0-0.8; Al 0-0.6; Ti 0-0.6; C 0-0.1	0
	12675-92-2	**Haynes alloy No. 188**	Ni(Co)	0
	11105-19-4	Alloy 400; ASTM B127; **ASTM B164-A**; H3261; Monel alloy 400; Monel (NiCu30Fe)	Ni 63-70; Cu 25-37, Fe 0-2.5, Mn 0-2, Si 0-0.5, C 0-0.3	0
Nickel oxides and hydroxides				
Nickel hydroxide (amorphous	12054-48-7 11113-74-9)	Nickel dihydroxide; nickel (II) hydroxide; nickel (2+) hydroxide; **nickel hydroxide ($Ni(OH)_2$)**; nickelous hydroxide	$Ni(OH)_2$	+2
Nickel monoxide	1313-99-1 11099-02-8	Black nickel oxide[d]; green nickel oxide; mononickel oxide; nickel monooxide; nickelous oxide; **nickel oxide (NiO)**; nickel (II) oxide; nickel (2+) oxide	NiO	+2
	34492-97-2	**Bunsenite (NiO)**		
Nickel trioxide	1314-06-3 (34875-54-2)	Black nickel oxide[d]; dinickel trioxide; nickelic oxide; nickel oxide; nickel (III) oxide; **nickel oxide (Ni_2O_3)**; nickel peroxide; nickel sesquioxide	Ni_2O_3	+3
Nickel sulfides				
Nickel disulfide	12035-51-7	**Nickel sulfide (NiS_2)**	NiS_2	+4
	12035-50-6	**Vaesite (NiS_2)**	NiS_2	+4

Table 1 (contd)

Chemical name	Chem. Abstr. Serv. Reg. Number[a]	Synonyms and trade names	Formula	Oxidation state[b]
Nickel sulfide (amorphous	16812-54-7 (1344-49-6) 11113-75-0)	Mononickel monosulfide; nickel monosulfide; nickel monosulfide (NiS); nickelous sulfide; nickel (II) sulfide; nickel (2+) sulfide; **nickel sulfide (NiS)**	NiS	+2
	1314-04-1 (61026-96-8)	**Millerite (NiS)**	NiS	+2
Nickel subsulfide	12035-72-2	Nickel sesquisulfide; nickel subsulfide (Ni_3S_2); **nickel sulfide (Ni_3S_2)**; trinickel disulfide	Ni_3S_2	NS
	12035-71-1	**Heazlewoodite (Ni_3S_2)**; Khizlevudite		
Pentlandite	53809-86-2	Pentlandite ($Fe_9Ni_9S_{16}$)	$Fe_9Ni_9S_{16}$	NS
	12174-14-0	Pentlandite	$(Fe_{0.4\text{-}0.6}Ni_{0.4\text{-}0.6})_9S_8$	NS
Nickel salts				
Nickel carbonate	3333-67-3	**Carbonic acid, nickel (2+) salt (1:1)**; nickel carbonate (1:1); nickel (II) carbonate; nickel (2+) carbonate; nickel carbonate ($NiCO_3$); nickel (2+) carbonate ($NiCO_3$); nickel monocarbonate; nickelous carbonate	$NiCO_3$	+2
Basic nickel carbonates	12607-70-4 (63091-15-6)	Carbonic acid, nickel salt, basic; nickel carbonate hydroxide ($Ni_3(CO_3)(OH)_4$); **nickel, (carbonato(2-)) tetrahydroxytri-**	$NiCO_3.2Ni(OH)_2$	+2
	12122-15-5	**Nickel bis(carbonato(2-))hexahydroxypenta-**; nickel hydroxycarbonate	$2NiCO_3.3Ni(OH)_2$	+2
Nickel acetate	373-02-4 (17593-69-0)	**Acetic acid, nickel (2+) salt**; nickel (II) acetate; nickel (2+) acetate; nickel diacetate; nickelous acetate	$Ni(OCOCH_3)_2$	+2
Nickel acetate tetrahydrate	6018-89-9	**Acetic acid, nickel (+2) salt, tetrahydrate**	$Ni(OCOCH_3)_2.4H_2O$	+2
Nickel ammonium sulfates	15699-18-0	Ammonium nickel sulfate ($(NH_4)_2Ni(SO_4)_2$); nickel ammonium sulfate ($Ni(NH_4)_2(SO_4)_2$); **sulfuric acid, ammonium nickel (2+) salt (2:2:1)**	$Ni(NH_4)_2(SO_4)_2$	+2
Nickel ammonium sulfate hexahydrate	25749-08-0	Ammonium nickel sulfate ($(NH_4)_2Ni_2(SO_4)_3$); **sulfuric acid, ammonium nickel (2+) salt (3:2:2)**	$Ni_2(NH_4)_2(SO_4)_3$	+2

Table 1 (contd)

Chemical name	Chem. Abstr. Serv. Reg. Number[a]	Synonyms and trade names	Formula	Oxidation state[b]
	7785-20-8 (51287-85-5, 55526-16-4)	Ammonium nickel (2+) sulfate hexahydrate; ammonium nickel sulfate ($(NH_4)_2Ni(SO_4)_2$); diammonium nickel disulfate hexahydrate; diammonium nickel (2+) disulfate hexahydrate; diammonium nickel (II) disulfate hexahydrate; nickel ammonium sulfate ($Ni(NH_4)_2(SO_4)_2$) hexahydrate; nickel diammonium disulfate hexahydrate; **sulfuric acid, ammonium nickel (2+) salt (2:2:1), hexahydrate**	$Ni(NH_4)_2(SO_4)_2.6H_2O$	+2
Nickel chromate	14721-18-7	**Chromium nickel oxide ($NiCrO_4$)**; nickel chromate ($NiCrO_4$); nickel chromium oxide ($NiCrO_4$)	$NiCrO_4$	+2
Nickel chloride	7718-54-9 (37211-05-5)	Nickel (II) chloride; nickel (2+) chloride; **nickel chloride ($NiCl_2$)**; nickel dichloride; nickel dichloride ($NiCl_2$); nickelous chloride	$NiCl_2$	+2
Nickel chloride hexahydrate	7791-20-0	**Nickel chloride ($NiCl_2$) hexahydrate**	$NiCl_2.6H_2O$	+2
Nickel nitrate hexahydrate	13478-00-7	Nickel (2+) bis(nitrate)hexahydrate; nickel dinitrate hexahydrate; nickel (II) nitrate hexahydrate; nickel nitrate ($Ni(NO_3)_2$) hexahydrate; nickelous nitrate hexahydrate; **nitric acid, nickel (2+) salt, hexahydrate**	$Ni(NO_3)_2.6H_2O$	+2
Nickel sulfate	7786-81-4	Nickel monosulfate; nickelous sulfate; nickel sulfate (1:1); nickel (II) sulfate; nickel (2+) sulfate; nickel (2+) sulfate (1:1); nickel sulfate ($NiSO_4$); **sulfuric acid, nickel (2+) salt (1:1)**	$NiSO_4$	+2
Nickel sulfate hexahydrate	10101-97-0	**Sulfuric acid, nickel (2+) salt (1:1), hexahydrate**	$NiSO_4.6H_2O$	+2
Nickel sulfate heptahydrate	10101-98-1	**Sulfuric acid, nickel (2+) salt (1:1), heptahydrate**	$NiSO_4.7H_2O$	+2
Other nickel compounds				
Nickel carbonyl	13463-39-3 (13005-31-7, 14875-95-7, 36252-60-5, 42126-46-5, 71327-12-3)	**Nickel carbonyl ($Ni(CO)_4$), (T-4)-**; nickel tetracarbonyl; tetracarbonylnickel; tetracarbonylnickel (0)	$Ni(CO)_4$	0

Table 1 (contd)

Chemical name	Chem. Abstr. Serv. Reg. Number[a]	Synonyms and trade names	Formula	Oxidation state[b]
Nickel antimonide	12035-52-8 (73482-18-5)	**Antimony compound with nickel (1:1)**; nickel antimonide (NiSb); nickel compound with antimony (1:1); nickel monoantimonide	NiSb	NS
	12125-61-0	**Breithauptite (SbNi)**	NiSb	NS
Nickel arsenides	27016-75-7 (12068-59-6 24440-79-7)	**Nickel arsenide (NiAs)**	NiAs	NS
	1303-13-5 (23292-74-2)	Nickeline; **nickeline (NiAs)**; nicolite	NiAs	NS
	12256-33-6	**Nickel arsenide ($Ni_{11}As_8$)**; nickel arsenide tetragonal	$Ni_{11}As_8$	NS
	12044-65-4	**Maucherite ($Ni_{11}As_8$)**; Placodine; Temiskamite	$Ni_{11}As_8$	NS
	12255-80-0	**Nickel arsenide (Ni_5As_2)**; nickel arsenide hexagonal	Ni_5As_2	NS
Nickel selenide	1314-05-2	Nickel monoselenide; **nickel selenide (NiSe)**	NiSe	NS
	12201-85-3	Maekinenite; **Makinenite (NiSe)**	NiSe	NS
Nickel subselenide	12137-13-2	**Nickel selenide (Ni_3Se_2)**	Ni_3Se_2	NS
Nickel sulfarsenide	12255-10-6	**Nickel arsenide sulfide (NiAsS)**	NiAsS	NS
	12255-11-7	**Gersdorffite (NiAsS)**	NiAsS	NS
Nickel telluride	12142-88-0	Nickel monotelluride; **nickel telluride (NiTe)**	NiTe	NS
	24270-51-7	**Imgreite (NiTe)**	NiTe	NS
Nickel titanate	12035-39-1	Nickel titanate(IV); nickel titanate ($NiTiO_3$); **nickel titanium oxide ($NiTiO_3$)**; nickel titanium trioxide	$NiTiO_3$	+2
Chrome iron nickel black spinel	71631-15-7	CI 77504; **CI Pigment Black 30**; DCMA-13-50-9; nickel iron chromite black spinel	$(Ni,Fe)(CrFe)_2O_4$	NS

Table 1 (contd)

Chemical name	Chem. Abstr. Serv. Reg. Number[a]	Synonyms and trade names	Formula	Oxidation state[b]
Nickel ferrite brown spinel	68187-10-0	**CI Pigment Brown 34**; DCMA-13-35-7	$NiFe_2O_4$	NS
Nickelocene	1271-28-9 (51269-44-4)	Bis(η5-2,4-cyclopentadien-1-yl)nickel; di-π-cyclopentadienylnickel; dicyclopentadienylnickel; nickel, bis(η5-2,4-cyclopentadien-1-yl)-; nickel, di-π-cyclopentadienyl-	π-$(C_5H_5)_2Ni$	+2

[a]Replaced CAS Registry numbers are given in parentheses.

[b]NS, not specified; mixed formal oxidation states of nickel and/or complex coordination in the solid form

[c]Chemical Abstracts Service Registry lists hundreds of these compounds; some typical examples are given.

[d]In commercial usage, 'black nickel oxide' usually refers to the low-temperature crystalline form of nickel monoxide, but nickel trioxide (Ni_2O_3), an unstable oxide of nickel, may also be called 'black nickel oxide'.

1.2 Chemical and physical properties of the pure substance

Known physical properties of some of the nickel compounds considered in this monograph are given in Table 2. Data on solubility refer to saturated solutions of the compound in water or other specified solvents. Nickel compounds are sometimes classed as soluble or insoluble in water; such a classification can be useful in technical applications of the various compounds but may not be relevant to determining their biological activity. Water-soluble nickel compounds include nickel chloride (642 g/l at 20°C) and nickel sulfate (293 g/l at 20°C), while nickel monosulfide (3.6 mg/l at 18°C) and nickel carbonate (93 mg/l at 25°C) are classed as insoluble (Weast, 1986). Compounds with solubilities towards the middle of this range are not easily classified in this way. Different forms of nominally the same nickel compound can have very different solubilities in a given solvent, and particle size, hydration and crystallinity can markedly affect the rate of dissolution. For example, anhydrous nickel sulfate and the hexahydrate are similarly soluble in unbuffered water (Grandjean, 1986), but the hexahydrate dissolves several orders of magnitude faster than the anhydrate.

Table 2. Physical properties of nickel and nickel compounds[a]

Chemical name	Atomic/ molecular weight	Melting-point (°C)	Boiling-point (°C)	Typical physical description	Solubility
Metallic nickel and nickel alloys					
Nickel	58.69	1455	2730	Lustrous white, hard ferromagnetic metal[b] or grey powder	Soluble in dilute nitric acid; slightly soluble in hydrochloric and sulfuric acids; insoluble in cold or hot water
Ferronickel alloy	–	–	–	Grey solid[c]	Combined properties of metallic iron and nickel, ammonia and alkali hydroxides
Nickel oxides and hydroxides					
Nickel hydroxide	92.70	230	–	Green crystals or amorphous solid	Nearly insoluble (0.13 g/l)[d] in cold water; soluble in acid, ammonium hydroxide
Nickel monoxide	74.69	1984	–	Grey, black or green[c] powder	Insoluble in water (0.0011 g/l at 20°C); soluble in acid, ammonium hydroxide[d]
Nickel sulfides					
Nickel disulfide	122.81	Decomposes at 400[d]	–	Black crystals[c] or powder	Insoluble in water[d]
Nickel sulfide					
Amorphous	90.75	797	–	Black crystals or powder	Nearly insoluble (0.0036 g/l, β-form)[d] in water at 18°C; soluble in aqua regia, nitric acid, potassium hydrosulfide; slightly soluble in acids
α-form	90.75	–	–	–	
β-form	90.75	–	–	Dark-green crystals[c]	
Nickel subsulfide (α-form)	240.19	790	–	Lustrous pale-yellowish or bronze metallic crystals	Insoluble in cold water; soluble in nitric acid

Table 2 (contd)

Chemical name	Atomic/ molecular weight	Melting-point (°C)	Boiling-point (°C)	Typical physical description	Solubility
Nickel salts					
Nickel acetate	176.78	Decom-poses	16.6	Dull-green crystals	Soluble in water (166 g/l at 20°C)[d]; insoluble in ethanol
Nickel acetate tetra-hydrate	248.84	Decom-poses	16	Dull-green crystals	Soluble in water (160 g/l at 20°C)[d]; soluble in dilute ethanol
Nickel ammonium sulfates					
Hexahydrate	394.94	–	–	–	Soluble in water (104 g/l at 20°C)[d]
Anhydrous	286.88	Decom-poses[e]	–	Green crystals[e]	Soluble in water (300 g/l at 20°C)[d]; less soluble in ammonium sulfate solution; insoluble in ethanol[e]
Nickel carbonate	118.70	Decom-poses	–	Light-green crystals	Nearly insoluble (0.093 g/l) in water at 25°C; insoluble in hot water, soluble in acids
Nickel hydroxycarbonate	587.67	Decom-poses	–	Light-green crystals or brown powder[e] or wet green paste	Insoluble in cold water; decomposes in hot water; soluble in acids
Nickel chlorides					
Anhydrous	129.60	1001	Sublimes at 973	Yellow deliquescent scales	Soluble in water at 20°C (642 g/l) and at 100°C (876 g/l); soluble in ethanol, ammonium hydroxide; insoluble in nitric acid
Hexahydrate	237.70	–	–	Green deliquescent crystals	Soluble in water (2540 g/l at 20°C)[d]; very soluble in ethanol
Nickel chromate	174.71	–	–	Black crystals	Insoluble in water

Table 2 (contd)

Chemical name	Atomic/ molecular weight	Melting-point (°C)	Boiling-point (°C)	Typical physical description	Solubility
Nickel nitrate hexahydrate	290.79	56.7	Decomposes at 136.7	Green deliquescent crystals	Soluble in water (2385 g/l at 0°C), ammonium hydroxide and ethanol
Nickel sulfates					
Anhydrous	154.75	Decomposes at 848	–	Pale-green to yellow crystals	Soluble in water (293 g/l at 20°C); insoluble in ethanol and diethyl ether[d,e]
Hexahydrate	262.84	53.3	–	Blue or emerald-green crystals[e]	Soluble in water (625 g/l at 0°C); soluble in ethanol[d]
Heptahydrate	280.85	99	–	Green crystals	Soluble in water (756 g/l at 20°C); soluble in ethanol[d]
Other nickel compounds					
Nickel antimonide	180.44	1158	Decomposes at 1400	Light-copper to mauve crystals[c]	Insoluble in water[d]
Nickel arsenides NiAs	133.61	968	–	Grey crystals[c]	Insoluble in hot or cold water, soluble in aqua regia
$Ni_{11}As_8$	1244.96	1000	–	Platinum-grey crystals	Insoluble in water[d]
Ni_5As_2	443.39	993	–	Grey crystals[c]	Insoluble in water[d]
Nickel carbonyl	170.73	-25	43	Colourless to yellow liquid	Nearly insoluble (0.18 g/l) in water at 9.8°C; soluble in aqua regia, ethanol, diethyl ether, benzene, nitric acid; insoluble in dilute acids or dilute alkali

Table 2 (contd)

Chemical name	Atomic/ molecular weight	Melting-point (°C)	Boiling-point (°C)	Typical physical description	Solubility
Nickelocene	188.88	171–173[e]	–	Dark-green crystals[e]	Soluble in most organic solvents; insoluble in water; decomposes in acetone, ethanol, diethyl ether
Nickel selenide (NiSe)	137.65	Red heat	–	White or grey crystals	Insoluble in water and hydrochloric acid; soluble in aqua regia, nitric acid
Nickel subselenide (Ni_3Se_2)	333.99	–	–	Green crystals[c]	Insoluble in water[d]
Nickel telluride	186.29	Decomposes at 600–900[d]	–	Grey crystals[c]	Insoluble in water; soluble in nitric acid, aqua regia, bromine water[d]
Nickel titanate	154.57	Decomposes at 1000	–	Yellow crystals[c]	Insoluble in water[d]

[a]From Weast (1986), unless otherwise specified; –, depending on composition

[b]From Windholz (1983)

[c]From Sunderman (1984)

[d]From Grandjean (1986)

[e]From Sax & Lewis (1987)

1.3 Technical products and impurities

This section does not include nickel-containing intermediates and by-products specific to nickel production and use, which are considered in section 2.

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

Ferronickel contains 20-50% nickel (Sibley, 1985). Other components include carbon (1.5-1.8%), sulfur (<0.3%), cobalt (<2%), silicon (1.8-4%), chromium (1.2-1.8%) and iron (balance of alloy). It is delivered as ingots or granules (ERAMET-SLN, 1986).

Pure unwrought *nickel* is available commercially in the form of cathodes, powder, briquets, pellets, rondelles, ingots and shot. Its chemical composition is >99% nickel, with carbon, copper, iron, sulfur and oxygen as impurities (Sibley, 1985). Metallic nickel undergoes surface oxidation in air; oxidation of finely divided nickel powder can result in the conversion of a large fraction of the metal to oxide upon prolonged storage (Cotton & Wilkinson, 1988).

Nickel-aluminium alloy (for the production of Raney nickel) is available as European Pharmacopoeia grade with the following typical analysis: nickel, 48-52%; aluminium, 48-52%; and chloride, 0.001% (Riedel-de Haën, 1986).

Nickel alloys can be categorized as nickel-chromium, nickel-chromium-cobalt, iron-nickel-chromium and copper-nickel alloys. Typical analyses are given in Table 3. Austenitic steels are the major group of *nickel-containing steels*. Typical compositions are given in Table 4.

(*b*) *Nickel oxides and hydroxides*

The temperature of formation of *nickel oxide* (up to 1045°C) determines the colour of the crystal (jet-black to apple green), the crystalline surface area and the nickel [III] content (<0.03-0.81% by weight). The temperature of formation may also affect the crystalline structure and the incidence of defects within it (Sunderman *et al.*, 1987; Benson *et al.*, 1988a).

Nickel monoxides are available commercially in different forms as laboratory reagents and as industrial products. Laboratory reagents are either green powder (Aldrich Chemical Co., Inc., 1988) or black powders; industrial products are either black powders, coarse particles (Sinter 75) or grey sintered rondelles (INCO, 1988; Queensland Nickel Sales Pty Ltd, 1989). Sinter 75 (76% Ni) contains about 22% oxygen and small amounts of copper (0.75%), iron (0.3%), sulfur (0.006%) and cobalt (1.0%) (Sibley, 1985). Sintered rondels (≥85% Ni) are formed by partially reducing a cylindrical pressing of granular nickel oxide to nickel metal. The degree of reduction achieved determines the nickel content of the finished rondel (Queensland Nickel Sales Pty Ltd, 1989).

Table 3. Elemental analyses of representative nickel alloys (weight %)[a]

Alloy	Ni	Cu	Cr	Co	Fe	Mo	W	Ta	Nb	Al	Ti	Mn	Si	C	Zr
Nickel–chromium															
Cast alloy 625	63.0	–	21.6	–	2.0	8.7	–	–	3.9	0.2	0.2	0.06	0.20	0.20	–
Hastelloy alloy X	47.0	–	22.0	1.5	18.5	9.0	0.6	–	–	–	–	0.50	0.50	0.10	–
Inconel alloy 617	54.0	–	22.0	12.5	–	9.0	–	–	–	1.0	–	–	–	0.07	–
Nickel–chromium–cobalt															
Haynes Alloy 1002	16.0	–	22.0	Bal	1.5	–	7.0	3.8	–	0.3	0.2	0.70	0.40	0.60	0.30
Haynes Alloy No. 188	22.0	–	22.0	39.0	3.0 max	–	14.0	–	–	–	–	1.25 max	0.40	0.10	–
Nickel–iron–chromium															
Haynes Alloy 556	20.0	–	22.0	20.0	29.0	3.0	2.5	0.9	0.1	0.3	–	1.50	0.40	0.10	–
Incoloy Alloy 800[b]	32.5	–	21.0	–	46.0	–	–	–	–	0.4	0.4	0.80	0.50	0.05	–
Nickel–copper															
Monel alloy 400[b]	66.5	31.5	–	–	1.3	–	–	–	–	–	–	1.0	0.25	0.15	–
Monel alloy K-500[b]	65.0	29.5	–	–	1.0	–	–	–	–	2.8	0.5	0.6	0.15	0.15	–

[a]From Nickel Development Institute (1987a); Bal, balance
[b]From Tien & Howson (1981)

Table 4. Typical composition of nickel-containing steels (weight %)[a]

Grade	Cr	Ni	Mn	Mo	C	Si	S	P	Fe
AISI-201	16-18	3.5-5.5	5.5-7.5	-	0.15	1.0	0.03	0.06	Balance
AISI-302	17-19	8.0-10.0	2.0	-	0.15	1.0	0.03	0.045	Balance
AISI-304	18-20	8.0-10.5	2.0	-	0.08	1.0	0.03	0.045	Balance
AISI-316	16-18	10-14	2.0	2-3	0.08	1.0	0.03	0.045	Balance

[a]From Nickel Development Institute (1987b); AISI, American Iron and Steel Institute

Nickel hydroxide is commercially available at 97% purity (Aldrich Chemical Co., Inc., 1988).

(*c*) *Nickel sulfides*

Nickel sulfide exists in three forms: the high-temperature, hexagonal crystal form, in which each nickel atom is octahedrally coordinated to six sulfur atoms; the low-temperature, rhombohedral form (which occurs naturally as millerite), in which each nickel atom is coordinated to two other nickel atoms and five sulfur atoms (Grice & Ferguson, 1974); and amorphous nickel sulfide. Amorphous nickel sulfide is gradually converted to nickel hydroxy sulfide on contact with air (Cotton & Wilkinson, 1988). Grice and Ferguson (1974) referred to the rhombohedral (millerite) form as β-nickel sulfide and the high-temperature hexagonal form as α-nickel sulfide. Different nomenclatures have been used by other authors (Abbracchio *et al.*, 1981; Grandjean, 1986). The term β-nickel sulfide is used to denote the rhombohedral millerite form throughout this monograph.

Nickel subsulfide exists in two forms: α-nickel subsulfide, the low-temperature, rhombohedral form (heazlewoodite), in which nickel atoms exist in distorted tetrahedral coordination and the sulfur atoms form an almost cubic body-centred sublattice, with six equidistant nickel neighbours; and β-nickel subsulfide, the high-temperature form (Sunderman & Maenza, 1976).

An examination of the surface of crystalline and amorphous nickel sulfide particles revealed that crystalline particles have a net negative surface charge, while the surface charge of amorphous nickel sulfide appears to be positive. X-Ray photoelectron spectroscopy analysis of amorphous and crystalline nickel sulfide showed that the outermost surface of the two compounds differed with respect to the Ni/S ratio and the sulfur oxidation state (Abbracchio *et al.*, 1981).

Nickel sulfides are intermediates in nickel smelting and refining which can be isolated as crude mattes for further processing but are not significant materials of commerce. Most nickel subsulfide is produced as an intermediate in many nickel refining processes (Boldt & Queneau, 1967).

(*d*) *Nickel salts*

Nickel acetate is available as the tetrahydrate at a purity of >97% (Mallinckrodt, Inc., 1987).

Nickel ammonium sulfate hexahydrate is available as analytical reagent-grade crystals at a purity of 99.0% min or at a grade for nickel plating (purity, 99-100%; Riedel-de-Haën, 1986).

Nickel carbonate is available mainly as hydroxycarbonates, such as basic nickel carbonate. Laboratory reagent grades may contain 47.5% or 45% nickel; industrial grades, as green powders or wet pastes, contain approximately 45% nickel (INCO, 1981-82; Pharmacie Centrale, 1988).

Nickel chloride is available as the hexahydrate as a laboratory reagent of >99% purity and as industrial products with about 24.7% nickel. It is also available in industrial quantities as an aqueous solution (ERAMET-SLN, 1985).

Nickel nitrate is available as the hexahydrate at >99% purity and as crystals and flakes (J.T. Baker, 1988).

Nickel sulfate is available as the heptahydrate at >99% purity and as the hexahydrate at 99% purity (Aldrich Chemical Co., Inc., 1988).

(*e*) *Other nickel compounds*

Nickelocene is available in solid form at >90% purity or as an 8-10% solution in toluene (American Tokyo Kasei, 1988).