CHROMIUM AND CHROMIUM COMPOUNDS

Chromium and chromium compounds were considered by previous IARC Working Groups, in 1972, 1979, 1982 and 1987 (IARC, 1973, 1979, 1980a, 1982, 1987a). 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 chromium alloys and compounds given in Table 1 is not exhaustive, nor does it necessarily reflect the commercial importance of the various chromium-containing substances, but it is indicative of the range of chromium alloys and compounds available.

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

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

Chemical name	Chem. Abstr. Services Reg. No.[a]	Synonyms and trade names	Formula[b]
Metallic chromium [0] and chromium [0] alloys			
Chromium	7440-47-3	**Chrome**	Cr
Cobalt-chromium alloy[c]	11114-92-4 (91700-55-9)	**Chromium alloy (nonbase), Co, Cr**; cobalt alloy (nonbase), Co, Cr	-
Cobalt-chromium-molybdenum alloy[c]	12629-02-6 (8064-15-1; 11068-92-1; 12618-69-8; 55345-18-1;	**Cobalt alloy (base), Co 56-68, Cr 25-29, Mo 5-6, Ni 1.8-3.8, Fe 0-3, Mn 0-1, Si 0-1, C 0.2-0.3 (ASTM A567-1)**	

Table 1 (contd)

Chemical name	Chem. Abstr. Services Reg. No.[a]	Synonyms and trade names	Formula[b]
	60382-64-1; 83272-15-5; 85131-98-2; 94076-26-3)	Akrit CoMo35; AMS 5385D; Celsit 290; F 75; HS 21; Protasul-2; Stellite 21; Vinertia; Vitallium; X25CoCr-Mo62 28 5; Zimalloy	
Chromium-containing stainless steels[c]	71631-40-8 (51204-69-4, 59601-19-3, 84723-14-8, 94197-89-4, 98286-69-2)	**Iron alloy (base), Fe 64-72, Cr 21-23, Ni 4.5-6.5, Mo 2.5-3.5, Mn 0-2, Si 0-1, N 0.1-0.2 (ASTM A276-S31803)** AF 22; AF 22-130; AISI 318L; Alloy 2205; Arosta 4462; AST 2205; Avesta 2205; Avesta 223FAL; CR22; 22Cr; 22Cr5Ni; CrNiMoN22-5-3; DIN 1.4462; ES 2205; FAL 223; 744LN; Mann AF-22; Nirosta 4462; NKK-Cr22; Novonox FALC 223; NU 744 LN; NU stainless 744LN; Remanit 4462; SAF 2205; Sandvik SAF 2205; SS 2377; Stainless steel 2205; Uddeholm Nu744LN; UHB 744LN; UNS S31803; Uranus 45N; UR45N; Vallourec VS22; VEW A903; VLX 562; VS 22; X2CrNiMoN2253; Z2 CND 22.5 AZ	-
Ferro-chrome[d]	11114-46-8 (11133-75-8, 11143-43-4, 12604-52-3)	**Chromium alloy (base), Cr, C, Fe, N, Si; ferrochromium**; carbon ferrochromium; chrome ferroalloy; chromium ferroalloy	-
Iron-nickel-chromium alloy	11121-96-3	**Iron alloy (base), 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 O-0.6, C 0-0.1 (ASTM B163-800)** AFNOR ZFeNC45-36; AISI 332; Alloy 800; Alloy 800NG; Cr20Ni32TiAl; 20Cr32NiTiAl; DIN 1.4876; FeCr21Ni32TiAl; IN 800; Incoloy 800; JIS NCF800; N800; NCF800; NCF 800 HTB; NCF steel; Nickel 800; Nicrofer 3220; Ni33Cr21TiAl; POLDI AKR 17; Pyro-met 800; Sanicro 31; Thermax 4876; TIG N800	-
Nickel-chromium alloy	12605-70-8	Nichrome; **Nickel alloy (base), Ni 57-62, Fe 22-28, Cr 14-18, Si 0.8-1.6, Mn 0-1, C 0-0.2 (ASTM B344-60 Ni, 16 Cr)** Chromel C; Kh15N60N; NiCr6015; PNKh; Tophet C	-
Chromium [III] compounds			
Basic chromic sulfate	12336-95-7 (39380-78-4)	Basic chromium sulfate; **chromium hydroxide sulfate ($Cr(OH)(SO_4)$)**; chromium sulfate; monobasic chromium sulfate; sulfuric acid, chromium salt, basic Chromedol; Chrometan; Chrome tan; Peachrome	$Cr(OH)SO_4$
	64093-79-4	**Neochromium**	$Cr(OH)SO_4.Na_2SO_4.H_2O$

Table 1 (contd)

Chemical name	Chem. Abstr. Services Reg. No.[a]	Synonyms and trade names	Formula[b]
Chromic acetate	1066-30-4	**Acetic acid, chromium (3+) salt**; chromium acetate; chromium [III] acetate; chromium triacetate	$Cr(OCOCH_3)_3$
Chromic chloride	10025-73-7	**Chromium chloride ($CrCl_3$)**; chromium [III] chloride; chromium trichloride; C.I. 77295; trichlorochromium	$CrCl_3$
Chromic hydroxide	1308-14-1	Chromic acid (H_3CrO_3); **chromium hydroxide ($Cr(OH)_3$)**; chromium [III] hydroxide; chromium (3+) hydroxide; chromium trihydroxide	$Cr(OH)_3$
Chromic nitrate	13548-38-4 (20249-21-2)	Chromium nitrate; chromium [III] nitrate; chromium (3+) nitrate; chromium trinitrate; **nitric acid, chromium (3+) salt**	$Cr(NO_3)_3$
Chromic oxide	1308-38-9	Chrome oxide; chromia; **chromium oxide (Cr_2O_3)**; chromium [III] oxide; chromium sesquioxide; chromium (3+) trioxide; C.I. 77288; C.I. Pigment Green 17; dichromium trioxide	Cr_2O_3
		Anadonis Green; Casalis Green; Chrome Green; Chrome Ochre; Chrome Oxide Green BX; Chrome Oxide Green GN-M; Chromium Oxide Pigment; Chromium 111 Oxide; Chromium Oxide Green; Chromium Oxide X1134; 11661 Green; Green Chrome Oxide; Green Chromic Oxide; Green Chromium Oxide; Green Cinnabar; Green Oxide of Chromium; Green Oxide of Chromium OC-31; Green Rouge; Guignet's Green; Leaf Green; Levanox Green GA (hydrated chromic oxide); Oil Green; Oxide of Chromium; P-106F10; Pure Chromium Oxide Green 59; Ultramarine Green	
Chromic perchlorate	13537-21-8	Chromium perchlorate; chromium triperchlorate; **perchloric acid, chromium (3+) salt**	$Cr(ClO_4)_3$
Chromic phosphate	7789-04-0	Chromium monophosphate; chromium orthophosphate; chromium phosphate; **phosphoric acid, chromium (3+) salt (1:1)**; phosphoric acid, chromium [III] salt	$CrPO_4$
		Arnaudon's Green (hemiheptahydrate); Plessy's Green (hemiheptahydrate)	
Chromic sulfate	10101-53-8 (39378-25-1)	Chromium sulfate (2:3); chromium [III] sulfate; dichromium sulfate; dichromium tris(sulfate); dichromium trisulfate; **sulfuric acid, chromium (3+) salt (3:2)**; C.I. 77305	$Cr_2(SO_4)_3$
		Baychrom A; Baychrom F; Chromitan B; Chromitan MS; Chromitan NA; Cromitan B; Koreon	
Chromite ore	1308-31-2 (61026-56-0)	Chrome ore; **chromite (Cr_2FeO_4)**; chromite mineral; iron chromite	$Cr_2O_3.FeO$
Nickel chromate	12018-18-7	**Chromic acid (H_2CrO_4), nickel salt (1:1)**	$NiCrO_4$

Table 1 (contd)

Chemical name	Chem. Abstr. Services Reg. No.[a]	Synonyms and trade names	Formula[b]
Potassium chromic sulfate	10141-00-1 (14766-82-6; 81827-72-7; 81827-73-8)	Chrome alum; chrome potash alum; chromic potassium sulfate; chromium potassium sulfate; potassium chromium alum; potassium chromium sulfate; potassium disulfatochromate [III]; **sulfuric acid, chromium (3+) potassium salt (2:1:1)** Chrome Alum 0% Basicity; Crystal Chrome Alum	$KCr(SO_4)_2$
Chromium[VI] compounds			
Ammonium chromate	7788-98-9	Chromic acid, ammonium salt; **chromic acid (H_2CrO_4), diammonium salt**; diammonium chromate; neutral ammonium chromate	$(NH_4)_2CrO_4$
Ammonium dichromate	7789-09-5	Ammonium bichromate; ammonium chromate; **chromic acid ($H_2Cr_2O_7$), diammonium salt**; diammonium dichromate; dichromic acid, diammonium salt	$(NH_4)_2Cr_2O_7$
Barium chromate	10294-40-3 (12000-34-9; 12231-18-4)	Barium chromate (VI); barium chromate (1:1); barium chromate oxide; **chromic acid (H_2CrO_4), barium salt (1:1)**; C.I. 77103; C.I. Pigment Yellow 31 Baryta Yellow; Lemon Chrome; Lemon Yellow; Permanent Yellow; Steinbuhl Yellow; Ultramarine Yellow	$BaCrO_4$
Basic lead chromate	1344-38-3 (54692-53-4)	C.I. 77601; **C.I. Pigment Orange 21**; C.I. Pigment Red; lead chromate oxide Arancio Cromo; Austrian Cinnabar; Basic Lead Chromate Orange; Chinese Red; Chrome Orange; Chrome Orange 54; Chrome Orange 56; Chrome Orange 57; Chrome Orange 58; Chrome Orange Dark; Chrome Orange Extra Light; Chrome Orange G; Chrome Orange Medium; Chrome Orange NC-22; Chrome Orange R; Chrome Orange 5R; Chrome Orange RF; Chrome Orange XL; Chrome Red; C.P. Chrome Orange Dark 2030; C.P. Chrome Orange Extra Dark 2040; C.P. Chrome Orange Light 2010; C.P. Chrome Orange Medium 2020; Dainichi Chrome Orange R; Dainichi Chrome Orange 5R; Genuine Acetate Orange Chrome; Genuine Orange Chrome; Indian Red; International Orange 2221; Irgachrome Orange OS; Light Orange Chrome; No. 156 Orange Chrome; Orange Chrome; Orange Nitrate Chrome; Pale Orange Chrome; Persian Red; Pigment Orange 21; Pure Orange Chrome M; Pure Orange Chrome Y; Red Lead Chromate; Vynamon Orange CR	$PbO.PbCrO_4$
Calcium chromate	13765-19-0	Calcium chromium oxide; calcium monochromate; **chromic acid (H_2CrO_4), calcium salt (1:1)**; C.I. 77223; C.I. Pigment Yellow 33 Calcium Chrome Yellow; Gelbin; Yellow Ultramarine	$CaCrO_4$

Table 1 (contd)

Chemical name	Chem. Abstr. Services Reg. No.[a]	Synonyms and trade names	Formula[b]
Chromium [VI] chloride	14986-48-2	Chromium hexachloride; **(OC-6-11)-chromium chloride ($CrCl_6$)**	$CrCl_6$
Chromium trioxide	1333-82-0 (12324-05-9; 12324-08-2)	Chromia; chromic acid; chromic [VI] acid; chromic acid, solid; chromic anhydride; chromic trioxide; **chromium oxide (CrO_3)**; chromium [VI] oxide; chromium (6+) trioxide; monochromium trioxide	CrO_3
Chromyl chloride	14977-61-8	Chlorochromic anhydride; chromium chloride oxide; chromium dichloride dioxide; **chromium, dichlorodioxo-(T-4)**; chromium dioxide dichloride; chromium dioxychloride; chromium oxychloride; dichlorodioxochromium	CrO_2Cl_2
Lead chromate	7758-97-6 (8049-64-7)	**Chromic acid (H_2CrO_4), lead (2+) salt (1:1)**; C.I. 77600; C.I. Pigment Yellow 34; crocoite; lead chromium oxide; phoenicochroite; plumbous chromate Canary Chrome Yellow 40-2250; Chrome Green; Chrome Green UC61; Chrome Green UC74; Chrome Green UC76; Chrome Lemon; Chrome Yellow; Chrome Yellow 5G; Chrome Yellow GF; Chrome Yellow LF; Chrome Yellow Light 1066; Chrome Yellow Light 1075; Chrome Yellow Medium 1074; Chrome Yellow Medium 1085; Chrome Yellow Medium 1295; Chrome Yellow Medium 1298; Chrome Yellow Primrose 1010; Chrome Yellow Primrose 1015; Cologne Yellow; Dainichi Chrome Yellow G; LD Chrome Yellow Supra 70 FS; Leipzig Yellow; Paris Yellow; Pigment Green 15; Primrose Chrome Yellow; Pure Lemon Chrome L3GS	$PbCrO_4$
Molybdenum orange	12656-85-8	**C.I. Pigment Red 104** Chrome Vermilion; Krolor Orange RKO 786D; Lead chromate molybdate sulfate red; Mineral Fire Red 5DDS; Mineral Fire Red 5GGS; Mineral Fire Red 5GS; Molybdate Orange; Molybdate Orange Y 786D; Molybdate Orange YE 421D; Molybdate Orange YE 698D; Molybdate Red; Molybdate Red AA 3; Molybden Red; Molybdenum Red; Renol Molybdate Red RGS; Vynamon Scarlet BY; Vynamon Scarlet Y	$PbMoO_4 \cdot PbCrO_4 \cdot PbSO_4$
Potassium chromate	7789-00-6	Bipotassium chromate; **chromic acid (H_2CrO_4), dipotassium salt**; dipotassium chromate; dipotassium monochromate; neutral potassium chromate; potassium chromate [VI]	K_2CrO_4

Table 1 (contd)

Chemical name	Chem. Abstr. Services Reg. No.[a]	Synonyms and trade names	Formula[b]
Potassium dichromate	7778-50-9	**Chromic acid ($H_2Cr_2O_7$), dipotassium salt**; dichromic acid, dipotassium salt; dipotassium bichromate; dipotassium dichromate; potassium bichromate; potassium dichromate [VI]	$K_2Cr_2O_7$
Sodium chromate	7775-11-3	**Chromic acid (H_2CrO_4), disodium salt**; chromium disodium oxide; chromium sodium oxide; disodium chromate; neutral sodium chromate; sodium chromium oxide	Na_2CrO_4
Sodium dichromate	10588-01-9 (12018-32-5)	Bichromate of soda; **chromic acid ($H_2Cr_2O_7$), disodium salt**; chromium sodium oxide; dichromic acid, disodium salt; disodium dichromate; sodium bichromate; sodium dichromate [VI]	$Na_2Cr_2O_7$
Strontium chromate	7789-06-2 (54322-60-0)	**Chromic acid (H_2CrO_4), strontium salt (1:1)**; C.I. Pigment Yellow 32; strontium chromate [VI]; strontium chromate (1:1) Deep Lemon Yellow; Strontium Chromate 12170; Strontium Chromate A; Strontium Chromate X-2396; Strontium Yellow; Sutokuro T	$SrCrO_4$
Zinc chromate[e]	13530-65-9 (1308-13-0; 1328-67-2; 14675-41-3)	**Chromic acid (H_2CrO_4), zinc salt (1:1)**; chromium zinc oxide; zinc chromium oxide; zinc tetraoxychromate; zinc tetroxychromate Buttercup Yellow	$ZnCrO_4$
Zinc chromate hydroxides	15930-94-6 (12206-12-1; 66516-58-3)	Basic zinc chromate; chromic acid (H_6CrO_6), zinc salt (1:2); chromic acid (H_4CrO_5), zinc salt (1:2), monohydrate; chromium zinc hydroxide oxide; zinc chromate hydroxide; zinc chromate [VI] hydroxide; **zinc chromate oxide ($Zn_2(CrO_4)O$), monohydrate**; zinc hydroxychromate; zinc tetrahydroxychromate; zinc yellow[f]	$Zn_2CrO_4(OH)_2$ and others
Zinc potassium chromates (hydroxides)	11103-86-9 (12527-08-1; 37809-34-0)	Basic zinc potassium chromate; chromic acid ($H_6Cr_2O_9$), potassium zinc salt (1:1:2); **potassium hydroxyoctaoxodizincatedichromate(1-)**; potassium zinc chromate hydroxide; zinc yellow[f]	$KZn_2(CrO_4)_2(OH)$ and others
Other chromium compounds			
Chromium carbonyl	13007-92-6 (13930-94-4)	**Chromium carbonyl ($Cr(CO)_6$)**; chromium hexacarbonyl; hexacarbonyl chromium	$Cr(CO)_6$
Chromic chromate	24613-89-6	**Chromic acid (H_2CrO_4), chromium (3+) salt (3:2)**; chromium chromate	$Cr_2(CrO_4)_3$
Chromium [II] chloride	10049-05-5	**Chromium chloride ($CrCl_2$)**; chromium dichloride; chromous chloride	$CrCl_2$

Table 1 (contd)

Chemical name	Chem. Abstr. Services Reg. No.[a]	Synonyms and trade names	Formula[b]
Chromium [IV] dioxide	12018-01-8	Chromium dioxide; **chromium oxide (CrO_2)**; chromium [IV] oxide	CrO_2

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

[b] Compounds with the same synonym or trade name can have different formulae.

[c] Thousands of alloys of chromium with other metals are listed by the Chemical Abstracts Registry Service; approximately 1300 contain cobalt, over 400 also contain molybdenum and nearly 100 are chromium-containing stainless steels. An example of each is listed here.

[d] Chemical Abstracts Registry Service lists several ferrochromium alloys; one example is given.

[e] The term 'zinc chromate' is also used to refer to a wide range of commercial zinc and zinc potassium chromates.

[f] 'Zinc yellow' can refer to several zinc chromate pigments; it has the CAS No. 37300-23-5.

1.2 Chemical and physical properties of pure substances

Known physical properties of some of the chromium compounds considered in this monograph are given in Table 2. Data on solubility refer to saturated solutions in water or other specified solvents. Hexavalent chromium compounds are customarily classed as soluble or insoluble in water; such a classification is useful in industry but might not be relevant to determining the biological properties of a compound. There is thus no general agreement on the definition of solubility: in practice, the aqueous solubility of Cr[VI] compounds has been classified as prompt (1 min) and short-term (30 min) (Van Bemst *et al.*, 1983). In laboratory studies, solubilization depends on, e.g., the medium used in in-vitro tests; for human exposures, solubility is related to the chemical environment in the respiratory tract. Examples of soluble hexavalent chromium compounds are sodium chromate (873 g/l at 30 °C) and potassium chromate (629 g/l at 20 °C). Hexavalent chromium compounds classed as insoluble include barium chromate (4.4 mg/l at 28 °C) and lead chromate (0.58 mg/l at 25 °C) (Windholz, 1983; Weast, 1985). Compounds with solubilities towards the middle of this range are not easily classified, and technical-grade compounds, such as the various zinc chromates, can have a wide range of solubilities.

1.3 Technical products and impurities

(*a*) *Chromite ore*

Chromite ore consists of varying percentages of chromium, iron, aluminium and magnesium oxides as the major components. It has been classified into three

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

Chemical name	Atomic/ molecular weight	Melting-point (°C)	Boiling-point (°C)	Typical physical description	Solubility
Metallic chromium [0]					
Chromium	51.996	1900	2642	Steel-grey, lustrous metal or powder	Insoluble in water; soluble in dilute hydrochloric acid and sulfuric acid; insoluble in nitric acid or nitrohydrochloric acid
Chromium[III] compounds					
Basic chromic sulfate[b]	165.06	--	--	Green powder	Soluble in water (approximately 700 g/l at 35°C[b])
Chromic acetate (hydrate)	229.14 (247.15)	--	--	Grey-green powder (blue-violet needles)	Slightly soluble in water; insoluble in ethanol; soluble in cold water, acetone (2 g/l at 15°C) and methanol (45.4 g/l at 15°C)
Chromic chloride (hexahydrate)	158.36 (266.45)	1150 (83)	Sublimes at 1300	Violet crystalline scales	Anhydrous form is insoluble in cold water, slightly soluble in hot water, but insoluble in ethanol, acetone, methanol and diethyl ether. The hydrated form is very soluble in water (585 g/l), soluble in ethanol, slightly soluble in acetone and insoluble in diethyl ether.
Chromic nitrate (7.5 hydrate) (nonahydrate)	238.03 (373.13) (400.15)	- (100) (60)	- Decomposes Decomposes at 100	Pale-green powder (brown crystals) (deep-violet crystals)	Soluble in water. Both hydrated forms soluble in water; the nonahydrate is soluble in acids, alkali, ethanol and acetone
Chromic oxide	151.99	2435	4000	Light to dark-green, fine crystals	Insoluble in water, acids, alkali and ethanol
Chromic phosphate (dihydrate)	147 (183.00)	> 1800°C	--	Violet crystalline solid	Insoluble in water. Hydrated form is slightly soluble in cold water; soluble in most acids and alkali but not in acetic acid

Table 2 (contd)

Chemical name	Atomic/ molecular weight	Melting-point (°C)	Boiling-point (°C)	Typical physical description	Solubility
Chromic sulfate	392.16	--	--	Violet or red powder	Insoluble in water; slightly soluble in ethanol; insoluble in acids
Potassium chromic sulfate (dodecahydrate)	283.23 (499.39)	(89)	(400)	(Violet ruby-red to black crystals)	Hydrated form is soluble in water (243.9 g/l at 25°C; 500 g/l in hot water); slightly soluble in dilute acids; insoluble in ethanol
Chromium[VI] compounds					
Ammonium chromate	152.07	180	--	Yellow acicular crystals	Soluble in water (405 g/l); insoluble in ethanol, slightly soluble in ammonia, acetone and methanol
Ammonium dichromate	252.06	170 (dec)[c]	--	Orange-red crystals	Soluble in water (308 g/l at 15°C; 890 g/l at 30°C) and ethanol; insoluble in acetone
Barium chromate	253.33	--	--	Yellow crystals	Very slightly soluble in water (4.4 mg/l at 28°C); soluble in mineral acids
Basic lead chromate	546.37	--	--	Red crystalline powder	Insoluble in water; soluble in acids and alkali
Calcium chromate (dihydrate)	156.09 (192.10)	(200)	--	Yellow crystalline powder	Slightly soluble in water and ethanol; soluble in acids. Hydrated form is soluble in water (163 g/l at 20°C; 182 g/l at 45°C), acids and ethanol
Chromium trioxide	99.99	196	Decomposes at 250[c]	Dark-red crystals, flakes or granular powder	Soluble in water (625 g/l at 20°C; 674.5 g/l at 100°C), ethanol, diethyl ether and sulfuric and nitric acids
Chromyl chloride	154.90	-96.5	117	Dark-red volatile liquid	Decomposes in water and ethanol; soluble in ether, acetic acid, carbon tetrachloride, carbon disulfide, benzene, nitrobenzene, chloroform and phosphorous oxychloride

Table 2 (contd)

Chemical name	Atomic/ molecular weight	Melting-point (°C)	Boiling-point (°C)	Typical physical description	Solubility
Lead chromate	323.18	844	Decomposes	Yellow to orange-yellow crystalline powder	Very slightly soluble in water (0.58 mg/l at 25°C); soluble in most acids and alkali but not in acetic acid or ammonia
Nickel chromate	174.71	—	—	—	Insoluble in water; soluble in nitric acid and hydrogen peroxide
Potassium chromate	194.20	968.3	Decomposes[c]	Lemon-yellow crystals	Soluble in water (629 g/l at 20°C; 792 g/l at 100°C); insoluble in ethanol
Potassium dichromate	294.19	398	Decomposes at 500	Bright orange-red crystals	Soluble in water (49 g/l at 0°C; 1020 g/l at 100°C); insoluble in ethanol
Sodium chromate	161.97	792	Decomposes[c]	Yellow crystals	Soluble in water (873 g/l at 30°C) and methanol (3.44 g/l at 25°C); slightly soluble in ethanol
Sodium dichromate (dihydrate)	262.00 (298.00)	356.7	Decomposes at 400[c]	Reddish to bright-orange crystals	Soluble in water (2380 g/l at 0°C; 5080 g/l at 80°C); and methanol (513.2 g/l at 19.4°C); insoluble in ethanol
Strontium chromate	203.61	Decomposes[d]	—	Yellow crystalline powder	Slightly soluble in water (1.2 g/l at 15°C; 30 g/l at 100°C); soluble in hydrochloric, nitric and acetic acids and ammonium salts
Zinc chromate	181.37	—	—	Lemon-yellow crystals	Insoluble in cold water; decomposes in hot water; soluble in acids and liquid ammonia
Zinc chromate hydroxide	280.74	—	—	Fine yellow powder	Slightly soluble in water; soluble in dilute acids, including acetic acid
Other chromium compounds					
Chromium carbonyl	220.06	Decomposes at 110	Explodes at 210	Colourless crystals or white solid	Insoluble in water; slightly soluble in carbon tetrachloride and iodoform; insoluble in ethanol, diethyl ether and acetic acid

Table 2 (contd)

Chemical name	Atomic/ molecular weight	Melting-point (°C)	Boiling-point (°C)	Typical physical description	Solubility
Chromium [II] chloride	122.90	824	--	White lustrous needles or fused fibrous mass	Soluble in water; insoluble in ethanol and diethyl ether
Chromium dioxide	83.99	300	--	Brown-black crystalline powder	Insoluble in water; soluble in nitric acid

[a]From Windholz (1983) and Weast (1985), unless otherwise specified

[b]From British Chrome & Chemical Ltd (1988)

[c]From Udy (1956)

[d]From Hartford (1979)

general grades associated with their use and chromic oxide content: metallurgical (greater than 46%), chemical (40-46%) and refractory (less than 40%) grades (Papp, 1985). During the past two decades, technological advances have allowed considerable interchangeability among the various grades, particularly the so-called chemical grade which can be utilized in all three industries. A more definitive classification is: (i) 'high-chromium' chromite (metallurgical-grade), containing a minimum of 46% chromic oxide and a chromium:iron ratio greater than 2:1; (ii) 'high-iron' chromite (chemical-grade), with 40-46% chromic oxide and a chromium:iron ratio of 1.5:1 to 2:1; and (iii) 'high-aluminium' chromite (refractory-grade), containing more than 20% aluminium oxide and more than 60% aluminium oxide plus chromic oxide (Papp, 1983).

Chromite from one US processor had the following typical analysis: chromium (as chromic oxide), 45.57%; iron (as ferric oxide), 29.80%; aluminium (as aluminium oxide), 13.80%; magnesium (as magnesium oxide), 9.28%; silicon (as silicon dioxide), 1.13%; and calcium (as calcium oxide), 0.40% (Cyprus Specialty Metals, 1988).

(*b*) *Metallic chromium and chromium alloys*

Chromium (pure) metal is a minor product of the metallurgical processing of chromium. It is available as electrolytic chromium (98.7-99.5% Cr; Elkem Metals Co., 1986), aluminothermic chromium (98.3% Cr (Morning, 1975) and 99.0-99.8% Cr (Delachaux, 1989)) and vacuum aluminothermic chromium (99.5-99.8% Cr; Delachaux, 1989). Electrolytic chromium and aluminothermic chromium typically contain traces of silicon, carbon, phosphorus, sulfur, iron, aluminium, nitrogen, oxygen and hydrogen (Elkem Metals Co., 1986; Belmont Metals, 1989). Chromium metal rapidly forms an oxide layer at the surface in air; such oxidation of finely divided chromium powder can result in the conversion of a large fraction of the metal to metal oxide upon prolonged storage (Sunderman *et al.*, 1974).

Ferrochromiums are the main intermediates in the metallurgical processing of chromium. There are three categories: high-carbon, low-carbon and ferrochromium silicon. The compositions of typical ferrochromiums are given in Table 3 (Morning, 1975).

Chromium-containing steels are usually stainless steels and are iron-base alloys. Some representative analyses of various grades are given in Table 4.

Chromium alloys can be categorized as nickel-chromium, cobalt-chromium and iron-nickel-chromium alloys. Some representative analyses are given in Table 5.

A range of chromium-containing alloys is used for surgical implants. Specifications of the American Society for Testing and Materials for such alloys are given in Table 6.

Table 3. Composition of typical ferrochromium and chromium metals[a]

Grade	Chromium	Silicon	Carbon	Sulfur (max)	Phosphorus (max)
High-carbon	65-70	1-2	5-6.5	0.04	0.03
Charge chromium:					
50-55% chromium	50-55	3-6	6-8	0.04	0.03
66-70% chromium	66-70	3	5-6.5	0.04	0.03
Low-carbon:					
0.025% carbon	67-75	1	0.025	0.025	0.03
0.05% carbon	67-75	1	0.05	0.025	0.03
Ferrochromium-silicon					
36/40 grade	35-37	39-41	0.05	-	-
40/43 grade	39-41	42-45	0.05	-	-

[a]From Morning (1975)

Table 4. Elemental analysis of representative grades of stainless steel[a]

Grade of steel	Elements in presence of iron (weight %)								
	Cr	Ni	Mn	Mo	C	Si	S	P	N
Austenitic									
AISI-201	16.0-18.0	3.5-5.5	5.5-7.5	-	0.15	1.0	0.03	0.06	0.25
AISI-302	17.0-19.0	8.0-10.0	2.0	-	0.15	1.0	0.03	0.05	-
AISI-304	18.0-20.0	8.0-10.5	2.0	-	0.08	1.0	0.03	0.05	-
AISI-316	16.0-18.0	10.0-14.0	2.0	2.0-3.0	0.08	1.0	0.03	0.05	-
Ferritic									
AISI-405	11.5-14.5	-	1.0	-	0.08	1.0	0.03	0.04	-
AISI-430	16.0-18.0	-	1.0	-	0.12	1.0	0.03	0.04	-
AISI-442	18.0-23.0	-	1.0	-	0.20	1.0	0.03	0.04	-
Martensitic									
AISI-403	11.5-13.0	-	1.0	-	0.15	0.50	0.03	0.04	-
AISI-440 A	16.0-18.0	-	1.0	0.75	0.60-0.75	1.0	0.03	0.04	-

[a]From Nickel Development Institute (1987a)

Table 5. Elemental analyses of representative chromium alloys (weight %)

Alloy	Cr	Ni	Co	Fe	Mo	W	Ta	Nb	Al	Ti	Mn	Si	C	B	Zr
Nickel base															
Cast alloys															
Cast alloy 625	21.6	63.0	–	2.0	8.7	–	–	3.9	0.2	0.2	0.06	0.20	0.20	–	–
Nimocast alloy 263	20.0	55.0	20.0	0.5	5.8	–	–	–	0.5	2.2	0.50	–	0.06	0.008	0.04
Udimet 500	18.0	52.0	19.0	–	4.2	–	–	–	3.0	3.0	–	–	0.07	0.007	0.05
Wrought alloys															
Hastelloy alloy X	22.0	47.0	1.5	18.5	9.0	0.6	–	–	–	–	0.50	0.50	0.10	–	–
Inconel alloy 617	22.0	54.0	12.5	–	9.0	–	–	–	1.0	–	–	–	0.07	–	–
Nimonic alloy PE 16	16.5	43.5	–	34.4	3.2	–	–	–	1.2	1.2	–	–	0.05	0.003	0.04
Cobalt base															
Cast alloys															
Haynes alloy 1002	22.0	16.0	Bal.	1.5	–	7.0	3.8	–	0.3	0.2	0.70	0.40	0.60	–	0.30
WI-52	21.0	–	63.0	2.0	–	11.0	–	2.0	–	–	0.25	0.25	0.45	–	–
Wrought alloy															
Haynes alloy 188	22.0	22.0	39.0	3.0 (max)	–	14.0	–	–	–	–	1.25 (max)	0.40	0.10	–	–
Iron–nickel base															
Wrought alloys															
Haynes alloy 556	22.0	20.0	20.0	29.0	3.0	2.5	0.9	0.1	0.3	–	1.50	0.40	0.10	–	–
Incoloy alloy 800	21.0	32.5	–	46.0	–	–	–	–	0.4	0.4	0.80	0.50	0.05	–	–

[a]From Nickel Development Institute (1987b); Bal, balance

Table 6. Composition specifications for four representative chromium–containing alloys used in surgical implants (weight %)[a]

Alloy	Cr	Mo	Ni	Fe	C	Si	Mn	N	P	S	Ti	W	Co
A	27.0–30.0	5.0–7.0	1.0 max	0.75 max	0.35 max	1.0 max	1.0 max	NA	NA	NA	NA	NA	Balance
B	19.0–21.0	9.0–10.5	33.0–37.0	1.0 max	0.025 max	0.15 max	0.15 max	NA	0.015 max	0.01 max	1.0 max	NA	Balance
C	18.0–22.0	3.0–4.0	15.0–25.0	4.0–6.0	0.05 max	0.50 max	1.0 max	NA	NA	0.01 max	0.5–3.5	3.0–4.0	Balance
D	26.0–30.0	5.0–7.0	1.0 max	0.75 max	0.35 max	1.0 max	1.0 max	0.25 max	NA	NA	NA	NA	Balance

[a]From American Society for Testing and Materials (1984a, 1987a,b, 1988a)

NA, not applicable

(*c*) *Chromium [III] compounds*

Basic chromic sulfate is produced by one company in the UK, as 67% basic chromic sulfate and 25-37% sodium sulfate (British Chrome & Chemical Ltd, 1988).

Chromic acetate is available as a 50% green aqueous solution with the following typical analysis; chromium, 11.4%; sulfate, less than 0.2%; chloride, less than 0.1% (McGean-Rohco, 1984).

Chromic chloride hexahydrate is available as a 62% green aqueous solution, typically containing 12% chromium and less than 0.2% sulfate (McGean-Rohco, 1984).

Chromic nitrate is available as a hydrate ($Cr(NO_3)_3.7.5\text{-}9H_2O$) in granules; 12.5-13.5% chromium and as the nonahydrate in liquid form (6.5-10.9% chromium) (McGean-Rohco, 1984).

Chromic oxide is available in several grades depending on its use in metallurgical and refractory industries. A typical analysis of a metallurgical grade is 99.4% chromium (as chromic oxide) and less than 0.1% moisture. A typical analysis of a refractory grade is 98.5-99.4% chromium (as chromic oxide), 0.1% alkali metals (as sodium oxide), 0.1% other metal oxides (mainly aluminium, iron and magnesium), and average particle size, 0.5-3.5 μm (American Chrome & Chemicals, undated a,b,c,d). Chromic oxide pigment (dark chromium oxide) typically contains > 99.0% chromium as chromic oxide (Mineral Pigments Corp., undated a).

Chrome base spinels are part of the family of mixed metal oxide organic coloured pigments. Two such pigments are (i) chromium iron nickel black spinel, the composition of which may include any one or a combination of cupric oxide, manganese oxide and manganese sesquioxide as modifiers, and (ii) chrome manganese zinc brown spinel, which may contain any one or a combination of aluminium oxide, nickel monoxide, silicon dioxide, stannous oxide and titanium dioxide as modifiers (Dry Color Manufacturers' Association, 1982).

Chromic phosphate tetrahydrate is available with a purity of 99.9% (National Chemical Co., undated a).

Analytical reagent-grade *chromium sulfate* hydrate is available with the following impurities: ammonium, 0.01% max; chloride, 0.002% max; insoluble matter, 0.01% max; and iron, 0.01% max. Analytical reagent-grade *potassium chromic sulfate* dodecahydrate is available at a purity greater than 98.0%. Potassium chromic sulfate with various degrees of hydration is available commercially as Chrome Alum Crystal (violet crystals) containing 10% chromium and Chrome Alum 0% Basicity (green powder) containing 15.4% chromium (McGean-Rohco, 1984).

(*d*) *Chromium[VI] compounds*

Ammonium dichromate is available as analytical reagent-grade crystals (99.5%) and as purified-grade crystals and granules with the following impurities: chloride, 0.005% max; fixed alkalis (as sulfate), 0.1-0.2% max; insoluble matter, 0.005% max; and sulfate, 0.005% max.

Calcium chromate is available at a purity of 96% min (Barium & Chemicals, 1988a). When used as a pigment for primer applications, it has the following typical analysis: chromium oxide, 45%; calcium oxide, 44%; chloride, less than 0.001%; sulfate, less than 0.001%; and moisture, 0.01% (National Chemical Co., undated b).

Chromium trioxide is available commercially at a purity of 99.9% (McGean-Rohco, 1984; Occidental Chemical Corp., 1987a; American Chrome & Chemicals, undated e). Two grades available from one company in Europe contain maxima of 20 and 100 mg/kg metallic impurities.

Analytical reagent-grade *potassium chromate* (crystals) is available at a purity of 99.0%. *Potassium dichromate* is available at a purity of 99.8% (Occidental Chemical Corp., 1987b).

Technical-grade anhydrous *sodium chromate* is available at a purity of 99.5% (Occidental Chemical Corp., 1987c). *Sodium dichromate* dihydrate is available at a purity of 100.0% (American Chrome & Chemicals, undated f). Anhydrous sodium dichromate is available at a purity of 99.70% (American Chrome & Chemicals, undated g).

Barium chromate is available at a purity of 98.5-99% (Atomergic Chemetals Corp., 1980; Barium & Chemicals, 1988b; National Chemical Co., undated c).

The term '*zinc chromate*' is a generic term for a series of commercial products with three kinds of molecular structure: (i) 'zinc chromate' type (like $ZnCrO_4$); (ii) 'basic zinc chromate' type (like zinc tetrahydroxychromate ($ZnCrO_4.4Zn(OH)_2$); and (iii) '(basic) zinc potassium chromate' type (like $3ZnCrO_4.Zn(OH)_2.K_2CrO_4.2H_2O$). Several different commercial 'zinc chromates' are also referred to as 'zinc yellow'.

Analytical reagent-grade *lead chromate* powder is available at a purity of >98%. The commercial lead chromate pigments, Primrose Chrome Yellow, Light Chrome Yellow and Medium Chrome Yellow, contain 65-89% lead chromate (Mineral Pigments Corp., undated b,c; National Chemical Co., undated d).

Molybdenum orange is described as a complex of lead molybdate, lead chromate and lead sulfate (National Chemical Co., undated e). One composition comprises 65% lead, 12% chromium and 3% molybdenum (Wayne Pigment Corp., 1985a,b).

Strontium chromate is available at a purity of 99% (National Chemical Co., undated f). A strontium chromate pigment is available with a typical analysis of 41.4% strontium and 46.7-47.3% chromium (Mineral Pigments Corp., undated d).